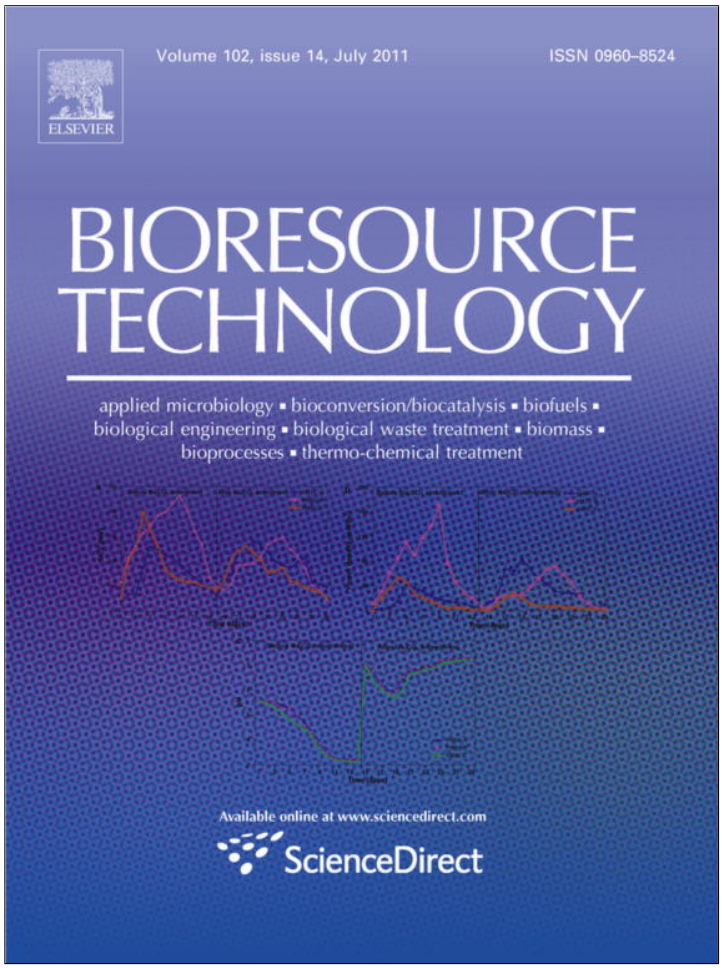

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Characterization of compost produced from separated pig manure and a variety of bulking agents at low initial C/N ratios

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ABSTRACT

The aim of this study was to investigate the composting of separated pig manure solids with or without a variety of bulking agents at a low initial C/N ratio (12.5–23.3). Compost stability was investigated using an oxygen uptake rate (OUR) test and compost maturity was investigated using a germination index test. All treatments showed typical patterns of compost temperature. Temperatures above 60 °C were achieved by Day 2, followed by a thermophilic phase (50–60 °C), which lasted for 1 to 2 weeks followed by a cooling phase. The stability of one of treatments which did not contain any bulking agent – OUR of 25 mmol O_2 kg^{-1} OM $hour^{-1}$ – was negatively affected by its initial high water content (69%). The addition of a bulking agent and initial water content below 60% were necessary to compost the separated solid fraction of pig manure at a low initial C/N ratio.

1. Introduction

1.1. Background

Traditionally, in Ireland, pig manure management involves land spreading. Since August 2006, in accordance with S.I. 378 of 2006 and its amendment (S.I.101 of 2009), the quantity of livestock manure applied to land, together with that deposited to land by livestock, can not exceed an amount containing 170 kg of organic nitrogen (N) per hectare per year. Consequently, farmland that had been used for spreading pig manure in the past may no longer be available. In addition, the amount of land in Ireland available for the application of pig manure is likely to be further restricted from January 2011. From this date, the current transitional provisions allowing application of plant available phosphorus (P), measured in Ireland as Morgan's P (Morgan, 1941), to soils at soil P Index 4 – soils with a $P_m > 8$ mg L^{-1} above which there is a risk of P loss to water (Schulte et al., 2010) – expires. Many soils which were previously used as spreadlands for pig manure may well be at Index 4, thereby preventing further manure application on such lands (Hackett, 2007).

For these reasons, alternative management strategies for pig manure, such as composting, should be considered and explored. Composting has the potential to increase the fertilizer value of the manure by binding the mineral nutrients into a stable organic structure (Burton and Turner, 2003).

1.2. Composting of pig manure

Composting is an aerobic process which involves the decomposition of organic matter (OM) under controlled temperature, moisture, oxygen and nutrient conditions. To ensure successful composting, careful material preparation must be undertaken, and compost stabilization and maturity must be achieved before the process is terminated. The preparation stage involves optimising water content (WC), nutrient balance, and the structure of the raw materials. Biological stabilization of the materials determines the effectiveness of the composting process. Stabilization of the OM is necessary to eliminate the risk of putrefaction and to prevent the production of metabolites, which are toxic to plants (Bernal et al., 2009; Luduvice, 2001). The stabilization and maturity of the compost is dependent on the preparation of the material and the correct initial conditions.

The C/N ratio of the initial material is of great importance. Carbon is mainly used as an energy source and for building microbial cells and N is required for microbial development and reproduction through protein synthesis (Sweeten and Auvermann, 2008). A low C/N ratio will reduce the amount of bulking agents needed and consequently the cost of composting (Zhu, 2007). However, to ensure that a low initial C/N ratio does not impair the compost process, it is essential to examine the stability and maturity of the final

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compost. According to Sweeten and Avermann (2008), the ideal initial C/N ratio for manure composting should be between 20 and 30. Bernal et al. (2009) propose a C/N ratio for composting in the range of 25–35. Eiland et al. (2001) used a mixture of *Miscanthus* straw and pig manure with initial C/N ratios of 25 and 16 without any adverse impact on the composting process. Zhu (2007) studied the effect of low initial C/N ratio when composting pig manure with rice straw and concluded that an initial C/N ratio of 20 could successfully produce high quality compost.

Compost quality is often defined by its maturity and stability. Maturity is related to phytotoxicity. The UK Composting Association (Gilbert et al., 2001) defined mature compost as 'compost that does not have a negative effect on seed germination or plant growth'. Stability is associated with the compost's microbial activity (Bernal et al., 2009), with more stable compost having less microbial activity.

However, other physical criteria such as odour, colour, temperature, particle size and inert material as well as chemical criteria such as nutrient content, ammonium, pH, soluble salts and pollutants also determine compost quality (Bernal et al., 2009).

