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Co-composting rice hulls and/or sawdust with poultry manure in NE Argentina

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ABSTRACT

Rice hulls and sawdust are two common C-rich wastes derived from rice and timber agro-industries in subtropical NE Argentina. An alternative to the current management of these wastes (from bedding to uncontrolled burning) is composting. However, given their C-rich nature and high C/N ratio, adequate composting requires mixing with a N-rich waste, such as poultry manure. The effect of different proportions of poultry manure, rice hulls and/or sawdust on composting efficiency and final compost quality was studied. Five piles were prepared with a 2:1 and 1:1 ratio of sawdust or rice hulls to poultry manure, and 1:1:1 of all three materials (V/V). Different indicators of compost stability and quality were measured. Thermophilic phase was shorter for piles with rice hulls than for piles with sawdust (60 days vs. 105 days). Time required for stability was similar for both C-rich wastes (about 180 days). Characteristics of final composts were: pH 5.8–7.2, electrical conductivity 2.5–3.3 mS/cm, organic C 20–26%, total N 2.2–2.9%, lignin 19–22%, total Ca 18–24 g/kg, and extractable P 6–8 g/kg, the latter representing 60% of total P. Nitrogen conservation was high in all piles, especially in the one containing both C-rich wastes. Piles with sawdust were characterized by high total and available N, while piles with only rice hulls had higher Si, K and pH. Extractable P was higher in 1:1 piles, and organic C in 2:1 piles.

1. Introduction

In the Mesopotamia region of NE Argentina (provinces of Misiones, Corrientes, and Entre Ríos) considerable amounts of C-rich wastes are generated from timber and rice agro-industries. Regarding timber industry, Misiones and Corrientes currently process 2,400,000 m^3 of sawn timber per year, with 40–50% of waste production in the form of sawdust, wood shavings and bark (SAGPyA, 2003). Concerning rice industry, almost 90% of Argentina's rice mills are located in Entre Ríos and Corrientes. Rice production in Corrientes during 2002–2003 was 300,000 t, and considering that 20% of this production is discarded as rice hulls, waste production in Corrientes alone amounted to 60,000 t for that period (DECPC, 2005). The fate of these wastes is diverse, from bedding or combustible materials to uncontrolled burning.

Considering the high proportion of sandy or highly weathered soils in this region, and the humid subtropical climate, an interesting alternative for processing these wastes is composting, because it produces stable organic matter and nutrients, which can be returned to the soil. However, neither rice hulls nor sawdust can be composted alone, because of their high C/N ratio (greater than 100), high cellulose and lignin concentration, and very low nutrient concentrations. Thus, they must be composted in mixtures with materials rich in nutrients, especially N and easily decomposable C (Rynk et al., 1992; Brodie et al., 2000). For example, in Asia rice hulls and sawdust are often co-composted with animal manures (Haga, 2001; Wang et al., 2005).

The province of Entre Ríos has the highest proportion (53%) of broilers in Argentina (37,000,000 birds) and 22% of layers (6,000,000 birds) (SAGPyA, 2007). It is usually considered that waste production is around 1 kg per bird per day for broiler (poultry litter), and 80–100 g per bird per day for layers (poultry manure). Since these wastes have very low C/N ratios (5–9) and high contents of P and base cations, co-composting rice hulls and sawdust with poultry manure is an economically and environmentally sound alternative.

Although both carbonous materials have high C/N ratios and low nutrient contents, rice hulls are characterized by a waxed surface and high silica contents which reduce water-holding capacity and could limit microbial attack (Wang et al., 2005; Massey et al., 2007). Thus, it can be expected that, when mixed with the same nutrient-rich manure, rice hulls and sawdust will differentially affect composting efficiency and final compost quality, in terms of length of the process, degree of stabilization, final quantity and quality of organic matter, and total and available nutrients. To elucidate the effect of type and proportion of both carbonous materials, either alone or combined, would contribute to optimize composting performance, and the production of composts with different characteristics and end uses. The main objective of this work was to study the effect of different proportions of rice hulls,

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sawdust and poultry manure on composting efficiency and final compost quality in experiments conducted as open systems in subtropical NE Argentina.

2. Materials and methods

2.1. Composting process

The composting experiments were conducted at 65 m a.s.l., 27° 27′ 25.70″ S and 58° 40′ 26.76″ W (Corrientes, Argentina), where mean annual temperature is 20–22 °C and mean annual precipitation is 1100 mm. Poultry manure (mixture of excreta, feather and some feed) was obtained from a layer facility and was partially dried. Rice hulls and sawdust were obtained from open piles accumulated in a rice mill and a sawmill, respectively.

Five piles were prepared at a pilot-scale (1.6 m high and 2 × 3 m base), with a high (2:1) and a low (1:1) ratio of C-rich material to poultry manure (V/V). The treatments were as follows: 1:1 sawdust: poultry manure (SP1); 2:1 sawdust: poultry manure (SP2); 1:1 rice hulls: poultry manure (RP1); 2:1 rice hulls: poultry manure (RP2), and 1:1:1 sawdust: rice hulls: poultry manure (SRP). Piles with 2:1 ratio and 1:1:1 ratio were watered with 0.35 m^3, and 1:1 ratio piles with 0.55 m^3 resulting in 55–65% moisture contents. During composting, piles were manually turned 6 times (at 11, 23, 60, 109, 152 and 219 days), and watered twice (at 60 and 109 days). The study was started in January (summer) and finished in September (spring) of the year 2006; during this period mean monthly temperatures varied from 28 °C to 16 °C, and total precipitation was 852 mm, the highest values corresponding to March (250 mm) and April (150 mm). For the first 40 days, piles were covered with a 200 μm-plastic film to avoid excess of moisture due to heavy rains, but because the piles tended to dry, the film was replaced by a shade cloth mesh. Temperatures were daily controlled at 0.20 and 0.40 m depth with a Reotemp® compost thermometer.

