

Stabilization of Organic Matter During Composting: Influence of Process and Feedstocks

Cédric Francou^{1,2}, Maelenn Poitrenaud³ and Sabine Houot¹

1. INRA-INA-PG, UMR *Environnement et Grandes Cultures*, Thiverval-Grignon, France

2. ADEME (*Agence de l'Environnement et de la Maitrise de l'Energie*), Paris, France

3. CREED (*Centre de Recherche sur l'Environnement l'Energie et les Dechets*), Limay, France

Information on compost organic matter stability is necessary to anticipate the effects of compost application on soil properties. Such information will soon be required by French legislation. The main objectives of the present work were: (1) to study the influence of the composting process and the composted waste on the kinetics of stabilization of organic matter during the composting process; (2) to validate physicochemical indicators of compost stabilization and also rapid tests used by the compost producers on the composting plants in order to be able to follow compost stabilization during the process. Ten compost windrows were sampled after 3, 4 and 6 months of composting at plants where green wastes (GW), biowastes (BIO), sludge (SG) or municipal solid wastes (MSW) were composted. In some plants, the composting process was accelerated by enforced aeration. The stability of the organic matter was assessed by laboratory incubations during which organic matter mineralization was followed. Maturity tests were run on compost samples which were then analyzed. For the GW, BIO and SG composts, the stabilization of organic matter occurred more rapidly than for the MSW composts and 3 to 4 months were enough for satisfying organic matter stabilization. For the MSW composts, 6 months were necessary to reach stabilization similar to the GW or BIO composts. The self-heating test was highly significantly correlated with the compost organic matter stability as evaluated from the incubation results and should be recommended to the compost producers rather than the Solvita test. Among the physicochemical characteristics of the composts, total organic C (TOC) appeared to be well correlated with organic matter stability of the composts and a better indicator than the C/N ratio, pH, electrical conductivity and $\text{N-NO}_3^-/\text{N-NH}_4^+$ ratio. The humic and fulvic acids (C-HA + C-FA) represented 9 to 27 percent of TOC and the humification index (C-HA/C-FA) was also well-correlated with organic matter stability.

Introduction

Only 7% of urban wastes are actually composted in France (ADEME, 2000). This should increase since landfills soon will be closed for untreated organic wastes and the Ministry of Environment has required the development of waste recycling up to 50% including organic wastes. Composts are mainly used in agriculture as organic amendments to increase soil organic matter. They can also be used as growing substrates or as mulch, for example in vineyards. In any case, information on compost organic matter stability is required and will be part of French legislation on organic amendment quality, actually under revision. In future European legislation, different sources of organic wastes will possibly undergo biological treatments to produce marketable compost including home sorted biowastes, green wastes and sewage sludge. Composting will also be possibly used for municipal solid waste stabilization before land-filling (Kuehle-Weeideier & H.Doedens 2003).

The composting process has been reviewed exten-

sively (Haug 1993). Schematically, the organic wastes first undergo an initial rapid stage of decomposition during which the temperature rises above 60°C, followed by a longer maturation stage where humification processes prevail. Different composting processes have been developed (de Bertoldi 1993; Stentiford 1996). They are all based on the control of temperature, humidity and aeration during composting. Some processes intend to accelerate the transformations during the initial degrading stage, by increasing the turning frequency or ventilation through the compost windrows.

The degree of decomposition of organic matter during the composting process has often been used to define compost maturity and stabilized organic matter characterized mature composts (Becker & Kotter 1995). Other approaches of compost maturity assessment include the evaluation of phytotoxicity risk: a compost should be considered as mature if no depressive effects are observed on plants related to compost use (Chefetz *et al.* 1996; Bernal *et al.* 1998a; Wu *et al.* 2000). Such depressive effects are often related to the lack of stability

of compost organic matter. The spreading of an unstabilized compost on soil highly stimulates soil microbial activity and provokes nitrogen immobilization or oxygen depletion in soils (Iglesias-Jimenez & Perez-Garcia 1989). However, the depressive effects can also be related to the presence of phytotoxic substances such as organic acids, high electrical conductivity or large ammonia concentration (Hirai *et al.* 1986; Garcia *et al.* 1992).

Various methods have been proposed to evaluate compost maturity. Tests based on respirometric activity are the most accurate to determine organic matter stability (Rynk 2003). Organic carbon mineralization can also be measured during incubation in controlled conditions after incorporation into a soil (Niclardot *et al.* 1986; Bernal *et al.* 1998b). Criteria based on the evolution during composting of physicochemical analysis, such as pH, mineral N, C/N ratio, electrical conductivity, humic over fulvic acid ratio, have been proposed (Sugahara & Ionoko 1981; Roletto *et al.* 1985a; Avnimelech *et al.* 1996; Chen *et al.* 1996). Rapid tests are also proposed to evaluate compost maturity based on (1) temperature evolution in a compost sample placed in a Dewar's flask (self-heating test) (Brinton *et al.* 1995; Weppen 2002), (2) CO₂ respiration and NH₃ emission (Solvita test) (Changa *et al.* 2003). Such tests are used to define compost standards in many countries (Hogg *et al.* 2002).

The main objectives of the present work were: (1) to determine the influence of the composting process and the type of wastes composted on the kinetics of organic matter stabilization during the composting process; (2) to validate physicochemical indicators of compost stabilization and also rapid tests used at composting plants in order for the compost producers to be able to follow compost stabilization during the

process. Many references have reviewed the various indicators used to estimate compost stability but they were often based on particular compost, or without relating the results to the composting process (Iglesias-Jimenez & Perez-Garcia 1989), making difficult the extrapolation of the conclusions to other situations.

Ten compost windrows were sampled after 3, 4 and 6 months of composting at plants where green wastes, biowastes, sludge or municipal solid wastes were composted. At some plants, the composting process was accelerated by enforced aeration. The stability of the organic matter was assessed by laboratory incubations during which organic matter mineralization was followed. Various maturity tests were run on compost samples which were then analyzed.