Therefore, along with physical and chemical characteristics, maturity parameters such as germination index (GI) and the degree of OM humification as well as stability parameters such as aerobic respiration rate and biologically available carbon are widely used to assess pig manure compost quality (Huang et al., 2006; Tiquia, 2010; Zhu, 2007).

Bernal et al. (2009) reviewed a wide range of manure compost quality parameters and highlighted the need for a harmonization of such criteria internationally if the development of a market for manure compost materials that supports and promotes a waste composting strategy is to be achieved. Prasad and Foster (2009) have reviewed some compost quality parameters and have recommended that an Oxygen Uptake Rate (OUR) test for evaluating stability should be used. This method is being considered as a standard test by the European Committee for Standardization (CEN-Comité Européen de Normalisation) (Prasad and Foster, 2009).

Oxygen (O_2) consumption, or OUR, is an indicator of compost stability and it gives information on the degree to which biodegradable OM is broken down within a specified time period. This is because compost with an abundance of easily biodegradable OM will have a high demand for O_2 as microorganisms that metabolise OM require oxygen.

For the evaluation of pig compost maturity, many studies have used a GI (Huang et al., 2004; Tiquia, 2010; Zhu, 2007). Germination Index is a combination of the germination rate and root elongation of the seeds used to detect the degree of toxicity present in a compost sample (Tiquia, 2010).

The aim of this study was to investigate the physicochemical parameters of a compost mixture comprising of the solid fraction of separated pig manure and a variety of bulking agents (sawdust, shredded green waste, chopped straw and woodchip) at a low initial C/N ratio (12.5–23.3). Compost stability was investigated using an OUR test and the compost maturity was investigated using a GI test.

2. Methods

2.1. Trials site and manure separation process

This experiment comprised two trials. Trial 1 commenced in June 2009 and finished in August 2009. Trial 2 commenced in October 2009 and finished in November 2009. In both trials, raw pig manure was collected from an overground aerated manure storage tank at Teagasc, Pig Development Department, Fermoy, Co. Cork, Ireland, and was a mixture of pig manure that came from all stages of production.

A decanter centrifuge (GEA Westfallia Separator UCD 205, GEA WestfaliaSurge GmbH, Bönen, Germany) was used to perform the mechanical separation of the liquid manure. Alum – in liquid form – and a water soluble polyacrylamide flocculent (PAM) were used to increase the efficiency of separation. Alum was applied at approximately 3 l/m^3 of slurry. Polyacrylamide flocculent was diluted with water to 0.4% by volume and added at approximately 17% by volume. For both trials, the separation process was replicated each day for 4 days to achieve 4 replicates.

Average dry matter (DM) for liquid pig manure before separation, solid fraction after separation, and liquid fraction after separation for Trial 1 were 2.4 ± 0.17%, 38.0 ± 3.19% and 0.3 ± 0.07%, respectively. For Trial 2, these values were 2.5 ± 0.98%, 30.6 ± 2.27% and 0.2 ± 0.05%, respectively.

2.2. Treatments and compost set up

In Trial 1, there were 4 treatments each using the solid fraction of separated pig manure (SPM) and the addition of bulking agents, were applicable, to achieve a C/N ratio of 20 or less: (T1) 38 kg of SPM; (T2) 38 kg of SPM + 9.5 kg of sawdust; (T3) 38 kg of SPM + 9.5 kg of shredded green waste and (T4) 38 kg of SPM + 2.8 kg of chopped straw. In Trial 2, there were also 4 treatments: (T1) 38 kg of SPM; (T2) 38 kg of SPM + 9.5 kg of sawdust (T3) 38 kg of SPM + 9.5 kg of woodchip and (T4) 38 kg of SRM + 4.75 kg of sawdust + 4.75 kg of woodchip. At the end of Trial 1, preliminary results indicated that sawdust was the most suitable bulking agent while the absence of bulking agent resulted in a compost of worse quality. Therefore, for Trial 2, it was decided to include these treatments again and to compare them to different bulking agents.

The straw (barley) was chopped to a length of 30–100 mm. The sawdust used was Sitka spruce (*Picea sitchensis*) and the woodchip was fir (*Abies*). The shredded green waste was a mixture of tree leaves, foliage and small twigs, and was collected from a local arboriculture management company. Selected physicochemical parameters for the solid fraction of the separated pig manure and bulking agents are presented in Table 1.

In both trails, each treatment was replicated four times (16 compost piles per trial). In each trial, 16 fully insulated compost tumblers (Jora JK270 Composter, Joraform AB, Mjölby, Sweden; built without the internal partition) were used to compost the mixtures. The two materials (manure and bulking agent) were mixed thoroughly to insure uniformity. The temperature of the compost pile was recorded every morning with long-stemmed thermometers (Traceable® X-long Stem Therm Ultra, Control Company, Texas, USA). Two thermometers were inserted into the middle of the pile at different locations and from different directions. The higher temperature was recorded. Aeration of the tumblers was provided by manually turning the tumblers twice-a-day (morning and afternoon) for the first week of each trial. From the second week, the tumblers were turned once-a-day. Tumblers were turned after the temperature was recorded. Fig. 1 shows the experimental design.

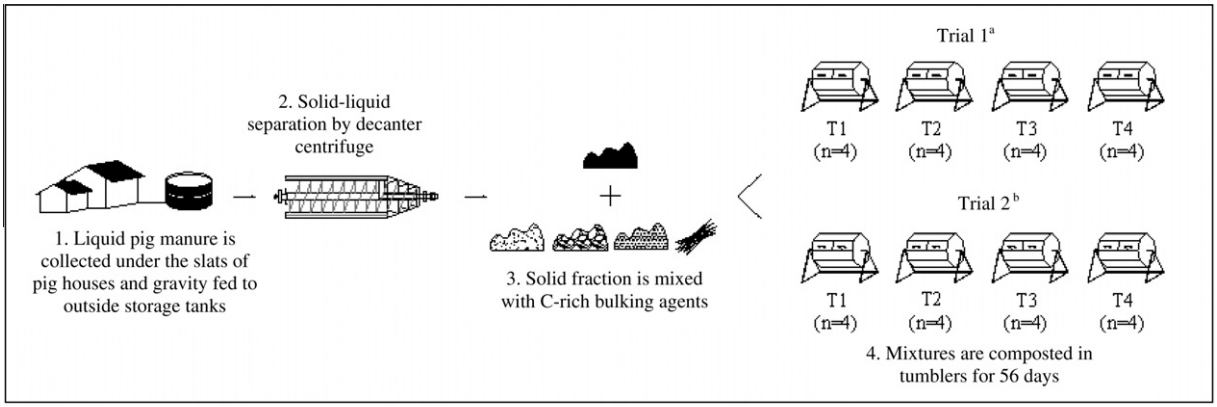
2.3. Analytical methods

Both trials were undertaken for 56 days and samples were collected from each tumbler on Days 0, 3, 7, 14, 21, 28, 42 and 56 for analyses. Each sample was a composite of 6 sub-samples – 3 sub-samples taken from the top and 3 from the bottom of the compost pile. Each of the 3 sub-samples was taken at different locations (right, centre and left of the pile). Analyses of WC and pH were performed on fresh samples on the day of collection. After determina-

Table 1
Physicochemical parameters for separated pig manure and bulking agents (means ± SD[a]).

