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Effect of sawdust addition on composting of separated raw and anaerobically digested pig manure

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A B S T R A C T

Manures need the addition of carbon-rich bulking agents to conserve N during composting, which increases the cost of the composting process. The recommended proportion of manure / sawdust, based on a carbon (C): nitrogen (N) ratio, is approximately 3:2. Two composting experiments were conducted to determine the impact of varying the proportion of sawdust to either separated raw, or separated anaerobically digested pig manures. To determine stability and maturity of the final compost, oxygen uptake rate (OUR) and germination index (GI) tests were conducted. For both experiments, three treatments were employed: manure-only (Treatment A), manure / sawdust mixed 4:1, fresh weight (Treatment B), and manure / sawdust mixed 3:2, fresh weight (Treatment C). The mixtures were composted in tumblers for 56 d with regular turning. The composting material was tested over the study duration for temperature, pH, water content, organic matter, C:N ratio and bulk density. For both Treatments B and C, the GI indicated low levels of phytotoxicity, and OUR values were lower than the recommended Irish threshold of 13 mmol O_2 kg $OM^{-1}h^{-1}$, indicating that a high quality compost was produced. The proportion of sawdust to separated manure used can be reduced to make a cost saving, while still producing a stable end-product: 60 % less sawdust is required to compost at a manure-to-sawdust ratio of 4:1 compared to the previously recommended ratio of 3:2.

Keywords: compost; swine; oxygen uptake rate; germination test; anaerobic digestion; carbon:nitrogen ratio.

1 Introduction

Thirty percent of sows in the European Union (EU) are located in a major pig production basin which stretches from Denmark, through north western Germany and the Netherlands to Vlaams Gewest in northern Belgium (Marquer, 2010). Other important regions include Cataluña and Murcia in Spain, Lombardia in Italy, and Brittany in France. In the Republic of Ireland, 38 % of the national sow herd is concentrated in counties Cork and Cavan (Boyle, 2010). Pig manure in these concentrated pig farming areas must be transported to less animal dense areas for landspreading, thereby increasing the cost of manure handling. As a result of the EU Nitrates Directive (91/676/EEC; EEC, 1991), the amount of livestock manure which can be applied to land has been limited to 170 kg of nitrogen (N) per hectare per yr. In Ireland, the land available for landspreading will further be restricted, starting in 2013, and culminating in 2017, when land spreading of pig manure can no longer exceed the crop's phosphorus (P) requirements for growth (S.I. 610 of 2010). The implication of this will be that an additional ~50 % land area will be required for manure application than is the case in 2012. The resulting increase in manure transport costs for farmers, along with the potential of surface and groundwater pollution from the landspreading of manure, has resulted in the need to examine practical and economical on-farm solutions for swine wastewater treatment. Recently, anaerobic digestion (AD) has become topical as a means of producing energy from farmyard by-products, including pig manure. However, AD does little to reduce the nutrient content of pig manure, which still needs to be recycled in the same way as undigested manure. One option may be to compost pig manures to produce a high quality, marketable product.

Composting of manures requires separation of the liquid manure to produce a solid and liquid fraction. The solid fraction concentrates the P and can be composted. Composting has the potential to stabilise the organic N fraction of manure and increase its fertiliser value, while, at the same time, reducing its volume and odour, making it cheaper and easier to transport (Bernal et al., 2009). The stabilisation of the OM in the composting materials determines the effectiveness of the composting process. For stabilisation to occur, key factors, such as temperature, aeration, water content (WC), pH and structure must be at an optimum level both initially and throughout the composting process. The C:N ratio is one of the most important factors influencing the quality of compost produced (Zhu, 2007). Sweeten and Auvermann (2008) recommend a C:N ratio of 20-30, while Rynk (1992) recommended 25-30. Since the C:N ratio of separated pig manure is reported to be 11.3 (Huang et al., 2006), the addition of C-rich bulking agents is required to provide optimum C:N conditions. Previous studies have looked at the effect of C:N ratio on composting of manures; however, composting of manure after AD has not been investigated.

Studies have found that the solid fraction from mechanically-separated pig manure was too wet to be composted alone and, therefore, required the use of low-moisture bulking agents (Georgacakis et al., 1996; Nolan et al., 2011). Bulking agents generally have low water and high C contents (Bernal et al., 2009) and, when added to manure before composting, act to increase the C:N ratio, decrease the WC, and improve the structure, porosity and free air space (FAS) of the composting mix. Nolan et al. (2011) investigated the composting of separated pig manure using chopped straw, sawdust, greenwaste and woodchip as bulking agents. Sawdust appeared to be the bulking agent which resulted in the most stable compost. However, the addition of sawdust adds an extra cost to the composting process (Nolan et al., 2012).