Materials and Methods

The Composts

Ten urban composts were sampled after 3, 4 and 6 months of composting: two green waste composts (GW1 and GW2), three composts issued from the co-composting of green wastes and biowastes (BIO1, BIO2 and BIO3), three municipal solid waste composts (MSW1, MSW2 and MSW3), and two composts issued from the cocomposting of sewage sludge and green wastes (SG1, SG2). The initial waste mixtures were not analyzed because the objective was to study the compost evolution only during the maturation phase, which was estimated to approximately start after 3 months of composting. The various composting processes and initial characterization are indicated in Table 1. When indicated, the degradation phase was ac-

TABLE 1.
Characterization of the composted wastes and summary of the composting process

Notation	Waste Composted	Initial Characterization (% Of Fresh Material Mass)						Sewage Sludge	Duration Of Enforced Aeration (Weeks)	Process			Screening Date	Size (mm)
		Green Waste	Kitchen Waste	Paper	Glass	Plastics	Other			No. Of Turnings	0-3 Months	3-4 Months		
GW1	Green wastes	100							5	8	2	4	1 month	20
GW2		100							No	2	1	0	3 months	20
BIO1	Source separated	37	54	9	0	0	0		12	0	2	3	No screening	
BIO2	biowastes	59	19	14	2	5	1		3	0	0	0	5 months	25
BIO3		58	14	21	2	0	5		4	7	1	2	1 month	15
BIO3st	+ green wastes	58	14	21	2	0	5		4	5	0	0	1 month	15
MSW1		30	12	18	6	21	13		No	12	1	2	6 days	20
MSW2	Municipal solid wastes	30	12	18	6	21	13		6	5	1	2	2 months	20
MSW3		17	25	25	14	6	11		3	7	1	1	10 days	10
MSW3st		17	25	25	14	6	11		3	4	0	0	10 days	10
SG1	Sewage sludge	70						30	No	4	0	0	2 months	20
SG2	+ green wastes	71						29	9	0	0	0	No screening	

celerated by frequent turning and enforced aeration and lasted from 3 weeks to 3 months. During the maturation phase (after 3 months), the number of pile turnings decreased, except for BIO1 (Table 1).

Two additional composts were sampled after 6 months of composting. They were issued from the same wastes than BIO3 and MSW3 but the composting was realized without turning the windrows neither checking their water content during the maturation step and will be referred as BIO3st and MSW3st (st for static), respectively.

The composting processes were followed by measuring the temperature and water content evolution in the windrows. After 3, 4 and 6 months of composting, the composts were sampled in different places of the windrow in order to obtain a representative sample of ten kilograms approximately.

As required in the rapid maturity tests, all compost samples were sieved to 10 mm. Part of the samples was kept at 4°C until their use for maturity testing and mineral N analysis. The remaining part was air dried and finely ground (<1mm) before analysis.

Laboratory Incubations

The kinetics of compost organic matter mineralization were followed during laboratory incubations of soil-compost mixtures, as defined by French normalization (AFNOR, in press). The soil sample came from a field experiment designed to evaluate urban compost fertility. The upper layer (0-28 cm) of a control plot was sampled. Immediately after sampling, the soil was sieved to 5 mm and stored until use at 4°C. The main physicochemical characteristics of the soil sample were: clay, 187 g.kg⁻¹, silt, 756 g.kg⁻¹, sand, 57 g.kg⁻¹, pH, 6.9, organic carbon, 11.6 g.kg⁻¹, total N, 1.19 g.kg⁻¹. Four replicates of soil-compost mixtures were incubated in 0.5 L jars hermetically closed during 3 months at 28±1°C, in the dark. The mixtures were realized with the equivalent of 25 g of dry soil. Dried and ground composts were used. The doses of incorporated composts were calculated to bring the same proportion of organic carbon in the mixture (4 g of organic carbon per kg of dry soil). The water content of the mixtures was adjusted to 80% of the soil water-holding capacity (19.11% on wet basis) with Milli-Q water and controlled during the incubation period. Control incubations were run with only soil. In each jar, carbon mineralized as CO₂ was trapped in 10 ml of 1 M NaOH replaced after 1, 3, 7, 10, 14, 21, 28, 35, 49, 63, 77, 91 and 105 days of incubation and analyzed by colorimetry on a continuous flow analyzer (Skalar, The Netherlands). The opening of the jars when replacing the CO₂ traps allowed to renew the jar atmosphere and to run the incubations un-

der aerobic conditions. Four additional empty jars were incubated with only the NaOH traps to take into account the initial CO₂ in the jars and the initial carbonate content of NaOH.

Physicochemical Analysis

Mineral N was extracted from the undried samples. 100ml of 1M KCl was added to 25g of sieved compost. After 1 hour of shaking at room temperature and centrifugation during 5 min at 2660 g, mineral N concentration was analyzed in the supernatant by colorimetry on a continuous flow analyzer (Skalar, The Netherlands) using Berthelot method for N-NH₄⁺ (Krom 1980), and Griess and Ilosvay method for N-NO₃⁻ (Greenberg *et al.* 1980)

The other analyses were done on dried ground compost samples. Total organic carbon and total N were determined by elementary analysis. Compost pH was measured in water (1/5,v/v) and electrical conductivity (1/25,m/v) at 25°C.

Humic Substance Extraction

Total humic substances (fulvic acids and humic acids) were extracted by shaking on a rotative agitator 2 g of dry and ground composts mixed with 100 mL of 0.1 N NaOH during 2 hours. The alcalino-soluble humic substances were then separated from the non alcalino soluble humin by centrifugation (15 min at 8627 g). The pH of 20 mL of the supernatant was acidified to pH 1.5 using 1.84 mL of 2M H₂SO₄. After overnight precipitation of the humic acids at 4°C, the acido-soluble fulvic acids were separated from the non acido-soluble humic acids by centrifugation (15 min at 6320 g) (Serra-Wittling *et al.* 1996).

Stability Tests

The self-heating test was carried out on the undried sieved samples as recommended by the FCQAO (1994). Before running the test, the compost water content was adjusted with Milli-Q (Millipore) water using the "fist test". A compost sample is pressed into the fist. If water beads escape between the fingers in the process, the sample is too wet. If the sample crumbles without further action when the fist is opened, the sample is too dry. There is a suitable moisture content if the pressed sample crumbles with light pressure; if it is only deformed, in contrast, it is too wet (FCQAO 1994). After 2 days of equilibration at room temperature, Dewar vessels (1,5 L, 100 mm inner diameter) were filled up with compost gently packed. The Dewar vessels were set up openly at room temperature and the evolution of tem-

perature was followed in the compost at 20 cm below surface during 10 days. The maximum temperature (T_{max}) reached was used to evaluate the rotting degree of the compost from I (fresh material, $T_{max} > 60^{\circ}\text{C}$) to V (mature compost, $T_{max} < 30^{\circ}\text{C}$). Composts were considered as finished when temperature did not exceed 40°C during the test (Rotting degree IV and V).