Parameters	Separated pig manure (Trial 1)	Separated pig manure (Trial 2)	Sawdust	Green Waste	Straw	Woodchip
pH	8.3 ± 0.17	8.9 ± 0.19	4.9 ± 0.09	5.2 ± 0.07	7.5 ± 0.07	6.0 ± 0.19
DM (%)	38.0 ± 3.19	30.6 ± 2.27	84.2 ± 3.04	52.9 ± 4.55	88.2 ± 2.25	89.6 ± 2.46
Nitrogen (% db)	3.3 ± 0.34	3.1 ± 0.19	0.1 ± 0.01	0.8 ± 0.07	0.6 ± 0.03	0.8 ± 0.004
Carbon (% db)	39.1 ± 0.97	38.3 ± 0.85	48.8 ± 0.25	49.3 ± 0.01	44.9 ± 0.37	47.2 ± 0.08
C/N	12.0 ± 1.12	12.5 ± 0.76	466.5 ± 58.6	60.8 ± 5.10	72.4 ± 2.55	513.4 ± 24.1
Bulk density	374 ± 43.1	498 ± 75.3	40.2 ± 1.67	50.1 ± 4.08	9.6 ± 0.81	45.2 ± 4.29
Ash	25.0 ± 1.30	26.8 ± 1.29	0.3 ± 0.02	3.3 ± 0.51	3.7 ± 0.06	0.3 ± 0.04

[a] SD (Standard Deviation) of $n = 4$ for pH; $n = 8$ for DM bulking agents; $n = 19$ for DM pig manure Trial 1; $n = 12$ for DM pig manure Trial 2; $n = 4$ for pig manure nitrogen and carbon; $n = 2$ for bulking agents nitrogen and carbon and $n = 3$ for bulk density and ash.



[a] Trial 1 - T1: manure only; T2: manure and sawdust; T3: manure and shredded green waste; T4: manure and chopped straw.
[b] Trial 2 - T1: manure only; T2: manure and sawdust; T3: manure and woodchip; T4: manure and sawdust and woodchip.

Fig. 1. Illustrative diagram of experimental design.

tion of WC, the dried material was milled and stored in a cold room (*c.* 2 °C) for C and N analyses later. Fresh samples were collected on Days 0 and 56 for bulk density, OM and respiration tests (OUR), and, on Day 56, for the cress seed germination test.

2.3.1. Physicochemical analyses

Water content was determined after Hao et al. (2004) by drying the samples in an oven at 60 °C until the weight of the dried samples remained constant. Measurement of pH was performed after Tiquia et al. (2002) using a bench top meter (SevenEasy, Mettler-Toledo, Switzerland) in water solution at a compost/distilled water ratio of 1:10 (w/v). Ash and OM were determined after Tiquia (2005) by incinerating pre-dried samples in a furnace (Carbolite, Sheffield, England) at 550 °C for 5 h. The loss of organic matter (OMLoss) was calculated from the Day 0 (OM_0) and Day 56 (OM_{56}) organic matter contents according to:

$$\mathrm{OMLoss} = \frac{\mathrm{OM}_0 - \mathrm{OM}_{56}}{\mathrm{OM}_0 \times (100 - \mathrm{OM}_{56})} x100 \quad (1)$$

Total C and N content were determined by loss of ignition (LOI) in a CHNOS Elemental Analyser Vario EL Cube (Elemental Analysensysteme GmbH, Hanau, Germany) at a combustion temperature of 1100–1200 °C. Bulking density was performed by suspending a funnel above a 1-litre measuring cylinder. The funnel was filled with the sample and allowed to flow freely into the measuring cylinder. The excess material on top of the measuring cylinder was scraped off. The sample and the cylinder were then weighed and the weight/volume (bulk density) was calculated in kg m^{-3}.

2.3.2. Oxygen uptake rate and cress seed germination tests

The aerobic biological activity of the compost was measured by calculating the OUR using a pressure transducer system (System OxiTop® Control ^{OC}110, WTW Gmbh, Weilheim, Germany). Two grams of OM of each compost sample were mixed with 180 ml of distilled water and 10 ml of a nutrient solution, 10 ml of pH buffer and 2.5 ml of a nitrification inhibitor (Appendix) in 1000 ml Duran® bottles. The control tests were performed without compost sample. The bottles were placed – unsealed – on a stirring platform and incubated at 30 ± 2 °C for 4 hours. Pressure transducer heads were then attached to the bottles and the samples returned to the incubator for 5 days. During this period, the rate at which oxygen was consumed by the inherent micro-organisms was estimated by measuring the pressure drop in the headspace above the water phase. Soda lime pellets, placed in a compartment in the headspace, were used to remove the effect of carbon dioxide (CO_2) production. The oxygen consumption was then calculated according to:

$$\mathrm{Oc} = \frac{\Delta P \times 10}{R \times (273.15 + T)} \frac{V_{\mathrm{gas}} \times 10000}{W \times \mathrm{DM} \times \mathrm{OM}} \quad (2)$$

where Oc is the oxygen consumption (mmol O_2 kg^{-1} OM $hour^{-1}$); ΔP, the pressure drop in the headspace (kPa); R, a gas constant (83.14 L kPa K^{-1} mol^{-1}); T, the temperature at which the measurement was performed (°C); W, the initial weight of the sample (kg); DM, the dry matter content of the sample (%-w); OM, the organic matter content of the sample (%-w); and V_{gas} is the volume of the gas phase (ml), calculated according to:

$$V_{\mathrm{gas}} = V_{\mathrm{vessel}} - \frac{W \times \mathrm{DM} \times 10000}{\rho} - V_{\mathrm{liquid}} \quad (3)$$

where V_{vessel} is the total volume of vessel (ml); V_{liquid}, all added liquids (water, nutrient solution, pH buffer and ATU solution; ml); and ρ is the sample density (kg m^{-3}), calculated according to:

$$\rho = \frac{1}{\frac{\mathrm{OM} \times W \times \mathrm{DM}}{1550}} + \frac{(1 - \mathrm{OM}) \times W \times \mathrm{DM}}{2650} \quad (4)$$

The oxygen uptake rate (OUR, mmol O_2 kg^{-1} OM $hour^{-1}$) was then calculated from Eqn. [2] and the related time period according to:

$$\mathrm{OUR} = \frac{\mathrm{Oc}}{\Delta t} \quad (5)$$

where: Δt is the time (in hours) when $\Delta P = 0$.