Three composite samples of each original material were air-dried, ground and analyzed for density, pH, electrical conductivity (EC), total organic C (TOC), total nutrients (N, P, Ca, Mg, K and Na), extractable P, water-soluble C (WSC), lignin, cellulose and hemicellulose. During the composting period, three composite samples were taken from each composting pile at 7 dates (t_0, 20, 40, 80, 120, 180 and 240 days). Each composite sample consisted of three sub-samples (about 1 kg each) taken at 0.30–0.40 m depth. Approximately 20 g of each composite fresh sample was used for assessing CO_2 evolution; the rest was air-dried, ground, and analyzed for pH, EC, TOC, total N (TN), NO_3^-—N, NH_4^+—N, and WSC.

Final composts were sampled from each pile one week after the last composting date (three composite samples), sieved by a 5-mm mesh, air-dried, and analyzed for pH, EC, TOC, cellulose, hemicellulose, lignin, TN, NO_3^-—N, NH_4^+—N, extractable P, and total P, Ca, Mg, K, Na and Si. Two of the three composite samples were analyzed for the following trace metals: As, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Se and Zn.

2.2. Analytical methods

To assess CO_2 evolution, fresh samples equivalent to 10 g dry weight were adjusted to 50% moisture, and incubated in sealed flasks at 31 °C with vials containing 1 N NaOH, where CO_2 was trapped. Blanks were also incubated. After 24, 48, and 72 h of incubation, the remaining NaOH was titrated with 0.5 N HCl after addition of excess $BaCl_2$. The following equation was applied (Anderson, 1982):

$$\text{mg of } CO_2 = (B - S) * N * E,$$

where B = mL of acid needed to titrate the NaOH in the blank vials; S = mL of acid needed to titrate the NaOH in the sample vials; N = normality of the acid; E = 22, equivalent weight to express as CO_2.

The CO_2 production rate (respiration rate) as mg CO_2–C/kg dry matter/h was calculated as an average of values for 48 and 72 h (Iannotti et al., 1994; Tognetti et al., 2007).

Electrical conductivity, pH, NO_3^-—N, NH_4^+—N and WSC were determined in 1:10 ratio water extracts (García et al., 1991; Laos et al., 2002). Ammonium was measured by the Berthelot reaction, NO_3^-—N by copperized Cd reduction, and WSC as Chemical Oxygen Demand by wet acid digestion (Laos et al., 2002). In the final composts, NH_4^+—N and NO_3^-—N were extracted with 2 M KCl (1:10). Total N was determined by the semi-micro Kjeldahl method plus NO_3^-—N, and TOC by ignition at 550 °C using a factor of 1.8 to convert organic matter to carbon (Rynk et al., 1992; Barrington et al., 2002). Losses of C and N during composting were calculated based on dry matter of initial (t_0) and final dates (t_{240}). To avoid the effect of dry matter loss and ash increase over time due to the mineralization of organic matter, losses were also calculated considering constant the ash content during the process. The following equation for TOC loss (or TN loss) was applied using the initial (X_i) and final (X_f) ash content (García-Gómez et al., 2003):

$$\text{TOC loss } (\%) = 100 - 100[(X_i \ \text{TOC}_f)/(X_f \ \text{TOC}_i)]$$

Samples digested for organic matter were extracted with HCl, and analyzed for total Ca, Mg, Na and K by atomic absorption spectrometry, and for total P by the molybdate–ascorbic acid method (Richards, 1993). Extractable P was analyzed in bicarbonate extracts (1:100) by the molybdate–ascorbic acid method (Sparks et al., 1996). To determine lignin, cellulose and hemicellulose, the Van Soest technique (1963) was employed. Si and trace elements were extracted with nitric–percloric wet digestion (1:1) and analyzed according to EPA Method 3050 (USEPA, 1986). All data were corrected by dry weight at 70 °C.

To better explain differences among final composts, principal component analysis (PCA) and cluster analysis with hierarchical ascendant classification (HAC) and Ward's aggregation criterion were applied. In a second step, a segmentation tree analysis was performed to identify the representative variables for each subgroup. The variables included were those highly correlated with the axes: pH, TOC, TN, C/N, NH_4^+—N, NO_3^-—N, Si, K, extractable P, lignin and cellulose. Total P was eliminated due to high autocorrelation with extractable P. Each sample was considered as an individual observation, so a total of 15 observations (three samples per each of the five treatments) were used. The variables were standardized because they differed in their measurement units. The software SPAD 4.5 (2000) was employed.

3. Results

Physico-chemical characteristics of original materials are given in Table 1. Poultry manure had greater nutrient concentrations and lower organic C than sawdust and rice hulls (3.7 vs. 0.5% total N; 15 vs. 0.2 g/kg total P; 18 vs. 2 g/kg total K; 29 vs. 42–53% TOC). It also had higher pH (8 vs. 6.6) associated to high Ca concentrations (19.4 vs. 2–4 g/kg). Total organic C in sawdust was higher than in rice hulls (53% and 42%, respectively), while C fractions (hemicellulose, cellulose and lignin) were quite similar. Lignin concentrations in sawdust and rice hulls (21–24%) were higher than in poultry manure (10%), and water-soluble C (WSC) was lower (3 vs. 14 g/kg).

3.1. Temperature and moisture profiles

Temperatures measured at 0.40 m are given in Fig. 1; values at 0.20 m followed a similar trend, but were slightly lower (data not

Table 1
Physico-chemical characteristics of poultry manure, sawdust and rice hulls.