The Solvita test was used as recommended by the producer using the same compost materials as for the self-heating test. The samples were placed in hermetic jars (110 mL of compost in 250 mL jar) with two paddles carrying color indicators: one for the mineralized carbon and one for the ammonia volatilization. The jars were kept at room temperature ($20\text{--}25^{\circ}\text{C}$) for 4 hours. The paddle colors were read after 4 hours and associated to color numbers, computed to a compost maturity index. The combined values gave maturity indices of 1-2 for raw composts, 3 to 6 for still active composts and 7-8 for finished composts.

Statistics

The correlation (Pearson correlation coefficient) between the indicators was calculated using the logiciel Xlstat (Microsoft).

Results and Discussion

Compost Organic Matter Stability

The kinetics of compost organic carbon mineralization were calculated by subtracting the C-CO_2 mineralized in the control soil incubated alone from the total C-CO_2 mineralized from the soil-compost mixtures. The effect of compost addition on soil organic carbon mineralization was thus neglected (Serra-Wittling 1995). Results were expressed as percentage of total organic carbon of compost (TOC, Table 2) mineralized during the incubations (Figure 1). All kinetics presented a first phase with larger rates of carbon mineralization resulting from the biodegradation of an easily mineralizable organic fraction. Then after 20 to 28 days, the mineralization rates decreased because the remaining organic matter was more recalcitrant to biodegradation. All kinetics were adjusted to the following model

$$\text{C-CO}_2 = C_0 * [1 - \exp(-k_0 * t)] + k_1 * t$$

assuming that total compost organic carbon could be divided in two pools: a labile organic pool C_0 (in percent of TOC) that mineralization followed a first order kinetics with a mineralization rate k_0 (day^{-1}) and a resistant organic pool C_1 ($100 - C_0$ in percent of TOC) that mineralization could be assumed as linear during the incubations (k_1 , mineralization rate in percent TOC

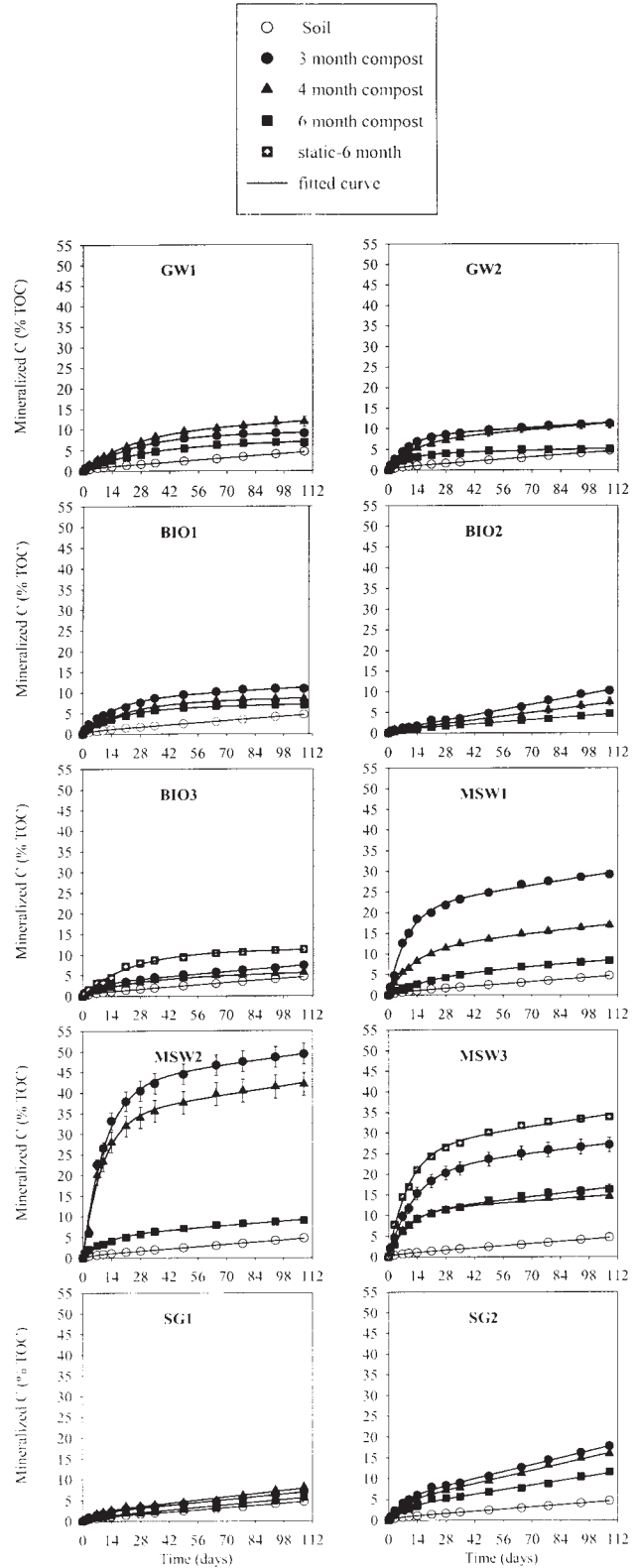


FIGURE 1. Kinetics of organic carbon mineralization during the incubation of soil-composts mixtures in laboratory conditions: experimental datas (symbols) and fitted curved (lines). Results expressed in percentage of initial total organic carbon (TOC) of compost.

TABLE 2.
Evolution of total compost organic C (TOC) and N
during the composting process

Compost	Age	TOC % D.W.	Total N	C/N
GW1	initial	26.9	1.0	27.4
	3 months	23.7	1.4	16.3
	4 months	20.7	1.4	15.1
	6 months	20.3	1.5	13.6
GW2	initial	24.4	1.5	15.9
	3 months	27.9	1.9	14.6
	4 months	19.6	1.7	11.6
	6 months	22.3	1.9	11.6
BIO1	initial	33.5	1.5	22.6
	3 months	24.3	1.8	13.4
	4 months	24.3	1.8	13.2
	6 months	20.9	1.7	12.5
BIO2	initial	21.5	1.2	17.9
	3 months	16.6	1.2	13.4
	4 months	15.5	1.4	11.8
	6 months	18.8	1.2	15.2
BIO3	initial	26.4	1.4	18.9
	3 months	19.8	1.4	14.4
	4 months	17.5	1.3	13.1
	6 months	18.2	1.4	12.7
BIO3st	6 months	21.5	1.4	15.7
MSW1	initial	37.2	1.4	27.0
	3 months	27.2	1.4	19.1
	4 months	24.4	1.5	15.9
	6 months	22.5	1.6	13.9
MSW2	initial	34.2	1.3	25.4
	3 months	27.9	1.5	17.9
	4 months	24.0	1.8	13.3
	6 months	21.0	1.9	11.1
MSW3	initial	27.5	1.8	15.6
	3 months	23.4	2.1	11.1
	4 months	24.3	2.2	11.0
	6 months	20.2	2.1	9.6
MSW3st	6 months	33.7	2.2	14.9
SG1	initial	31.3	2.2	14.1
	3 months	20.2	1.9	10.4
	4 months	20.3	1.8	11.3
	6 months	19.6	1.9	10.3
SG2	initial	30.6	2.7	11.5
	3 months	29.9	2.5	12.1
	4 months	28.9	2.5	11.4
	6 months	27.2	2.4	11.4

day⁻¹). All parameters are presented in Table 3 and the simulated kinetics in Figure 1.