A cress seed germination test was performed after Prasad et al. (2010) on a mixture of 50% compost and 50% peat moss in a 10 mm-long by 10 mm-wide Petri dish to assess the compost maturity. The dish was completely filled with the compost and peat mixture. Ten cress seeds were sown per dish. To ensure that there was good contact with the sample material, approximately 0.5 ml of water was added to each seed. The dishes, inclined at a 70–80° angle to the horizontal with the seeds on the underside, were incubated at 25 ± 2 °C, in the dark. After 72 h, the number of germinated seeds was counted and the root length measured. The control test was performed with fertilised peat. Each treatment was performed in triplicate. Germination index was then calculated after Tiquia and Tam (1998):

$$GI = \frac{\text{Mean germination in treatment (\%)}}{\text{Mean germination in control (\%)}} \times \frac{\text{Mean root lenght in treatment (\%)}}{\text{Mean root lenght in control (\%)}} \times 100 \quad (6)$$

2.4. Statistical analysis

Data were analyzed using the Statistical Analyses System (SAS, V9.1.3, 2002–2003). For comparison of WC, pH, bulk density, OM, N content, C/N ratio and OUR, repeated measures ANOVA was used (Mixed procedure). The dependent variables were: WC, pH, bulk density, OM, N content, C/N ratio and OUR. For all the above analyses, the fixed effects were: treatment, day and tumbler. Day was the repeated measure, and starting day was included as a random variable.

Model fit was determined by choosing the model with the minimum finite-sample corrected Akaike's Information Criteria (AIC). A compound symmetry structure was the best fit for OM (Trials 1 and 2) and for bulk density (Trials 1 and 2). The covariance structure that provided the best model fit for OUR (Trials 1 and 2), WC (Trial 1), pH (Trial 2), N content (Trials 1and 2) and C/N ratio (Trials 1 and 2) was the heterogeneous first-order autoregressive structure ARH(1). An autoregressive type 1 covariate structure (AR1) was the best fit for pH (Trial 1). An unstructured covariance model was the best fit for WC (Trial 2). Differences in least squares means were investigated using Tukey's adjustment for multiple comparisons. Comparison of GI at Day 56 was performed using the Proc Mixed SAS procedure. Germination Index was the dependent variable. Treatment was included as a fixed effect and start day was included as a random variable. For all analyses, significance was at $P \leqslant 0.05$.

3. Results and discussion

3.1. Physical changes

In the first 5 days, all the composts had a malodour and attracted a great amount of flies. During this period, there was also a smell of ammonia (NH_3) when the tumblers were opened for sampling. After 7–8 days, the presence of flies was greatly reduced and there was no longer a malodour.

At the end of the composting period, most of the treatments had a reduced malodour, especially the green waste treatment. However, in the manure-only treatments (T1), the bad odour remained and conglomerates (small spheres) were formed over time during the turning of the tumblers. The manure in the other treatments, however, remained loose, in small particles and well mixed with the bulking agents. The structure of these composts improved with time and, by the end of the composting period, the majority had achieved a peat-like appearance. This was reflected in the results of initial and final bulk density (Table 2, P values for Day 0 vs. Day 56 comparison not shown). In both trials, Day 0 and Day 56 bulk density for all the treatments with added bulking agents was the same (P values >0.05). For T1, Trial 2, bulk density increased with time ($P = 0.0086$). The bulking density increase for T1, Trial 2 was not statistically significant ($P = 0.57$) most likely because its lower initial WC of 62%; the initial WC for T1, Trial 2 was

Table 2
Mean bulk density, nitrogen (N) content, carbon (C)/N ratio, organic matter, oxygen uptake rate (OUR), and germination index for compost treatments (means ± SD; $n = 4$).

	Trial 1						Trial 2					
	T1	T2	T3	T4	s.e.	P	T1	T2	T3	T4	s.e.	P
Bulk density ($kg\ m^{-3}$)												
Day 0	374 ± 43.1^{A}	268 ± 46.1^{C}	300 ± 28.6^{AC}	231 ± 53.6^{C}	23.19	<0.01	498 ± 75.3^{A}	339 ± 64.3^{B}	359 ± 56.3^{B}	376 ± 66.3^{B}	27.17	<0.01
Day 56	428 ± 94.0^{a}	273 ± 3.8^{b}	324 ± 21.1^{b}	228 ± 15.2^{b}	23.19	<0.01	582 ± 53.8^{a}	330 ± 46.3^{b}	341 ± 30.0^{b}	362 ± 17.7^{b}	27.17	<0.01
N content (%)												
Day 0	3.3 ± 0.34^{A}	2.3 ± 0.28^{B}	2.6 ± 0.15^{AB}	2.7 ± 0.39^{AB}	0.08	<0.01	3.1 ± 0.19^{A}	2.2 ± 0.25^{B}	1.9 ± 0.38^{B}	2.0 ± 0.29^{B}	0.14	<0.01
Day 56	3.5 ± 0.13^{a}	2.3 ± 0.12^{c}	3.1 ± 0.18^{b}	3.3 ± 0.18^{ab}	0.04	<0.01	3.1 ± 0.23^{a}	2.2 ± 0.13^{b}	1.8 ± 0.13^{b}	2.2 ± 0.12^{b}	0.08	<0.01
C/N ratio												
Day 0	12.0 ± 1.12^{A}	18.2 ± 3.14^{B}	16.0 ± 1.21^{AB}	14.6 ± 1.93^{AB}	0.50	<0.01	12.5 ± 0.76^{A}	18.3 ± 2.12^{AB}	23.3 ± 5.49^{B}	21.7 ± 3.79^{B}	1.76	<0.01
Day 56	9.4 ± 0.42^{a}	16.6 ± 1.28^{b}	12.4 ± 0.76^{c}	10.3 ± 0.39^{a}	0.14	<0.01	11.1 ± 0.80^{a}	17.9 ± 0.96^{b}	23.4 ± 1.76^{c}	17.5 ± 1.13^{b}	0.61	<0.01
Organic Matter (%)												
Day 0	75.0 ± 1.66^{A}	85.1 ± 4.26^{B}	83.4 ± 2.90^{BC}	78.3 ± 2.03^{AC}	1.31	<0.01	73.2 ± 1.18^{A}	84.3 ± 2.85^{B}	81.2 ± 2.06^{B}	83.5 ± 4.14^{B}	1.29	<0.01
Day 56	65.4 ± 1.38^{a}	83.0 ± 3.73^{b}	74.0 ± 2.14^{c}	68.4 ± 0.87^{ac}	1.31	<0.01	68.1 ± 1.10^{a}	83.5 ± 0.53^{b}	82.6 ± 4.42^{b}	83.3 ± 1.18^{b}	1.29	<0.01
OUR ($mmol\ O_2\ kg^{-1}\ OM\ hour^{-1}$)												
Day 0	50.8 ± 11.73	47.4 ± 12.20	43.2 ± 13.11	40.0 ± 9.42	5.91	0.59	35.6 ± 11.09	30.2 ± 8.36	35.0 ± 6.61	33.2 ± 4.76	4.16	0.78
Day 56	13.4 ± 1.28^{a}	6.8 ± 2.05^{b}	12.5 ± 2.65^{a}	13.8 ± 3.11^{a}	1.19	<0.01	25.2 ± 4.22^{a}	11.0 ± 1.44^{b}	12.3 ± 1.52^{b}	13.3 ± 2.51^{b}	1.28	<0.01
Germination Index Day 56	78 ± 6.0^{a}	92 ± 11.2^{b}	93 ± 6.0^{b}	76 ± 12.1^{a}	4.64	<0.01	101 ± 12.0	99 ± 2.4	100 ± 6.9	97 ± 5.6	3.41	0.81