	Sawdust	Rice hulls	Poultry manure
Moisture (%)	64.2 ± 3.8	5.4 ± 0.6	38.2 ± 2.6
Density (g/mL)	0.24 ± 0.04	0.14 ± 0.02	0.47 ± 0.03
pH	6.7 ± 0.1	6.5 ± 0.1	8.0 ± 0.1
EC (mS/cm)	0.4 ± 0.1	0.4 ± 0.1	4.3 ± 0.2
TOC (%)	53.2 ± 0.5	42.0 ± 0.8	29.0 ± 2.4
TN (%)	0.6 ± 0.1	0.4 ± 0.1	3.7 ± 0.3
C/N	106 ± 3	109 ± 9	9.0 ± 0.6
WSC (g/kg)	2.6 ± 0.2	3.1 ± 0.2	13.7 ± 0.4
Cellulose (%)	57.4 ± 5.5	59.0 ± 6.0	60.7 ± 4.7
Hemicellulose (%)	14.3 ± 3.0	12.1 ± 2.8	8.5 ± 1.9
Lignin (%)	24.1 ± 2.8	20.9 ± 2.4	9.5 ± 0.7
Extractable P (g/kg)	0.03 ± 0.01	0.07 ± 0.01	4.15 ± 0.19
Total elements (g/kg)			
P	0.15 ± 0.01	0.26 ± 0.03	14.81 ± 1.49
Ca	1.6 ± 0.3	3.8 ± 0.3	19.4 ± 3.0
Mg	0.5 ± 0.1	0.4 ± 0.1	6.6 ± 0.1
K	1.9 ± 0.1	1.8 ± 0.1	17.6 ± 4.0
Na	0.4 ± 0.4	0.3 ± 0.1	2.9 ± 0.6

Values are average of three samples ± standard deviation. TOC = total organic C; TN = total N; EC = electrical conductivity; WSC = water-soluble C.

shown). One day after pile establishment, temperatures reached values between 50 °C and 68 °C, increasing to 61–76 °C during the second day. In order to cool piles, these were turned twice during the first 25 days; however, after each turn, temperatures increased to very high values within 24 h. Piles with sawdust had a longer thermophilic phase (about 105 days) than rice hull piles (40–60 days); the pile with both carbonous materials (SRP) had a similar profile as sawdust piles, and a 96 day thermophilic phase. Initial temperatures in piles with rice hulls were higher than in sawdust piles (76 °C versus 70 °C for the first 20 days).

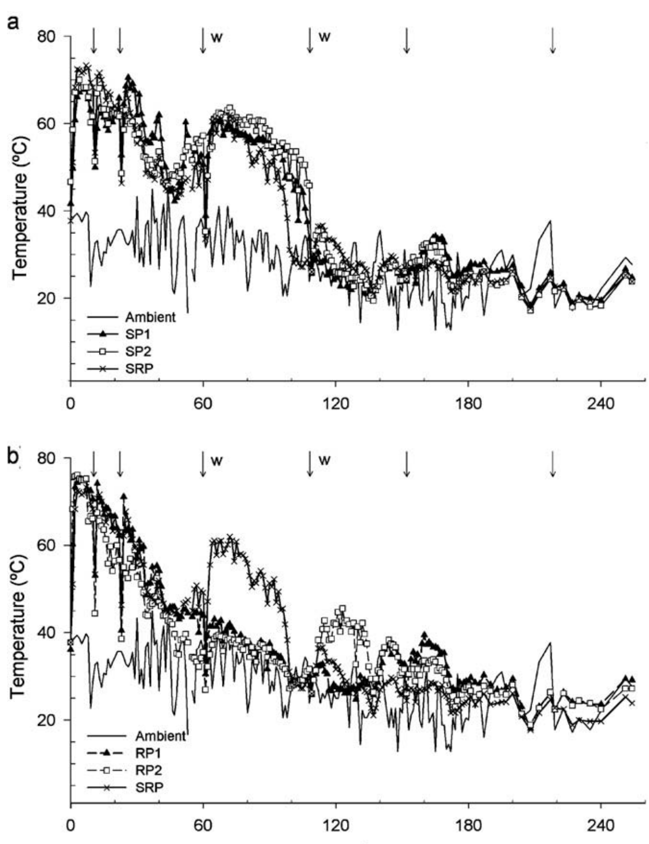

Fig. 1. Temperature profiles during composting: (a) piles of sawdust and poultry manure (b) piles of rice hulls and poultry manure. Pile with sawdust, rice hulls and poultry manure is given in (a) and (b). Arrows indicate turnings and "w" watering. Symbols of treatments: SP1 = sawdust + poultry manure (1:1); SP2 = sawdust + poultry manure (2:1); RP1 = rice hulls + poultry manure (1:1); SP2 = rice hulls + poultry manure (2:1) and SRP = sawdust + rice hulls + poultry manure (1:1:1).

Initial moisture values were between 55% and 65%, but high initial temperatures determined a moisture decrease in all piles (Fig. 2), which in turn resulted in a temperature decrease to near 42–46 °C at 40 days. Afterwards piles were uncovered to allow moistening by rainfall. Since temperatures tended to increase under the effect of the heavy rains of March and April, but rewetting throughout the pile was not uniform, all piles were homogenously watered while turning at 60 days (first rewetting) and at 109 days (second rewetting). Despite the fact that moisture in the piles with sawdust (SP1, SP2) was within the optimum range (50–55%), temperatures increased again after the first rewetting to values between 60 °C and 63 °C. Rice hull piles retained less water (39–58%) than sawdust piles (42–65%); SRP showed a similar profile as sawdust piles, but with lower values (32–61%). After the second rewetting, temperature increased only in RP2 but without reaching thermophilic values. In all piles, ambient temperatures were reached after approximately 180 days of pile establishment.

3.2. CO_2 evolution

The highest values of the respiration rate (Fig. 3) were observed at t_0 (340–466 mg/kg/h) decreasing markedly afterwards (37–90 mg/kg/h at 40 days). Rewetting at 60 days increased respiration to about 200 mg/kg/h only in sawdust piles (SP1, SP2) associated to an increase of temperature. After the second rewetting, respiration rates rose slightly in RP2 (100 mg/kg/h) associated again to an increase of temperature. Like temperatures, stable values of respiration rates were reached after approximately 180 days of pile establishment, and ranged between 20 and 75 mg/kg/h.