In the control soil, less than 5% of TOC was mineralized after 3 months of incubation corresponding to the classical mineralization rates of soil humified or-

TABLE 3.
Parameters of the model $C-CO_2=C_0*[1-\exp(-k_0*t)]+k_1*t$
used to fit the experimental datas of organic carbon
mineralization during the incubations

Compost	Age	C_0 (% of TOC)	k_0 (Day ⁻¹)	k_1 % of TOC Day ⁻¹	R ²	
GW1	3 months	8.6	0.04	0.01	0.997*	
	4 months	9.1	0.04	0.03	0.998*	
	6 months	5.7	0.04	0.01	0.989*	
GW2	3 months	8.1	0.11	0.03	0.998*	
	4 months	6.9	0.08	0.04	0.995*	
	6 months	4.0	0.12	0.01	0.995*	
BIO1	3 months	8.4	0.07	0.03	0.991*	
	4 months	7.4	0.05	0.01	0.992*	
	6 months	6.0	0.06	0.01	0.989*	
BIO2	3 months	0.6	0.64	0.09	0.995*	
	4 months	0.5	1.00	0.06	0.992*	
	6 months	1.2	0.03	0.03	0.992*	
BIO3	3 months	2.9	0.12	0.04	0.994*	
	4 months	3.9	0.05	0.02	0.997*	
	6 months	3.9	0.05	0.02	0.997*	
BIO3st	6 months	10.5	0.05	0.01	0.994*	
MSW1	3 months	21.0	0.11	0.08	0.996*	
	4 months	11.1	0.08	0.06	0.999*	
	6 months	4.6	0.05	0.04	0.997*	
MSW2	3 months	42.1	0.09	0.07	0.992*	
	4 months	34.4	0.10	0.07	0.994*	
	6 months	5.1	0.10	0.04	0.980*	
MSW3	3 months	21.0	0.08	0.06	0.999*	
	4 months	11.1	0.11	0.03	0.998*	
	6 months	10.6	0.11	0.06	0.997*	
MSW3st	6 months	26.1	0.10	0.08	0.997*	
	SG1	3 months	1.8	0.16	0.05	0.996*
		4 months	2.1	0.16	0.05	0.990*
6 months		0.8	0.22	0.04	0.990*	
SG2	3 months	5.0	0.16	0.12	0.998*	
	4 months	4.1	0.16	0.11	0.997*	
	6 months	3.0	0.13	0.08	0.994*	

*indicates significance at P<0.01

ganic matter (Costa *et al.* 1989). For all composts, TOC mineralization decreased when the duration of composting increased due to the stabilization of the organic matter during the composting process. For the green waste compost GW1, 10% of TOC were mineralized at the end of the incubation of the 3, 4 and 6-month old compost. The composting process was not accelerated in the case of the other green waste compost GW2. Thereby after 3 months of composting, 10% of TOC was mineralized at the end of the incubation. After 6 months of composting, smaller mineralization intensity was observed than in the case of GW1 showing a greater organic matter stabilization of GW2 than GW1,

between 3 and 6 months. The accelerated process of GW1 made decrease mineralization rate of labile pool of organic matter as compared to GW2 (k_o , Table 3).

Less than 12% of TOC was mineralized at the end of the incubations of all the BIO composts. The results observed between 3, 4 and 6-month old composts were not statistically different. At the 3 composting plants, the degradation phase was accelerated by enforced aeration, which allowed the fast stabilization of compost organic matter within 3 months. At the end of the incubation of BIO3st-6m, 11% of TOC were mineralized that was significantly larger than the 6% of TOC mineralized observed in the case of BIO3-6m. The control of compost water content and the turning of the windrows during the maturation phase was necessary to ensure compost organic matter stabilization. Large size of screening probably favored the windrow aeration thus good stabilization of BIO2 although it was not turned during the maturation phase.

Although the degradation phase was not accelerated by enforced aeration, the stabilization of organic matter was achieved after 3 months of composting in the case of SG1 because of the frequent turning of the windrows. No significant differences of organic carbon mineralization were observed between the 3, 4 and 6-month old composts and 7 to 9% of TOC were mineralized at the end of the incubations. On the contrary, enforced aeration with only one windrow turning, during the degrading phase was not enough to ensure a rapid stabilization of the organic matter in the case of SG2 and 19% of TOC were mineralized at the end of the incubation of the 3-month old SG2. The mineralized proportion decreased to 12% TOC after 6 months of composting. For SG2, the mineralization kinetics differed with larger rates of mineralization of the second resistant pool of organic matter (k_1 , Table 3).

The MSW composts differed from the other composts with larger differences observed between the 3 and 6-month old composts. After 3 months of composting, the easily biodegradable organic matter still represented 21 (MSW1) to 42% (MSW2) of TOC. (C_o , Table 3). After 6 months of composting (excepted MSW3st), the labile organic pool decreased to proportions similar to the other composts (4 to 10% of TOC, Table 3). The largest mineralization intensity was observed in the case of the 3 and 4-month old MSW2, for which the process was accelerated during 6 weeks. Again, case of MSW3 and MSW3st shows that the process control during the maturation phase and after an accelerated degradation phase (MSW3), allowed to accelerate the organic matter stabilization. At the end of the incubation of the 6-month old composts, the carbon mineralization represented 15% of TOC for MSW3-6m but reached 35% of TOC in the case of

MSW3st-6m (Figure 1).

The compost organic matter stability as revealed by the mineralization kinetics was used as reference to evaluate the sensitivity of the other analytical characteristics or indicators used to estimate compost stabilization.