$^{abc/ABC}$Means without the same subscript, in a row, for the same Trial, were significantly different ($P < 0.05$).
Trial 1 – T1: manure only; T2: manure and sawdust; T3: manure and shredded green waste; T4: manure and chopped straw.
Trial 2 – T1: manure only; T2: manure and sawdust; T3: manure and woodchip; T4: manure and sawdust and woodchip.

Table 3
Water content (%) for compost piles (means ± SD; $n = 4$).

	Trial 1						Trial 2					
	T1	T2	T3	T4	s.e.	p	T1	T2	T3	T4	s.e.	p
Day 0	64.1 ± 2.8	51.8± 7.31	61.0 ± 1.82	58.2 ± 4.21	3.64	0.14	69.3 ± 1.71^{a}	58.3 ± 5.89^{b}	56.9 ± 3.44^{b}	55.9 ± 5.26^{b}	1.96	<0.01
Day 3	62.3 ± 4.0	53.4 ± 5.3	60.0 ± 1.99	58.2 ± 2.48	3.28	0.29	68.5 ± 2.00^{a}	57.8 ± 2.86^{b}	54.6 ± 2.15^{b}	57.6 ± 2.82^{b}	1.44	<0.01
Day 7	63.3 ± 2.8^{a}	52.3 ± 0.7^{b}	59.4 ± 3.63^{a}	56.9 ± 4.31^{a}	2.02	0.01	68.7 ± 1.97^{a}	55.8 ± 5.36^{b}	53.3 ± 3.32^{b}	54.4 ± 3.91^{b}	1.71	<0.01
Day 14	60.3 ± 5.3^{a}	49.0 ± 2.6^{b}	57.5 ± 3.16^{a}	53.7 ± 7.00^{a}	2.18	<0.01	68.3 ± 2.14^{a}	57.7 ± 5.14^{b}	53.5 ± 1.33^{b}	55.1 ± 3.21^{b}	1.51	<0.01
Day 21	62.1 ± 3.4^{a}	51.0 ± 2.3^{c}	58.3 ± 1.78^{ab}	55.5 ± 5.16^{bc}	1.51	<0.01	68.0 ± 2.22^{a}	57.5 ± 3.80^{b}	53.1 ± 2.00^{b}	55.8 ± 3.61^{b}	1.43	<0.01
Day 28	62.2 ± 3.3^{a}	50.6 ± 2.6^{c}	58.1 ± 1.86^{ab}	55.7 ± 4.29^{b}	1.51	<0.01	68.1 ± 1.84^{a}	57.2 ± 3.94^{b}	53.1 ± 3.04^{b}	55.3 ± 3.76^{b}	1.53	<0.01
Day 42	62.5 ± 4.2^{a}	51.9 ± 1.5^{c}	59.0 ± 2.00^{ab}	56.8 ± 3.95^{b}	1.42	<0.01	67.9 ± 1.61^{a}	57.6 ± 3.92^{b}	53.9 ± 1.78^{b}	56.2 ± 4.12^{b}	1.42	<0.01
Day 56	62.1 ± 4.0^{a}	52.0 ± 0.5^{c}	59.2 ± 2.08^{ab}	57.5 ± 4.18^{b}	1.42	<0.01	68.3 ± 1.05^{a}	57.7 ± 4.40^{b}	52.7 ± 2.66^{b}	56.8 ± 3.79^{b}	1.60	<0.01

^{abc}Means without the same subscript, in a row, for the same Trial, were significantly different ($P < 0.05$).
Trial 1 – T1: manure only; T2: manure and sawdust; T3: manure and shredded green waste; T4: manure and chopped straw; Trial 2 – T1: manure only; T2: manure and sawdust; T3: manure and woodchip; T4: manure and sawdust and woodchip.

69% (Table 3). Moreover, in both trials, bulk density at Day 56 for the manure only treatment was higher than the bulk density of the other treatments (Table 2).

3.2. Temperature

Changes in the temperature of composts for both trials are shown in Fig. 2. The pattern of temperature change in a pig manure composting pile has been used to monitor the stabilization of the composting process in many studies (Cronje et al., 2004; Eiland et al., 2001; Huang et al., 2004, 2006; Szanto et al., 2007; Tiquia et al., 1996; Tiquia, 2005). The temperature variation during composting in these studies followed the same 3-phase pattern as the one observed in the present study: (i) initial heating phase, (ii) thermophilic phase, and (iii) cooling/maturing phase.