3.3. Changes in physico-chemical parameters

Initial pH values were alkaline (8.0–8.4) in all piles and descended to values under 7.0 in sawdust piles between 80 and 120 days (Fig. 4a), while in rice hull piles values were maintained around 7.0. The treatment with the highest proportion of sawdust (SP2) showed a more pronounced decrease, reaching values of 5.6; the SRP pile was similar to SP1 (around 6.0).

Initial electrical conductivity varied between 2.5 and 3.1 mS/cm, and the lowest values corresponded to the higher proportion

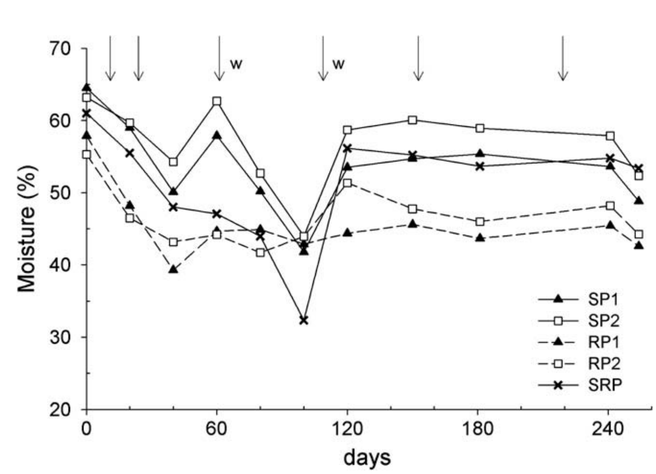

Fig. 2. Moisture profiles during composting. Symbols of treatments and arrows as in Fig. 1.

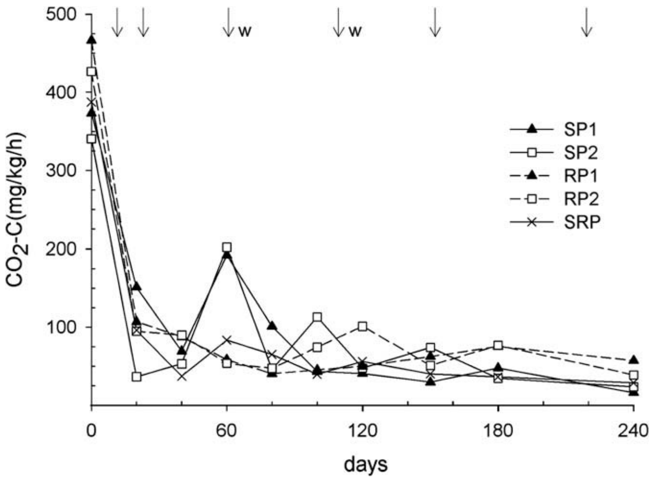

Fig. 3. Evolution of CO_2 during composting. Symbols of treatments as in Fig. 1.

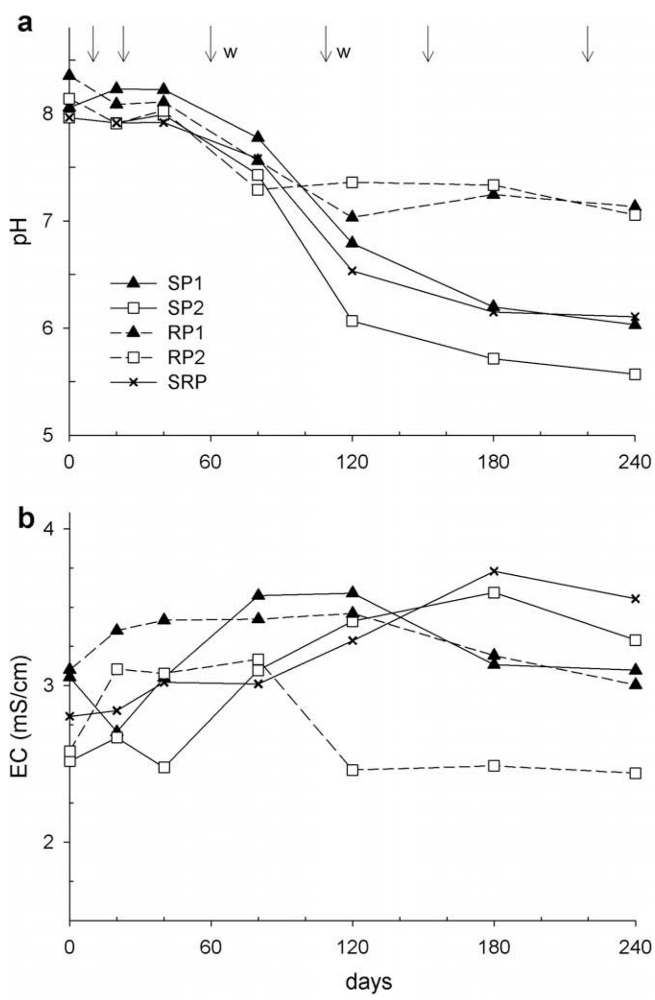

Fig. 4. Changes of (a) pH and (b) electrical conductivity during composting. Symbols of treatments as in Fig. 1.

of carbonous materials (Fig. 4b). A slight increase was observed during the process, ending in values between 3.0 and 3.6 mS/cm. The exception was the treatment with the higher proportion of rice hulls (RP2) that dropped to 2.4 mS/cm between 80 and 120 days.