Rapid Compost Maturity Testing

The self-heating test confirmed the incubation results (Table 4). The accelerated degradation phase of GW1 allowed producing finished composts after only

TABLE 4.
Compost stability as measured with the self-heating and Solvita tests

Compost	Age	Self-Heating		CO ₂ Index	Solvita NH ₃ Index	Maturity Index
		Tmax (°C)	Rotting Degree			
GW1	3 months	24	V	5	3	4
	4 months	NA	NA	5	4	5
	6 months	19	V	6	5	6
GW2	3 months	61	I	3	3	3
	4 months	34	IV	7	2	5
	6 months	28	V	6	5	6
BIO1	3 months	23	V	3	5	3
	4 months	NA	NA	5	5	5
	6 months	23	V	5	5	5
BIO2	3 months	21	V	3	5	3
	4 months	NA	NA	7	5	7
BIO3	6 months	21	V	7	5	7
	3 months	24	V	3	5	3
	4 months	NA	NA	6	5	6
BIO3st	6 months	22	V	6	5	6
	6 months	34	IV	5	3	3
MSW1	3 months	62	I	2	4	2
	4 months	54	II	5	3	4
	6 months	23	V	5	4	5
MSW2	3 months	61	I	2	4	2
	4 months	50	III	4	5	4
	6 months	24	V	6	4	6
MSW3	3 months	61	I	1	5	1
	4 months	60	I	2	3	1
	6 months	41	III	3	4	6
MSW3st	6 months	70	I	5	4	5
SG1	3 months	33	IV	3	3	3
	4 months	24	V	7	2	5
	6 months	29	V	6	5	6
SG2	3 months	51	II	3	5	3
	4 months	38	IV	4	5	4
	6 months	36	IV	5	5	5

Tmax: maximum temperature reached by the compost during the test;
NA: not analyzed

3 months of composting. Four months were necessary in the case of GW2 without accelerated degrading phase. The three BIO composts were already considered as finished after 3 months of composting (rotting degree of IV and V). In the case of BIO3st, the lack of process control during the maturation phase decreased the rotting degree from V (BIO3-6m) to IV (BIO3st-6m), which still could be considered as finished compost. The sludge composts were mature after 3 and 4 months, respectively for SG1 and SG2. With MSW composts, only MSW1 and MSW2 reached a rotting degree of V and could be considered as mature at 6 months.

Most composts were considered as "active" composts from the Solvita test results (Table 4). Only the BIO2 compost was considered as finished after 4 months of composting and only the 3-month old MSW composts were considered as "raw".

On the whole, the results of the self-heating and Solvita tests were significantly correlated (Table 5). However some divergent results appeared. Very large variability of Solvita maturity index (3 – 7) was observed for composts characterized as finished from the self-heating test (rotting degree IV and V). Even in the very low ammonia rating (all the BIO composts), large variability of CO₂ results was observed (from 3 to 7). On the contrary, the MSW3st-6m compost considered as "raw" compost from the self-heating test reached a Solvita maturity index of 5. The two tests have been realized simultaneously and compost evolution during storage in the laboratory could not explain the divergences. Similar discrepancies have previously been observed and were attributed to the different scale between the two tests for the cured composts (Brinton & Evans 2000).

The results of the self-heating test were highly significantly ($p < 0.01$) correlated with the proportion of TOC mineralized during the incubation (Table 5) and could be used as a good indicator of compost organic matter stability. The results of the Solvita test were

also significantly correlated with the proportion of mineralized TOC, but with a lower correlation coefficient ($p < 0.05$).

Mineral N Content of Undried Composts

Mineral N was analyzed immediately after sampling on undried composts and always represented less than 10% of total N (Table 6). During the composting process, organic N is first mineralized as ammonia during the active phase of degradation, followed by nitrification during the maturation stage. Thus, nitrate presence and more often the ratio $N-NO_3^-/N-NH_4^+$ have been used as indicator of compost maturity (Forster *et al.* 1993).

In all the sampled composts, ammonia concentration tended to decrease between 3 and 6 months while nitrate concentration increased. Larger concentrations of ammonia were detected in the GW2 compost than in the GW1 which organic matter was more stabilized after 3 months of composting. Ammonia concentration remained large in GW2 without nitrate formation even after 6 months of composting although the stabilization of the compost organic matter as shown by the mineralization results. On the contrary, nitrate concentration increased in GW1 and the ratio $N-NO_3^-/N-NH_4^+$ exceeded 1 only after 6 months, indicating a mature compost.

In the 3 BIO composts (except BIO3st-6m), the ratio $N-NO_3^-/N-NH_4^+$ exceeded 1 after 6 months of composting. In the case of BIO3st-6m, the ratio $N-NO_3^-/N-NH_4^+$ remained below 1 possibly due to the lack of windrow turning during the maturation phase preventing the good aeration of the compost, necessary for nitrification. In all the MSW composts, ammonia concentration remained high throughout the 6 months of composting and nitrates were detected in relevant concentrations only after 6 months. Nevertheless, the ratio $N-NO_3^-/N-NH_4^+$ never exceeded 1,

TABLE 5.
Correlation coefficients between common stability indexes

	% of mineralized C (105 days)	TOC	pH	Electrical Conductivity	NO ₃ /NH ₄	C/N	C-HA/C-FA	Self- Heating
TOC	0.606**							
pH	-0.190	-0.525**						
Electrical conductivity	0.465**	0.457**	-0.385*					
NO ₃ /NH ₄	-0.324	-0.361*	0.216	-0.004				
C/N	0.413*	0.317	0.033	-0.056	-0.058			
C-HA/C-FA	-0.587**	-0.608**	0.114	-0.454**	0.058	-0.372*		
Self-heating	-0.735**	-0.690**	0.417*	-0.514**	0.381*	-0.282	0.569**	
Solvita	-0.503**	-0.416*	0.003	-0.203	0.405*	-0.188	0.480**	0.681**

* or ** indicates significance at $P < 0.05$ or 0.01 , respectively.