In the initial heating phase, the temperature inside the compost piles began to rise immediately, rapidly achieving peak temperatures. In Trial 1, temperatures had reached >60 °C for all treatments by Day 3. In Trial 2, temperatures had reached >50 °C for all treatments by Day 1. In this initial heating phase, mesophilic bacteria and fungi metabolized readily degradable compounds such as sugar, fats, starch, amino acids and protein, producing CO_2, NH_3, H_2O, organic acids and heat (Bernal et al., 2009). The accumulation of this heat was responsible for the rise in temperature of the compost mass. Although temperatures in both trials followed similar patterns (Fig. 2), in Trial 2 the temperatures failed to remain as high for as long. The average daily ambient temperature during Trial 2 was lower (min 6.9 °C, max 14.2 °C) than that during Trial 1 (min 14.6 °C, max 21.5 °C), which may account for the slightly lower temperatures in the second trial.

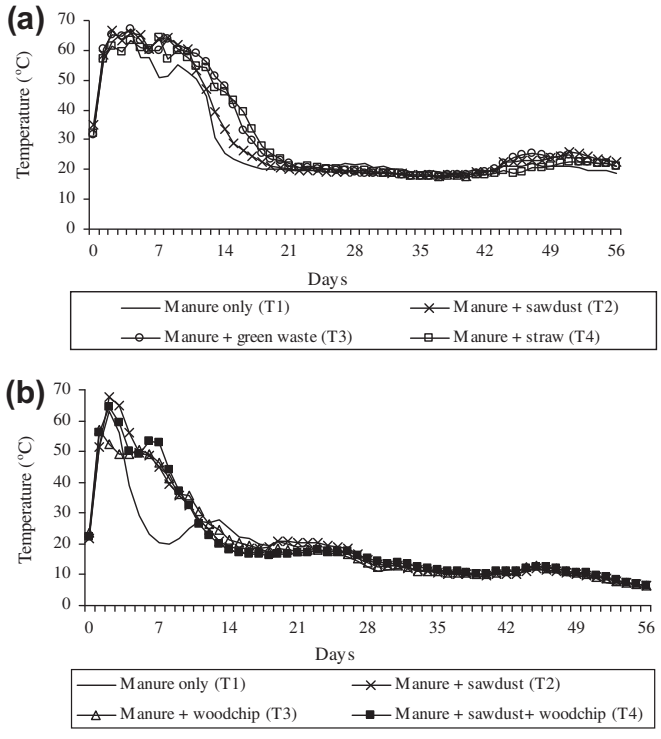


Fig. 2. Compost temperature for Trial 1 (a) and Trial 2 (b).

Cronje et al. (2004), studying the relationship of stability and temperature in composting of pig manure and straw, reported that the highest rate of bacterial activity occurred at around 60 °C. They concluded that this temperature corresponded with the compost of greatest stability, and therefore it is the optimum temperature at which a composting mix of pig manure and straw should operate. Bernal et al. (2009) identified an optimum temperature range of 40–65 °C for composting. In the present study, during the second phase of composting, this ideal thermophilic temperature (50–65 °C) was maintained for a period of 1–2 weeks. In Trial 1, temperatures remained above 50 °C for a period of *c.* 2 weeks for all 4 treatments. In Trial 2, temperatures remained above 45 °C for a period of 8 or 9 days for T2–4. However, temperature for T1 dropped below 40 °C on Day 4. The final composting phase was characterized by a drop in temperature, indicating that thermophilic bacterial activity had slowed down.

While temperatures of around 40–65 °C are optimum for composting, temperatures above 55 °C are required to kill pathogenic microorganisms (Bernal et al., 2009). In both trials, all the treatments achieved temperatures above 55 °C.

McCarthy et al. (2011) conducted microbiological analyses on samples from the current study. This showed that *E. coli* and *Enterococcus* were present on Day 0 at 4.12–5.33 and 4.26–4.89 $\log_{10}$ CFU g^{-1}, respectively. They were reduced by day 7 and were undetectable (<2.0 $\log_{10}$ CFU g^{-1}) in the final compost at Day 56. Coliforms, however, were still present at 3.66–4.43 $\log_{10}$ CFU g^{-1} on Day 56. McCarthy et al. (2011) demonstrated that the final compost complied with EU regulations (EC/208/2006; EC, 2006), which states that a marketable, processed manure product must be free from *Salmonella,* with *E. coli* or *Enterococcus* counts not exceeding 3.0 $\log_{10}$ CFU g^{-1}.

3.3. Water content

Water contents for the treatments throughout the 56 days of the trials are shown in Table 3. In both trials, within each treatment, WC remained the same during the 56 days ($P > 0.05$). This is most likely because enclosed vessels (tumblers) were used to carry out the composting in our study. With the rise in tempera-

ture, the water which evaporated from the piles could not easily escape the tumblers. Much of the water vapour condensed on the inner walls of the tumbler, replacing the water that was initially lost through evaporation. This phenomenon could be clearly seen when the tumblers were opened for sampling.

The ideal WC of a manure compost pile is between 40% and 60% (Sweeten and Auvermann, 2008; Tiquia, 2005). Results show that the addition of bulking agents to the separated fraction of pig manure reduced WC to adequate levels for composting. In both trials, the Water Content for the 3 treatments that contained bulking agents remained within the range of 49–61%. WC for the manure only treatments remained above 60% in Trial 1 and above 68% in Trial 2. T1 lacked the bulking agent to absorb the high initial WC of the separated pig manure. As a result, the WC of these piles had a significant effect on the microbial activity. This was more evident in Trial 2 because of its higher initial WC (Table 3). With a high initial WC of 69%, O_2 movement within the pile became restricted, resulting in anaerobic conditions (Das and Keener, 1997). Consequently, microbial activity slowed down and the production of heat was diminished. As a result, temperature dropped below 40 °C on Day 4 (Fig. 2). This also had a detrimental effect on the stability of this treatment (Section 3.7).

3.4. pH

Changes in pH for both trials are shown in Fig. 3. In both trials, the change in pH for the 4 treatments followed a similar pattern. The increase in pH values between Day 0 and Days 3 and 7 coincide with the highest temperatures in the compost (Fig. 2). Higher temperatures are indicative of higher microbiological activity (Tiquia, 2005). This higher microbiological activity resulted in a higher NH_3 production due to the mineralization of the organic nitrogen (Eklind and Kirchmann, 2000b). Finally, the higher NH_3 production was reflected in the elevated pHs. The subsequent decrease in pH was caused by nitrate formation as a result of H^+ released during microbial nitrification (Eklind and Kirchmann, 2000b).