Total organic C (TOC) decreased at the end of the process (Fig. 5a), losses being about 33% for sawdust piles and 13–17% for SRP and rice hull piles. Based on ash contents, TOC losses were more evident: 58–60% for sawdust piles and 23–34% for SRP and rice hull piles. Water-soluble C (WSC) increased during the thermophilic phase from about 8 g/kg to 17–20 g/kg, and decreased thereafter to stable values of around 4 g/kg (Fig. 6a). Peaks of WSC depended on the type of carbonous material, with an earlier peak for rice hull and SRP piles (at 20 days) than for sawdust piles (40–80 days).

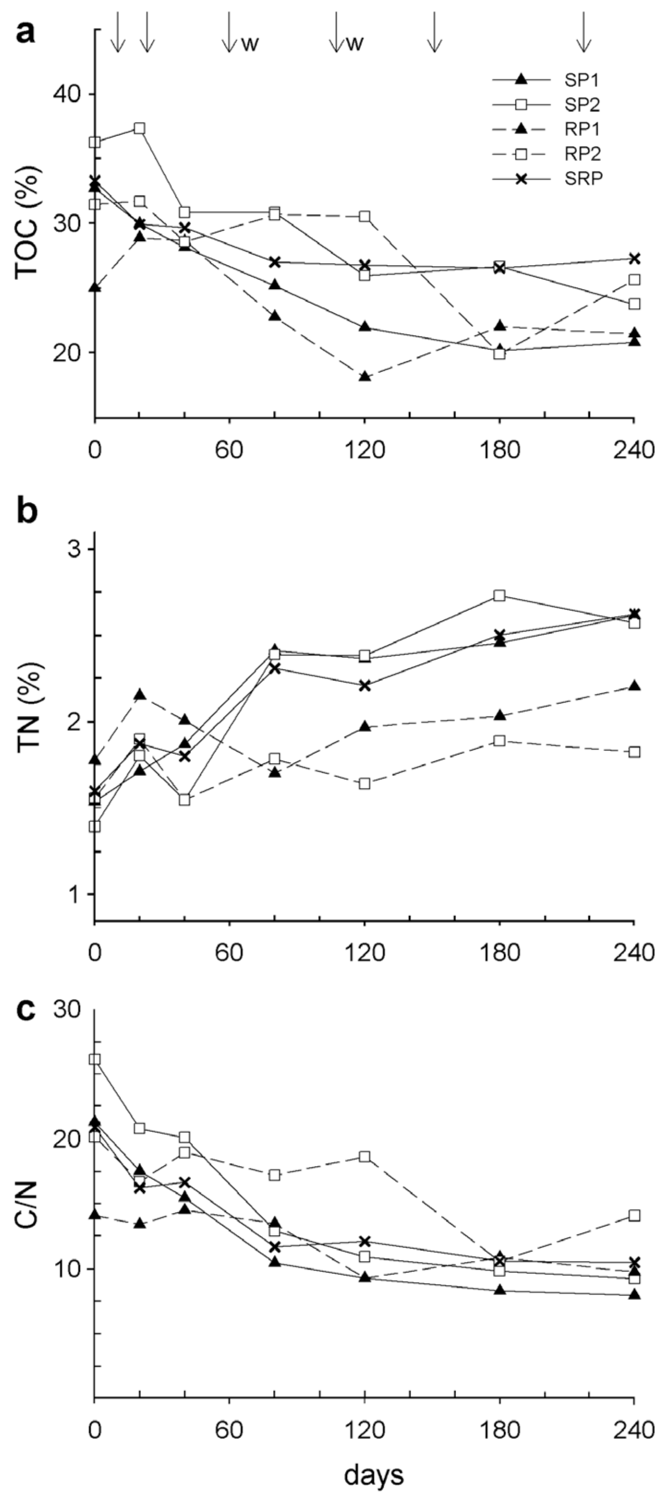

Fig. 5. Changes of (a) total organic C, (b) total N and (c) C/N ratio during composting. Symbols of treatments as in Fig. 1.

Contrary to TOC, total N (TN) increased during composting from 1.4–1.8% to 1.8–2.6%, increases being 65–85% for sawdust and SRP treatments, and 18–25% for rice hull piles (Fig. 5b). However, when calculated on ash content basis, N increases over time were less marked (12% for sawdust piles and RP1, and 30% for SRP), and even a slight decrease was observed for RP2 (6%). Main forms of inorganic N changed over the composting process from high values of NH_4^+—N at the beginning to even higher values of NO_3^-—N at the end (Fig. 6b and c). During the thermophilic phase, NH_4^+—N values increased from 450–580 mg/kg at t_0 to 700–890 mg/kg, being higher over a longer period in sawdust piles; afterwards NH_4^+—N values dropped strikingly, and in most treatments they remained stable around 25–100 mg/kg after 120 days. The decrease of NH_4^+—N was coupled to a steady increase of NO_3^-—N throughout the mesophilic maturity phase, reaching very high values (770–2300 mg/kg) at 240 days. Rates of nitrification in sawdust and SRP piles were 2–3 times higher than in rice hull piles. The ratio NH_4^+—N to NO_3^-—N, often employed as a stability and/or maturity index, was 0.1–0.3 after 120 days.

Since TOC decreased and N increased, the C/N ratio dropped throughout the process from initial values of 14–26 to final values of 8–12 (Fig. 5c); this was more evident for sawdust and SRP piles. The WSC/TN ratio, other index of stability and/or maturity, showed a similar trend as WSC profiles with high values (0.8–0.9) during the thermophilic phase; after 120 days values were low and almost stable around 0.2–0.4.