TABLE 6.
Physicochemical characteristics of the composts

Compost	Age	Dry Matter	pH	Electrical	N-NO ₃	Undried compost		N-NO ₃ / N-NH ₄
		% Total Fresh Matter				Water	Conductivity ms.cm ⁻¹	
GW1	3 months	68	8.2	0.61	15 ± 1	178 ± 7	0.1	
	4 months	70	8.2	0.62	32 ± 1	353 ± 1	0.1	
	6 months	71	8.3	0.74	258 ± 13	123 ± 13	2.1	
GW2	3 months	64	6.5	1.31	1 ± 1	2192 ± 50	0.0	
	4 months	64	8.0	1.05	1 ± 1	1682 ± 109	0.0	
	6 months	68	8.0	1.14	0 ± 0	1906 ± 22	0.0	
BIO1	3 months	40	8.9	1.13	26 ± 4	73 ± 5	0.4	
	4 months	39	8.9	1.12	10 ± 1	137 ± 7	0.1	
	6 months	55	8.6	1.43	487 ± 12	133 ± 6	3.7	
BIO2	3 months	58	8.2	0.81	167 ± 11	850 ± 31	0.2	
	4 months	65	8.1	0.89	218 ± 15	712 ± 17	0.3	
	6 months	58	8.7	0.76	115 ± 6	0 ± 0		
BIO3	3 months	65	8.4	1.04	385 ± 14	425 ± 24	0.9	
	4 months	61	8.4	1.04	395 ± 14	192 ± 5	2.	
	6 months	65	8.4	1.33	956 ± 11	3 ± 1	329.6	
BIO3st	6 months	85	8.4	1.18	140 ± 3	895 ± 37	0.2	
MSW1	3 months	60	8.6	1.61	6 ± 0	1748 ± 89	0.0	
	4 months	58	8.5	1.66	1 ± 0	1948 ± 79	0.0	
	6 months	47	8.3	2.16	643 ± 31	1247 ± 27	0.5	
MSW2	3 months	68	8.3	1.53	4 ± 0	2352 ± 260	0.0	
	4 months	60	8.5	1.62	10 ± 5	1833 ± 131	0.0	
	6 months	50	8.4	2.11	368 ± 43	1856 ± 104	0.2	
MSW3	3 months	62	8.3	1.62	1 ± 0	3481 ± 198	0.0	
	4 months	63	8.1	1.73	1 ± 0	4361 ± 145	0.0	
	6 months	68	8.4	2.21	240 ± 7	4126 ± 58	0.1	
MSW3st	6 months	81	5.7	3.06	0 ± 0	1442 ± 228	0.0	
SG1	3 months	56	8.3	1.33	1 ± 0	3643 ± 6	0.0	
	4 months	53	7.8	1.15	0 ± 0	3892 ± 23	0.0	
	6 months	45	8.1	1.17	0 ± 0	4940 ± 412	0.0	
SG2	3 months	33	7.7	1.05	414 ± 159	5390 ± 412	0.1	
	4 months	32	7.7	1.27	1099 ± 190	20 ± 0	55.8	
	6 months	34	7.9	1.2	607 ± 159	13 ± 4	46.7	

although a clear stabilization of the compost organic matter was observed through the incubations and the self-heating tests.

Large concentrations of ammonia were analyzed in SG1, larger than for SG2 although the compost organic matter was stabilized after 3 months in the case of SG1. Large concentration of ammonia was also analyzed in SG2-3m and could be due to the sewage sludge always characterized by large ammonia concentrations. The N-NO₃⁻/N-NH₄⁺ exceeded 1 only in the case of 4 and 6-month old SG2 although both the incubations and the self-heating test pointed out that SG1 compost was more stabilized than SG2.

Larger concentrations of ammonia were detected in the less stabilized compost samples as characterized by carbon mineralization during the incubations. On the contrary, larger nitrate concentrations were observed in the most stabilized compost samples. In most cases, the ammonia color developed in the Solvita test corresponded to the analyzed ammonia concentrations. However, some discrepancies were observed. For example, MSW3-3m should get an ammonia index of 3 instead of 5 from its pH and ammonia concentration. That could be related to the pH sometimes lower than 7, which partly prevented ammonia volatilization. The ratio N-NO₃⁻/N-NH₄⁺ was significantly cor-

related with the results of the self-heating and Solvita tests and with the mineralization intensity. However, many samples could be considered as stabilized from the self-heating test or the mineralization results but presented a ratio $N-NO_3^-/N-NH_4^+$ smaller than 1. This indicator should not be used to appreciate compost organic matter stabilization but rather to evaluate a potential risk of phytotoxicity for composts to be used in large proportions, such as in growing substrates.

Physicochemical Characteristics Of The Dried Composts

Total Organic Carbon (TOC), Total N And C/N

It is known that a large proportion of the initial organic matter is mineralized during the composting process, leading to a faster decrease in TOC at the beginning of the process because of the degradation of the most easily biodegradable organic matter fractions (Morel *et al.* 1986; Chen & Inbar 1993). Thus TOC decreased between 3 and 6 months for all the composts (Table 2). When no windrow turning occurred during the maturation phase, TOC decreased less (BIO3st-6m and MSW3st-6m). The concentration of TOC was significantly correlated with the proportion of C mineralized during the incubations and with the maturity tests (Table 5).

N concentration tended to increase during the composting process since less N than C was lost during the composting process. The C/N ratio is frequently used as maturity indicator. C/N ratio smaller than 25 (Roletto *et al.* 1985b) and generally smaller than 20 or 15 characterized mature composts (Sugahara & Ionoko 1981; Iannotti *et al.* 1994). For all the sampled composts, the C/N ratio tended to decrease between 3 and 6 months and was smaller than 20. The ranges of C/N decrease between 3 and 6 months varied from 19.1 - 13.9 (MSW1) to 11.1 - 9.6 (MSW3) without any relation with stabilization of compost organic matter. Indeed all composts could be considered as mature after 6 months of composting from the self-heating test except the MSW3 that only reached a rotting degree III after 6 months. The same sample had the lowest C/N ratio (9.6). The C/N ratio was not well correlated with any of the other measured parameters related with compost organic matter stabilization and could not be retained as a satisfying maturity indicator (Table 5).

pH And Electrical Conductivity

Most composts had basic pH (7.7 - 8.9) except SG2-3m and MSW3st-6m which were slightly acid (pH of 6.5 and 5.7 respectively; Table 6). No clear

change in pH between 3 and 6 months of composting was observed, nor differences according to the type of composted wastes. For the MSW composts, little variations of pH were observed, although important stabilization of the organic matter occurred. For these MSW composts, the management of the composting process during the maturation phase appeared necessary since pH decreased to 5.7 when no windrow turning occurred, probably due to organic acid production (Michel & Reddy 1998).

The electrical conductivity varied between 0.61 to 3.06 mS.cm⁻¹ (Table 6). The largest values corresponded to the MSW composts (1.5 to 3 mS.cm⁻¹) as reported elsewhere (Avnimelech *et al.* 1996). Except for BIO2 and SG1, the electrical conductivity increased between 3 and 6 months for all the composts and the largest increases were observed for the 3 MSW composts. This increase could be explained by the organic matter loss which occurred an increase of mineral cation concentration not attenuated by salts leaching or by the binding to stable organic complex. Compost phytotoxicity has been related to electrical conductivity larger than 4 mS.cm⁻¹ when composts were used as growing substrate (Garcia *et al.* 1992). From our results, composts which organic matter was considered as stabilized from the self-heating test or the incubation results had a electrical conductivity close to 4. They could thus remain phytotoxic when used as growing substrate. In this case, phytotoxicity tests would be necessary to select the compost to be used.