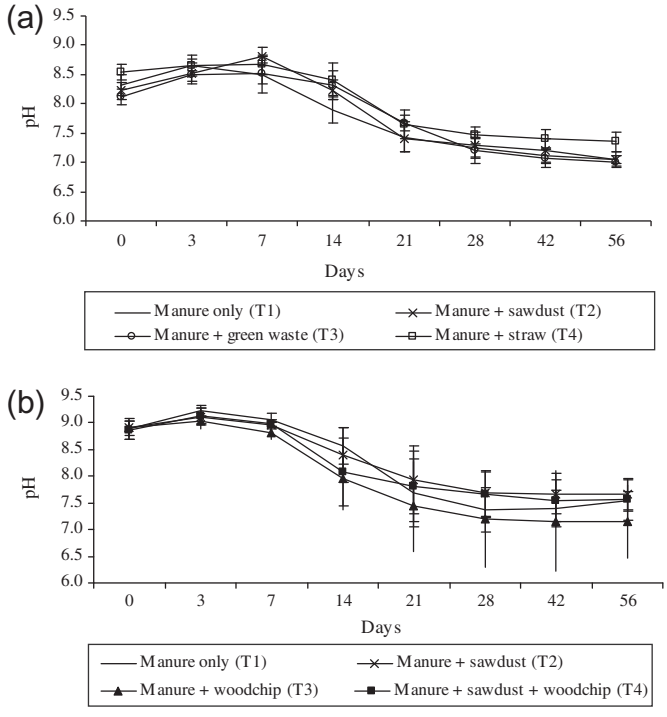


Fig. 3. Compost pH for Trial 1 (a) and Trial 2 (b).

3.5. Organic matter

Results for OM are shown in Table 2. In Trial 1, final OM for T1, T3 and T4 was significantly lower than initial OM ($P < 0.001$). However, for T2, initial and final OM was not significantly different ($P = 0.46$). Consequently, average loss of OM for T2 (16.6%) was lower than OM loss for Treatments 1, 3 and 4 (37.0%, 42.9% and 40.0%, respectively). In Trial 2, for T2, T3 and T4, initial and final OM were not significantly different ($P = 0.99$, 0.93 and 1.0, respectively). Organic Matter for T1 decreased significantly over time ($P = 0.01$). Consequently, average OM loss for T1 (22.1%) was higher than OM loss for T2, T3 and T4 (4.9%, −13% and 1.3%, respectively).

Szanto et al. (2007) recorded a 57% loss of OM during the composting of straw rich pig manure (initial C/N ratio of 13) in turned piles. The smaller value of OM loss in the present study (40% for T4, Trial 1) can be explained by the methodologies used. In the present study, the OM losses were calculated as the difference in concentration of OM only. The piles were not weighed at the end of the composting process. Therefore, it was not possible to take into account the dry weight reduction of the pile as in Szanto et al. (2007). Huang et al. (2004) did not take into account the dry weight reduction of the piles and found a comparably small (5%) loss of OM when composting pig manure and sawdust at a C/N ratio of 15.

The lower loss of OM in T2 (Trial 1) and T2–4 (Trial 2) when compared to the other treatments in the same trial can be explained by nature of the bulking agents used (sawdust and woodchip). Woody materials have a high content of lignin (Eklind and Kirchmann, 2000a). Lignin is extremely resistant to chemical and enzymatic degradation. During a 150-day compost of sugar beet vinasse, Madejón et al. (2001) did not record any lignin degradation. When composting cattle manure, Hao et al. (2004) and Michel et al. (2004) also found a lower decomposition of the compost substrate when using bulking materials rich in lignin (woodchip and sawdust) compared to composting with straw, which had a lower lignin content. Alternatively, the lower degradability of the woodchip mixture, when compared to the sawdust mixture (Trial 2), may have been associated with its smaller surface area-to-mass ratio.

Prasad and Foster (2009) recommended a 20% minimum OM for Irish compost. In both trials all treatments exceeded this limit.

3.6. C/N ratio

Day 0 and Day 56 C/N ratios as well as N content are shown in Table 2. For all treatments, initial C/N ratio was higher than final C/N ratio, except T3 (Trial 2). The lower C/N ratio at the end of the compost was a result of the degradation of the carbon fraction of the materials composted, as the N content remained the same (Table 2). During the compost process, carbonaceous materials such as carbohydrates, fats and amino acids (degraded quickly in the first stage of compost), and also cellulose, hemicelluloses and lignin (partially degraded at a later stage) are partially mineralised, leading to carbon losses throughout the process (Bernal et al., 2009).

As discussed earlier, the recalcitrant nature of the lignin present in the woodchip, as well as its lower surface-to-mass ratio area, can help explain the lower degradation that occurred in T3 (Trial 2).

C/N ratio has been used to assess compost maturity (Hsu and Lo, 1999; Huang et al., 2004, 2006) where a final C/N ratio of 20 or less was indicative of mature compost, (when initial C/N ratio was above 20). In the present study, the final C/N ratio was below 20 for all treatments, except T3, Trial 2. However, the initial C/N ratios were already below 20 for most of the treatments (Table 2). Analysing the compost produced from pig manure and sawdust, Huang

et al. (2004) considered that the C/N ratio cannot be used as an absolute indicator of compost maturation due to the large variation in initial C/N ratio of the starting material. Likewise, in the present study final C/N ratio should not be used as an indicator of compost maturity.

3.7. Oxygen uptake rate

Fig. 4 shows Day 0 and Day 56 pressure profile for T2, Trial 1 and for control sample throughout a 5-day incubation period. Pressure drop (maximum reading minus final reading) for Day 0 (178 hPa) was much higher than the pressure drop on Day 56 (58 hPa) reflecting the higher demand for O_2 in the initial, unstable material. Pressure drop for Day 0 and Day 56 for all the treatments followed the same trend (data not shown). Pressure in the control tests remained virtually unchanged (Fig. 4).

Results for the OUR tests across all trials and treatments are presented in Table 2 (P values for Day 0 vs. Day 56 comparison not shown). For all treatments, in both trials, OUR Day 0 was significantly higher ($P < 0.01$) than OUR Day 56, except for Treatment 1, Trial 2 ($P = 0.38$). In both trials, with the exception of T1 in Trial 2, all treatments achieved OUR values below 14 mmol O_2 kg^{-1} OM $hour^{-1}$. The proposed OUR value for stable compost for Irish compost standards is 13 mmol O_2 kg^{-1} OM $hour^{-1}$ (Prasad and Foster, 2009). This value is similar to that used in Belgium and The Netherlands where values below 15 mmol O_2 kg^{-1} OM $hour^{-1}$are considered stable. Our results show that, with the exception of T1 (Trial 2), a good degree of OM stabilization was achieved for all treatments.