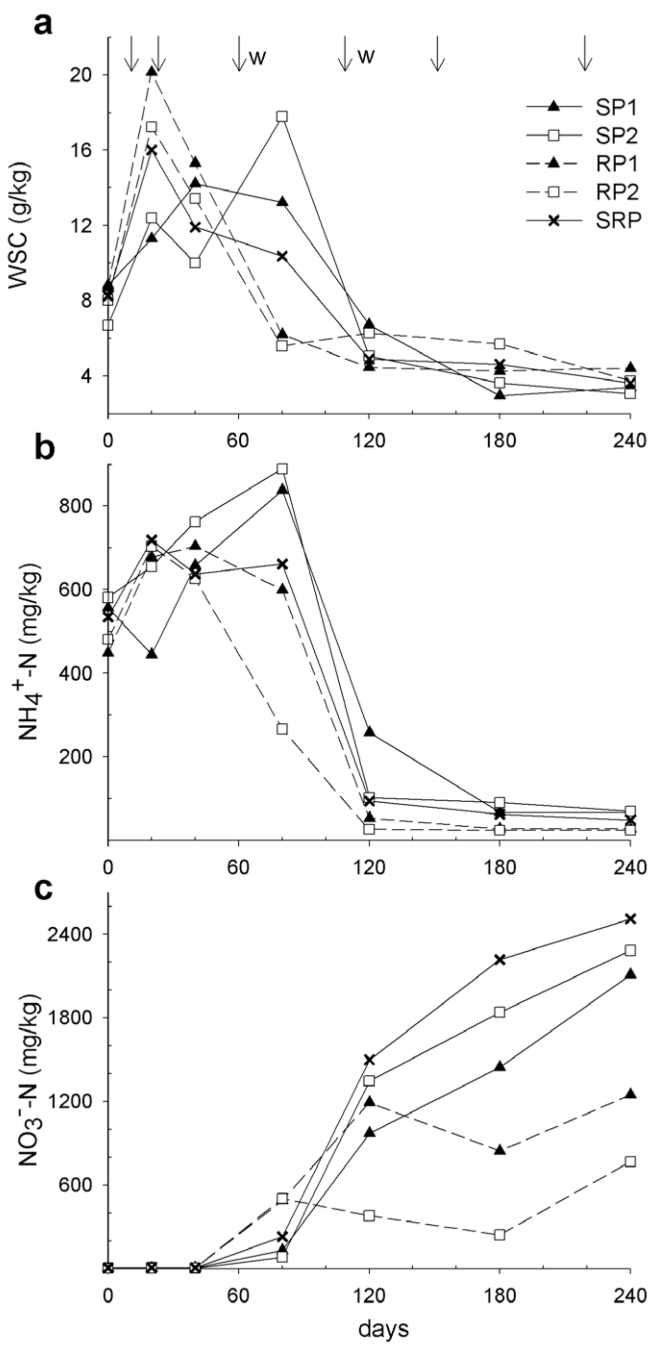

Fig. 6. Changes of (a) water-soluble C, (b) NH_4^+—N and (c) NO_3^-—N during composting. Symbols of treatments as in Fig. 1.

3.4. Characteristics of the final compost

Compost characteristics were analyzed in the 5-mm fraction, which represented 90–95% of total compost weight. In general, composts were slightly acidic to neutral (5.8–7.2), with relative high electrical conductivity (around 3 mS/cm), low C/N ratio (9–13), and high total N (2–3%), total Ca (around 20 g/kg), and extractable P (6–8 g/kg), the latter representing 60% of total P (Table 2). Trace elements in all final products (Table 3) were below the more restrictive threshold values established for composts in Spain and France (Houot et al., 2005; BOE, 2005).

When applying PCA, the two first axes explained 71% of the total variation (Fig. 7). Two observations (SP1-1 and SRP-3) were discarded because they were poorly represented. Higher total C was found in the treatments with higher proportion of carbonous materials (2:1), which were differentiated by cellulose (sawdust) and C/N ratio (rice hulls). Higher extractable P corresponded to 1:1 treatments. When analyzing by HAC, the cut-off line produces 2 groups: the first group formed by rice hull composts (RP1, RP2) with high pH, K and Si, and low TN, NH_4^+—N and NO_3^-—N and the second group formed by all treatments containing sawdust (SP1, SP2, SRP) with low pH, K and Si, and high TN, NH_4^+—N and NO_3^-—N.

4. Discussion

Nutrient and organic matter concentrations of the original materials were within the range given elsewhere (Cooperband and Good, 2002; Wang et al., 2005), with much higher nutrients and less organic C in poultry manure than in sawdust and rice hulls. These carbonous materials were characterized by high values of recalcitrant C (lignin), and low values of easily degradable water-soluble C (WSC).

During composting all piles reached temperatures required to meet guidelines for pathogen reduction (USEPA, 1993). The carbonous materials determined the length of the thermophilic phase regardless of the mixing ratio, being longer in piles containing sawdust than in piles with only rice hulls. Results suggest that sawdust enhances microbial activity possibly due to higher C amount, water retention capacity, and accessibility to microbial attack (higher specific surface). Low water retention and less microbial activity in rice hull piles could be related to the presence of superficial waxes and high silica contents (Wang et al., 2005; Massey et al., 2007), which contributed to less losses of total organic C even in the pile with both carbonous materials.

Despite longer thermophilic phase in sawdust piles, initial temperatures were higher in rice hull piles, temperature profiles being closely related to WSC profiles. This implies that microbial activity was regulated by the availability of easily degradable C. In this context, Charest et al. (2004) suggested that the increase of WSC during the thermophilic phase would be the result of cellulose and hemicellulose biodegradation, while the posterior WSC decrease would indicate that microorganisms used it as a source of energy.

Table 2
Physico-chemical characteristics of the final composts sieved by 5 mm mesh.