Chemical Fractionation Of Organic Matter

The organic carbon extracted as fulvic (C-FA), and humic acids (C-HA) represented 9 to 27% of TOC (Table 7) as usually found in other composts (Serra-Wittling *et al.* 1996; Bernal *et al.* 1998a; Eggen & Vethe 2001). The largest proportions of HA were found in the composts with the slowest process: enforced aeration was not used for GW2 and SG1; only 3 weeks of enforced aeration were used in the case of BIO2 without windrow turning.

For all composts, the FA concentrations tended to decrease between 3 and 6 months while HA concentrations increased, because of waste organic matter humification during the composting process. The largest increases in HA concentrations were observed in the MSW2 and MSW3 composts, for which stabilization of organic matter was important between 3 and 6 months. No clear evolution of HA was observed in the composts with the largest proportions of HA although FA proportions tended to decrease between 3 and 6 months of composting.

TABLE 7.

Fulvic (C-FA) and humic (C-HA) acid concentrations in the compost expressed as percent of total organic carbon – ratio C-HA to C-FA used as stability index

Compost	Age	C-FA % TOC	C-HA	C-HA/ C-FA
GW1	3 months	4.1	5.0	1.2
	4 months	5.4	6.1	1.1
	6 months	5.4	6.1	1.1
GW2	3 months	8.7	12.1	1.4
	4 months	8.9	18.2	2.0
	6 months	5.0	16.0	3.2
BIO1	3 months	5.9	8.6	1.5
	4 months	5.2	7.6	1.4
	6 months	6.1	9.7	1.6
BIO2	3 months	3.5	14.0	4.1
	4 months	3.8	14.5	3.8
	6 months	2.2	9.5	4.3
BIO3	3 months	3.9	6.9	1.8
	4 months	3.9	6.9	1.8
	6 months	3.8	7.1	1.9
BIO3st	6 months	6.0	7.9	1.3
MSW1	3 months	8.5	6.4	0.8
	4 months	6.6	6.3	1.0
	6 months	4.1	6.6	1.6
MSW2	3 months	8.2	6.4	0.8
	4 months	9.1	6.4	0.7
	6 months	5.9	9.9	1.7
MSW3	3 months	10.0	7.1	0.7
	4 months	7.9	7.9	1.0
	6 months	9.1	11.4	1.3
MSW3st	6 months	14.8	5.0	0.3
SG1	3 months	5.9	16.1	2.7
	4 months	4.9	13.5	2.8
	6 months	4.5	14.3	3.2
SG2	3 months	5.7	9.7	1.7
	4 months	5.9	9.7	1.6
	6 months	4.8	9.6	2.0

It's widely found (Chen & Inbar 1993) that the humification index C-HA/C-FA increases during the composting process and has been proposed as an indicator of compost organic matter stabilization. Various thresholds have been proposed: more than 1 (Roletto *et al.* 1985a), more than 3 (Chen *et al.* 1996). Following these criteria, all GW, BIO and SG composts could be considered as stabilized. Among these composts, the humification index clearly increased only for GW2 but not for SG2 which presented the same pattern of organic matter stabilization as revealed by the kinetics of organic carbon mineralization.

For the 3 MSW compost, the humification index increased between 3 and 6 months and exceeded 1 after 6 months of composting, when composts could be considered as stabilized from the results of C mineralization and rapid maturity tests. This indicator was significantly correlated with C mineralization during the incubations and with the self-heating and Solvita tests (Table 5).

Conclusion

The first objective of the present work was to study the influence of the composting process and the composted waste on the kinetics of stabilization of organic matter during the composting process. For that purpose, 10 compost windrows were sampled after 3, 4 and 6 months of composting on plants where green wastes (GW), biowastes (BIO), sludge (SG) or municipal solid wastes (MSW) were composted, using accelerated process by enforced aeration or not. The stability of the organic matter was assessed by laboratory incubations during which organic matter mineralization was followed. In the GW, BIO and SG composts, green wastes represented a large proportion of the initial wastes composted. For all these composts, the stabilization of organic matter occurred more rapidly than for the MSW composts and 3 to 4 months were enough to obtain stabilized organic matter. Enforced aeration alone was not enough to ensure a good stabilization of organic matter but accelerated the stabilization if windrow turning also occurred. The control of the maturation phase by windrow turning and humidity checking was also necessary to the stabilization of organic matter in good conditions, especially for the compost screened into smaller pieces. For the MSW composts, 6 months were necessary to reach stabilization similar to the 3 or 4 month old GW or BIO composts.

The second objective of the work was to validate physicochemical indicators of compost stabilization and also rapid maturity tests used at the composting plants in order for the compost producers to be able to follow compost stabilization during the process. The degree of compost stability was estimated by results of carbon mineralization during soil-compost incubations. On this basis, several methods of compost stability estimation were tested. Physicochemical characteristics such as pH, electrical conductivity, C/N ratio, did not allow the estimation of the compost stability. The humification index (C-HA/C-FA) appeared as a correct stability indicator. Among both practical tools used to estimate stability of compost (Solvita test and self-heating test), the self-heating test appeared to be the most reliable.

Acknowledgements

The authors are grateful to the industrial plant managers who made this work possible, and to Jean-Noël Rampon for his active collaboration during the laboratory experiments. The work was financially supported by ADEME and CREED.