In Trial 2, the final OUR was higher ($P < 0.01$) for T1 when compared to T2–4. One factor that could have affected the stability of T1 was its very low initial C/N ratio (12.5). However, T1 in Trial 1 (also a manure-only treatment), had a similar initial low C/N ratio (12.0) and OUR value of 13.4 mmol O_2 kg^{-1} OM $hour^{-1}$. The initial WC of the pig manure used in Trial 1 was not as high as that in the manure used in Trial 2 (62% and 69.4%, respectively; Table 1). Therefore, the lack of a bulking agent and the initial low C/N ratio did not affect T1 in Trial 1 as significantly as it did in Trial 2. The drop in temperature was not as evident in Trial 1 as it was in Trial 2 (Fig 2). It appears that the high WC was responsible for the poor stability of the manure-only treatment in Trial 2.

These results show that the high initial WC of the separated pig manure used had a negative impact on the composting process. The high initial WC hampered the free passage of air through the empty spaces of the compost mass, resulting in zones of anaerobic conditions (Das and Keener, 1997). As a result, aerobic microbiological activity was impaired and less heat was produced, which was also reflected in the lower compost temperatures achieved with this treatment (Fig. 2).

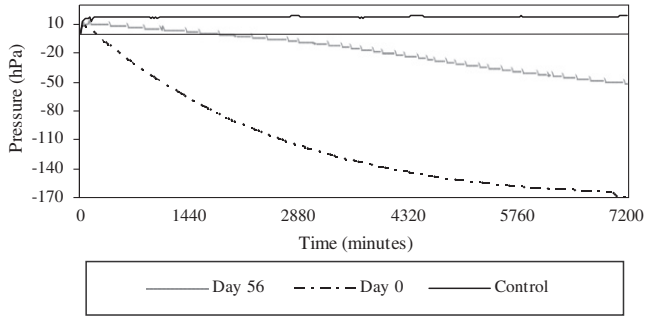


Fig. 4. Effect of incubation time on pressure drop on Day 0 and Day 56 of Treatment 2, Trial 1 (separated pig manure + sawdust) and blank control (no compost sample).

Tiquia et al. (1996) studied the effect of different WCs (50, 60 and 70%) on the composting of spent litter (a mixture of partially decomposed sawdust and pig manure). They showed that the decomposition process on the 70% WC pile was slower than that on the piles with 50 and 60% WC. At a WC of 70%, not only the microbial activity during thermophilic phase was lower, but there was also a delay in reaching peak temperatures. They found that high WC resulted in a cooling effect and also influenced gaseous exchange by limiting diffusion and thus restricting oxygen utilization by the microbial mass.

3.8. Cress seed germination test

Germination indices are shown in Table 3. In Trial 1, the GI for T1 and T4 were lower ($P < 0.01$) than that of T2 and T3. In Trial 2, there was no difference ($P = 0.81$) between the GIs for all treatments.

Different studies have proposed different GIs to indicate the disappearance of phytotoxicity compounds in manure composts. Tiquia et al. (1996) propose a GI above 80–85%. Many manure compost studies follow this threshold (Huang et al., 2004; Tiquia and Tam, 1998; Tiquia, 2005). In the present study, 6 out of 8 composts achieved GIs above 90% with the other two (T1 and T4, Trial 1) being >78%.

The cress seed test and the OUR test were used in this study to measure different parameters of compost quality. The cress seed test measures compost maturity and is indicative of the presence or absence of phytotoxic components in the compost, while the OUR test indicates the stability of the compost. However, because phytotoxic compounds are produced by the microorganisms present in unstable composts (Zucconi et al., 1985), it was expected that results from both tests would present some correlation. In Trial 1, the OUR of T1 and T4 were above the recommended 13 mmol O_2 kg^{-1} OM $hour^{-1}$. Therefore, their lower GI could be explained by the production of phytotoxic compounds by the microorganisms present in these less stable composts. In Trial 2, all treatments presented the same high GI even though the OUR value for T1 was significantly higher when compared to the other treatments.

Our results show that unstable composts will not always inhibit germination. According to Zucconi et al. (1981), toxins are produced only during certain stages of decomposition and tend to be quickly inactivated. Moreover, when the first contact between roots and organic matter is not lethal, the plant shows a capability to recover and thrive in solids enriched with organic matter (Zucconi et al., 1981). This might explain why the unstable compost in our study did not produce a detrimental effect on seed germination and root elongation.

Compost quality (maturity and stability) is not related to only one compost characteristic and, therefore, it should not be measured by a single parameter. In this study, especially in Trial 2, the GI results, or any other parameter for that matter, should not be analysed on their own. For T1, when including the results of OUR tests, C/N ratios and physical properties into the analyses of compost quality, it can be concluded that even though the GI was 101.6, the compost was not of good quality. Furthermore, for T3, although the OUR value was below 13 mmol O_2 kg^{-1} OM $hour^{-1}$, the results of C/N ratio and OM degradability indicated that the compost might not have achieved complete maturation.

4. Conclusions

The addition of bulking agents and an initial WC less than 60% were necessary to successfully compost the solid fraction of pig

manure at a low initial C/N ratio. Suitable bulking agents were sawdust, chopped straw and shredded green waste. Woodchip, due to the presence of recalcitrant lignin and its large surface area, was not a suitable bulking agent when used on its own. However, when used with sawdust, it provided good quality compost. Test results for GI, OUR and C/N ratio highlight the need to use parameters that measure maturity and stability simultaneously when assessing compost quality.

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Appendix A

A.1. Solutions used in OUR test

A.1.1. Nutrient solution

Add 1 ml of micronutrient solution to 1 litre of macronutrient solution.

Macro nutrient solution: NH_4CL (4.3 g l−1), $CaCl_2.2H_2O$ (5.4 g l^{-1}), $MgSO_4.7H_2O$ (4.3 g l^{-1}) and $FeCl_3.6H_2O$ (0.03 g l^{-1}). *Micro nutrient solution:* EDDHA 6% iron chelate (5.0 g L^{-1}), $MnSO_4$ (1.4 g L^{-1}), $ZnSO_4$ (1.1 g l^{-1}), $Na_2B_4O_7$ (4.2 g l^{-1}), $CuSO_4$ (0.2 g l^{-1}); $NaMoO_4$ (0.13 g l^{-1}) and HCl (36%; 1 ml l^{-1}).

A.1.2. pH buffer

KH_2PO_4 (43 g per 500 ml of deionised water) and $Na_2HPO_4.2H_2O$ (89 g L^{-1} of deionised water). Mixed ratio of about 1:4 for pH 7.

ATU (nitrification inhibitor): N-Allylthiourea – $C_4H_8N_2S$ (4 g l^{-1})

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