	SP1	SP2	RP1	RP2	SRP
pH	6.2 ± 0.1	5.8 ± 0.1	7.2 ± 0.1	7.1 ± 0.1	6.3 ± 0.1
EC (mS/cm)	2.8 ± 0.3	3.1 ± 0.3	2.9 ± 0.1	2.5 ± 0.1	3.3 ± 0.3
TOC (%)	21.7 ± 1.6	24.1 ± 4.5	19.9 ± 2.1	25.8 ± 1.1	24.3 ± 3.4
NH_4^+—N (mg/kg)	81 ± 5	157 ± 41	50 ± 3	25 ± 9	84 ± 13
NO_3^-—N (mg/kg)	2570 ± 370	3030 ± 480	1390 ± 180	900 ± 150	2510 ± 300
TN (%)	2.7 ± 0.3	2.9 ± 0.4	2.4 ± 0.1	2.2 ± 0.1	2.8 ± 0.1
C/N	8.0 ± 1.3	8.4 ± 1.3	8.5 ± 0.9	12.0 ± 0.2	8.8 ± 0.8
Cellulose (%)	64.1 ± 3.2	68.3 ± 1.4	58.5 ± 0.7	61.2 ± 3.2	60.7 ± 3.9
Lignin (%)	20.0 ± 0.3	18.8 ± 0.3	19.6 ± 0.9	21.5 ± 2.1	20.6 ± 2.4
Extractable P (g/kg)	7.5 ± 0.1	6.1 ± 0.7	7.7 ± 0.6	6.0 ± 0.4	6.7 ± 0.4
Total elements (g/kg)					
P	12.2 ± 0.3	9.9 ± 1.1	12.6 ± 1.6	9.8 ± 0.2	10.1 ± 0.8
Ca	24.1 ± 0.1	21.0 ± 4.9	20.9 ± 1.6	17.5 ± 1.6	19.0 ± 2.3
Mg	5.6 ± 0.1	3.8 ± 1.2	5.7 ± 0.1	4.9 ± 0.3	4.9 ± 0.5
K	6.1 ± 0.3	5.7 ± 1.6	7.7 ± 0.2	8.4 ± 2.8	6.6 ± 0.6
Na	1.1 ± 0.1	1.0 ± 0.2	1.4 ± 0.1	1.2 ± 0.6	1.2 ± 0.1
Si	0.4 ± 0.1	0.2 ± 0.1	1.5 ± 0.4	2.0 ± 0.2	1.2 ± 0.4

Values are average of three samples ± standard deviation. Symbols of variables as in Table 1 and treatments as in Fig. 1.

Table 3
Trace elements of the final composts sieved by 5 mm mesh.

	SP1	SP2	RP1	RP2	SRP	European compost limits
Trace elements (mg/kg)						
As	<3.0	<3.0	<3.0	<3.0	<3.0	18
Cd	0.48	0.15	0.38	0.28	0.56	0.70–3.0
Cr	0.90	0.65	<0.5	1.52	1.06	70–120
Cu	21	25	17	28	51	70–400
Hg	<0.05	<0.05	<0.05	<0.05	<0.05	0.4–2
Mo	0.72	0.95	1.20	0.59	0.98	–
Ni	1.3	1.9	2.1	2.2	0.9	25–60
Pb	4.0	3.0	1.8	3.6	3.3	45–180
Se	3.7	3.1	2.3	2.5	2.7	12
Zn	130	92	91	104	116	200–1000

Values are average of two samples. Symbols of treatments as in Fig. 1.

In our case, however, no relationship was found between microbial activity, assessed as respiration, and the profiles of temperatures and WSC: respiration was very high at the initial date but then decreased markedly, while temperatures and WSC remained high. Some authors have suggested that this discrepancy between the length of the thermophilic phase and microbial respiration is due to thermic inertia (Tremier et al., 2005; Tognetti et al., 2007). This was not the case in this work because after the first two turnings, temperatures increased to very high values in less than 24 h. Results suggest that high microbial activity is not always related to high respiration rates; heat production could be due to exothermic hydrolysis reactions other than respiration. Methodological drawbacks cannot be discarded, since CO_2 evolution was measured in incubations at mesophilic temperatures even when evaluating the thermophilic phase, as recommended by several authors (Hue and Liu, 1995; García-Gómez et al., 2003; Banegas et al., 2007; Tognetti et al., 2007).

The differential effect of the carbonous material was again evident in the pH profiles: pH was markedly reduced in the piles containing sawdust after the thermophilic phase, coinciding with very high nitrification rates. The oxidation of ammonia to nitrate is a strong acidifying process mediated by nitrifying bacteria active at mesophilic temperatures, and the relation between pH decrease and nitrification has been often mentioned in studies conducted with similar feedstocks (among others, Huang et al., 2004; Banegas et al., 2007). Ammonification of organic N during the thermophilic phase was evident in all piles, followed by steady nitrification during the subsequent mesophilic phase, reaching NO_3^-—N values

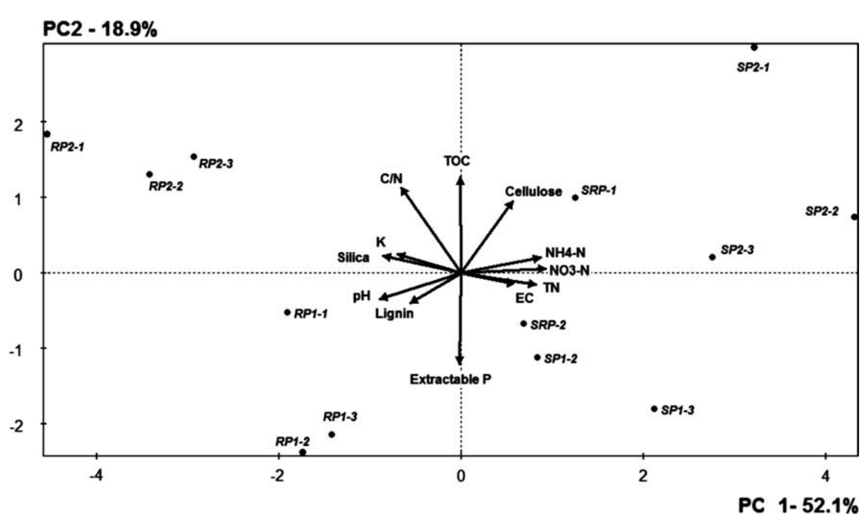

Fig. 7. Principal component analysis showing the relationships between indicators of quality and the five composts. Symbols of variables as in Table 1 and treatments as in Fig. 1. Numbers following treatment symbols indicate individual observations.

much higher than the previously produced NH_4^+—N. This indicates that mineralization of organic N proceeded intensely also during this mesophilic phase.