References

- ADEME. 2000. Les déchets municipaux: les chiffres clés 2e édition, pp. 12.
- AFNOR. in press. Determination of potentially mineralizable carbon and nitrogen – Method of incubation under controlled conditions. XPU 44-163.
- Avnimelech, Y., M. Bruner, I. Ezrony, R. Sela, and M. Kochba. 1996. Stability indexes for municipal solid waste compost. *Compost Science & Utilization*, 4, 2:13-20.
- Becker, G. and A. Kotter. 1995. A standard measurement for compost maturity. Proceedings of Intl. Symposium "Biological Waste Management - A wasted chance?", 1:8.
- Bernal, M. P., C. Paredes, M. A. Sanchez-Monedero, and J. Cegarra. 1998a. Maturity and stability parameters of composts prepared with a wide range of organic wastes. *Bioresource Technology*, 63:91-99.
- Bernal, M. P., M. A. Sanchez-Monedero, C. Paredes, and A. Roig. 1998b. Carbon mineralization from organic wastes at different composting stages during their incubation with soil. *Agriculture Ecosystems and Environment*, 69:175-189.
- Brinton, W. F. and E. Evans. 2000. Plant performance in relation to depletion, CO₂-rate and volatile fatty acids in container media composts of varying maturity, *Proceedings of the conference of Microbiology composting - Innsbruck*, 1:12.
- Brinton, W. F., E. Evans, M. L. Droffner, and R. B. Brinton. 1995. Standardized test for evaluation of compost self-heating. *BioCycle*, 64-69.
- Changa, C.M., P. Wang, M.E. Watson, H. A. J. Hoitink, and F.C. Michel Jr. 2003. Assessment of the reliability of a commercial maturity test kit for composted manure. *Compost Science & Utilization*, 11, 2: 125-143.
- Chefetz, B., P. G. Hatcher, Y. Hadar, and Y. Chen. 1996. Chemical and biological characterization of organic matter during composting of municipal solid waste. *J. Environ. Qual.*, 25:776-785.
- Chen, Y., B. Chefetz, & Y. Hadar. 1996. Formation and properties of humic substances originating from composts. In: de Bertoldi et al. (eds.). *The Science of composting*. Blackie Academic and Professional, Bologna, pp. 382-393.
- Chen, Y. & Y. Inbar. 1993. Chemical and spectroscopical analysis of organic matter transformations during composting in relation to compost maturity. In: Hoitink, H.A. and H.M. Keener (eds.). *Science and Engineering of Composting*. The Ohio State University, pp. 551-600.
- Costa, F., I. Moreno, T. Hernandez, A. Lax, J. Cegarra, and A. Roig. 1989. Mineralization of organic materials in calcareous soil. *Biological Wastes*, 28:189-201.
- De Bertoldi, M. 1993. Compost quality and standard specifications: European perspectives. In: Hoitink, H.A. and H.M. Keener (eds.). *Science and Engineering of Composting*. The Ohio State University, pp. 523-535.
- Eggen, T., and O. Vethe. 2001. Stability indices for different composts. *Compost Science & Utilization*, 9, 1: 19-26.
- FCQAO. 1994. *Methods book for the analysis of compost - Kompost information Nr 230*. BGK ed.
- Forster, J. C., W. Zech, and E. Würdinger. 1993. Comparison of chemical and microbial methods for the characterization of the maturity of composts from contrasting sources. *Biol. Fertil. Soils*, 16:93-99.
- Garcia, C., T. Hernandez, F. Costa, and J. A. Pascual. 1992. Phytotoxicity due to the agricultural use of urban wastes. Germination experiments. *J. Sci. Food Agric.*, 59:313-319.
- Greenberg, A., J. Connors and D. Jenkins. 1980. Standard methods for the examination of water and waste water, 15th edition, *American public health association*, pp. 380.
- Haug, R.T. 1993. *The practical handbook of compost engineering*, Lewis Publishers (Eds.), pp. 717.
- Hirai, M. F., A. Katayama, and H. Kubota. 1986. Effect of compost maturity on plant growth. *BioCycle*, 27:58-61.
- Hogg, G., J. Barth, E. Favoino, M. Centemero, V. Caimi, F. Amlinger, W. Devlieger, W. Brinton, and S. Antler. 2002. Comparison of compost standards within the EU, North America and Australia. *The Waste and Resources Action Programme (WRAP)*, pp. 20.
- Iannotti, D. A., M. E Grebus, B. L. Toth, L. V. Madden, and A. J. Hoitink. 1994. Oxygen respirometry to assess stability and maturity of composted municipal solid waste. *J. Environ. Qual.*, 23:1177-1183.
- Iglesias-Jimenez, E. and V. Perez -Garcia. 1989. Evaluation of city refuse compost maturity: A review. *Biological Wastes*, 27:115-142.
- Kuehle-Weeideier, M. and H. Doedens. 2003. Landfilling and properties of mechanical and biological pre-treated waste. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.). *Proceedings of the 9th Intl. Waste Management and Landfill Symposium*, 26:29.
- Krom, M. 1980. Spectrophotometric determination of ammonia: a study of modified Berthelot reaction using salicylate and dichloroisocyanurate, *The Analyst*, April.
- Michel, F. C. and C. A. Reddy. 1998. Effect of oxygenation level on yard trimmings composting rate, odor production, and compost quality in bench-scale reactors. *Compost Science & Utilization*, 6, 4:6-14.
- Morel, J. L., A. Guckert, B. Nicolardot, D. Benistant, G. Catroux, and J. C. Germon. 1986. Etude de l'évolution des caractéristiques physico-chimiques et de la stabilité biologique des ordures ménagères au cours du compostage. *Agronomie*, 6, 8:693-701.
- Nicolardot, B., R. Chaussod, J. L. Morel, A. Guckert, D. Benistant, C. Troux G., and J. C. Germon. 1986. Appréciation simple de la maturité des composts urbains en relation avec leurs effets sur la production végétale. *Agronomie*, 6, 9:819-827.
- Roletto, E., R. Barberis, M. Consiglio, and R. Jodice. 1985a. Chemical parameters for evaluating compost maturity. *BioCycle*, 26:46-47.
- Roletto, E., R. Chiono, and E. Barberis. 1985b. Investigation on humic matter from decomposing poplar bark. *Agricultural Wastes*, 12, 12:261-272.

- Rynk, R. 2003. Introduction: The art in the science of composting. *Compost Science & Utilization*, 11, 2: 94-95.
- Serra-Wittling, C. 1995. Valorization de composts d'ordures ménagères en protection des cultures: Influence de l'apport de composts sur le développement des maladies d'origine tellurique et le comportement de pesticides dans un sol. *Mémoire de thèse pour l'obtention du diplôme de docteur de l'INA-PG*, pp. 220.
- Serra-Wittling, C., E. Barriuso, & S. Houot. 1996. Impact of composting type on composts organic matter characteristics. In : de Bertoldi et al. (eds.). *The Science of composting*. Blackie Academic and Professional, Bologne.
- Stentiford, E.I. 1996. Diversity of composting system. In: Hoitink, H.A. and H.M. Keener (eds.). *Science and Engineering of Composting*. The Ohio State University, pp. 95-100.
- Sugahara, K. and A. Ionoko. 1981. Composition analysis of humus and characterization of humic acid obtained from city refuse compost. *Soil Sci. Plant Nutri.*, 27, 2:213-224.
- Weppen, P. 2002. Determining compost maturity: Evaluation of analytical properties. *Compost Science & Utilization*, 10, 1: 6-10.
- Wu, L., L. Q. Ma, and G. A. Martinez. 2000. Comparison of methods for evaluating stability and maturity of biosolids compost. *J. Environ. Qual.*, 29:424-429.