High losses of N as ammonia volatilization are a commonplace in the literature on composting attributed to high temperatures and pH (Charest and Beauchamp, 2002; Tognetti et al., 2007). In the present work, however, N losses were not detected even though some piles had low initial C/N ratios; moreover, N increased throughout the process. This was mainly associated to the loss of organic C, sawdust piles showing higher C losses and consequently, higher increase of N than rice hull piles. When N was calculated based on ash contents, this increase was less evident, nevertheless it implies N conservation. The pile with sawdust + rice hulls was a particular case, since the C loss was as low as in rice hull piles while the N increase was similar to sawdust piles; this resulted in the highest increase of N on ash basis. Though loss of N during composting is a major concern in most works, some authors also found N conservation (Huang et al., 2004; Banegas et al., 2007), most likely due to the use of lignocellulosic materials in the mixture, which enhance N immobilization in microbial biomass.

Electrical conductivity (EC) was high but below the values considered detrimental for plant growth and seed germination (Rynk et al., 1992; Banegas et al., 2007). Initial values were directly related to high poultry manure values; the following slightly EC increase was due to the release of soluble salts, such as nitrates and phosphates, over the process. Only in the pile with the highest proportion of rice hulls, EC decreased, suggesting a net loss of soluble salts possibly attributable to lower water retention capacity and higher leaching.

To evaluate composting efficiency, it is essential to know when stability is achieved. Stability is referred to the bioavailability of organic matter, in terms of degradable C and microbial activity (Cooperband et al., 2003). Many physico-chemical and biological indicators of stability are recommended, but some of them are time consuming and/or expensive, for example N and C mineralization assays, which last several weeks and require specialized laboratories (Laos et al., 2002). Other indicators are simpler, can be conducted in any soil and plant tissue testing laboratories, and are used worldwide, alone or combined. Some of these indicators and recommended threshold values are: NH_4^+—N <400 mg/kg or <500 mg/kg, WSC <10 g/kg, WSC/TN <0.7, CO_2 <120 mg/kg/h, NH_4^+—N/NO_3^-—N <0.16 or <3 (Hue and Liu, 1995; CCQC, 2001; Laos et al., 2002). In the present work, these values were achieved for most indicators at around the end of the thermophilic phase, but they fluctuated, suggesting that active decomposition still proceeded; only after 180 days they remained stable in all piles. This implies that besides a threshold value, the constancy of the value should be considered.

The quality of the final composts was high in terms of N and P, the most limiting nutrients for plant growth. They also showed high amounts of Ca and substantial amounts of K. Poultry manure was the main source of nutrients, but the amounts in the final compost were determined by the type of carbonous material (higher total and available N in piles containing sawdust, and higher K and Si in piles with only rice hulls) or the mixture proportion (higher P in 1:1 and higher TOC, C/N and cellulose in 2:1). Organic matter varied from 40% to 50% with high values of lignin (19–22%), a compound resistant to microbial decomposition that contributes to recalcitrant C accretion when applied to soils, and is included in the biochemical fractionation recommended by the French standards of compost quality (Houot et al., 2005; Kowaljow and Mazzarino, 2007). Due to high N conservation during composting, values of total N were quite high, which coupled to low C/N ratios, would contribute to net N mineralization in soils. Despite that composting was conducted in an open site under heavy rains, losses of soluble nutrients were apparently low since final composts had relative high values of electrical conductivity and high concentrations of nitrates and phosphates.

Extractable P in the final composts represented about 60% of total P; since it was less than 30% in the original poultry manure, results indicate a significant release of P during composting. There is an increasing concern about over-application of P when animal manures are applied according to N plant requirements, because they have low N/P ratio (2–3) while plants need about 6–8 times more N than P (Cooperband and Good, 2002). In our case, low N/P ratios and a high proportion of extractable P are a drawback that should be further considered when calculating rates of application of compost to soil. An alternative is to increase the proportion of carbonous material during composting, which would contribute to reduce excess of available nutrients, to increase recalcitrant organic matter, and to avoid environmental problems while improving fertility of sandy or weathered soils of the Mesopotamia region of Argentina.

5. Conclusions

When co-composting poultry manure with rice hulls or sawdust, the type of carbonous material differentially affected the thermophilic phase. It was shorter with rice hulls (40–60 days) than with sawdust (105 days) associated to lower water retention, less organic C, and possibly less accessibility to microbial attack due to waxy coatings, and higher silica concentrations and particle size in rice hull piles. However, the process efficiency in terms of the time required to reach stability (stable values of CO_2, WSC, WSC/TN, NH_4^+-N) was similar in all cases (180 days). Based on ash contents, sawdust piles lost much more organic C than rice hull piles (33% vs. 15%), but all treatments had high N conservation, particularly the one with both carbonous materials.

All final composts were rich in Ca (18–24 g/kg), but showed quality differences determined by the type of carbonous material and the proportion of the original mixture. Total and available N were higher in piles containing sawdust, while pH, K and Si were higher in piles with only rice hulls. Phosphorus (total and extractable) was higher in 1:1 piles, while total organic C, C/N and cellulose were higher in 2:1 piles. Very high values of extractable P (>6 g/kg) pose a risk for the environment and require special attention when calculating application rates. Trace elements in all composts were very low and below threshold values established for application without restriction.

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