There are many different methods used to test compost quality including: germination index (GI) (Tiquia, 2005; Zhu, 2007), oxygen uptake rate (OUR) or CO_2 production rate (Wang et al., 2004), water soluble organic C: total organic N ratio (Hue and Liu, 1995; Bernal et al., 1998) and degree of OM humification (Hue and Liu, 1995). Industry-led quality standards for biodegradable material-derived compost are currently being developed for

Ireland (Prasad and Foster, 2006). As part of these standards, an OUR test has been recommended for measuring compost stability. As manure-based compost will have to adhere to these new standards, it is imperative that farmers are provided with the necessary information to enable compliance. There are currently no European standards for compost and growing media (Baumgarten, 2011). However, this may not be the case in the future as the European Peat Media Association has called for standards to be developed. These standards would likely be based on CEN test methods, including EN 106086-2, Determination of plant response (cress seed germination test) and EN 10087-1, Determination of the aerobic biological activity (OUR test) (Baumgarten, 2011). The aim of this study was to investigate the effect of adding different quantities of sawdust as a bulking agent to separated raw and anaerobically digested pig manures on the physico-chemical properties, maturity and stability of the compost produced. Compost maturity was measured using a GI test, while stability was measured using an OUR test.

2 Materials and methods

2.1 Raw materials for composting

Two composting trials were conducted to determine the effect varying the proportion of sawdust to either separated raw or separated anaerobically digested pig manures. In trial 1 (T1), raw pig manure was collected from an uncovered over-ground manure storage tank at the Teagasc Pig Development Department, Moorepark, Fermoy, Co. Cork, Ireland, and was a mixture of pig manure from all stages of pig production. In trial 2 (T2), anaerobically digested pig manure was collected from another pig farm and transferred to the study site before separation. This manure also came from all stages of production and was aerated prior to AD. Since the pig manure from each trial was taken from different pig farms, with different diets and manure management systems, it was not possible to compare the composts from T1 and T2.

A decanter centrifuge (GEA Westfallia Separator UCD 205, Bönen, Germany) was used to perform the mechanical separation of both the raw pig manure and the anaerobic digestate. A coagulant, aluminium salt in liquid form (PC31, Celtic Water Care, Cork, Ireland), and a flocculent, a water soluble polyacrylamide (C1900P, Celtic Water Care, Cork, Ireland), were used to increase the efficiency of separation. The coagulant was added at 3 L per m^3 and the flocculent was diluted with water to 0.4 % by volume and added to the manure at approximately 17 % by volume. Approximately 10 m^3 of liquid feedstock was separated for each trial. Ten samples for each the liquid pig manure before separation, solid fraction after separation, and liquid fraction after separation were analysed for dry matter in T1 and T2. The results obtained were 1.5 ± 0.71 %, 32.7 ± 2.66 % and 0.3 ± 0.14 %, respectively, in T1. For T2, the results obtained were 2.3 ± 0.68 %, 30.6 ± 3.09 % and 0.6 ± 0.07 %, respectively. Sitka spruce (*Picea sitchensis*) sawdust was added as a bulking agent to adjust the C:N ratio and to reduce the WC. The sawdust and separated manure were thoroughly mixed to ensure homogeneity. Samples were taken from the raw and anaerobically digested pig manures before separation and the separated solid and liquid fractions after separation. The WC, pH, bulk density, C:N ratio and OM of the separated solids and of the sawdust were determined before mixing (Table 1).

2.2 Compost preparation and sampling

Fifteen insulated tumblers (Jora 270 Organic waste composters, Mjölby, Sweden) were used to compost the swine manures and sawdust mixtures. Each tumbler had a working volume of 270 L. Three sawdust rates were added to the manures: Treatment A consisted of 40 kg (fresh weight) of separated manure solids and no sawdust. Treatment B consisted of 40 kg of separated solids and 10 kg of sawdust (to provide an initial C:N ratio of ~16). Treatment C consisted of 30 kg of separated solids and 20 kg of sawdust (to provide an initial C:N ratio of ~ 30). Each treatment was replicated five times except for Treatment A in T2, which consisted of only four replications. One replication of each treatment commenced on each day over 5 d until all 5 replicates were commenced.

Aeration was provided by manually rotating the tumblers twice daily (morning and afternoon) during the first week of the trial and once-a-day for the remainder of the trial. The tumblers were rotated fully around their axis 3 times for each turning event. The addition of water during composting was not required because the WC did not fall below 40 % for any treatment at any time during the process. The temperature of each compost pile was recorded daily before turning, using long stemmed thermometers (Control Company, Friendswood, TX, USA). Two thermometers were inserted 0.15 m into the pile at different positions. The higher temperature was recorded. Samples (0.5 kg) were taken from the compost piles at 0, 3, 7, 14, 21, 28, 42 and 56 d. Each sample consisted of 6 small sub-samples, half from the top 200 mm of the compost pile and half from the bottom 200 mm.

2.3 Physico-chemical analyses

Fresh samples collected from the compost piles were tested for pH and WC on all sample days. Bulk density was measured on fresh samples collected on day 0 and 56. Ash content, OM, C, N, and H contents were determined from dried samples collected on day 0 and 56. Bulk density was determined according to Nolan et al. (2011). The WCs were determined by drying the samples in an oven at 60^{o}C for 24 h to a constant weight (Hao et al., 2004). Measurement of pH was performed in water solution using a bench top meter (SevenEasy, Mettler-Toledo, Switzerland) at a compost/distilled water ratio of 1:10 (w/v) (Tiquia et al., 2002). Carbon and N content was determined using a CHNOS Elemental

Analyser Vario EL Cube (Elemental Analysensysteme GmbH, Hanau, Germany) at a combustion temperature of 1100 – 1200 ^{o}C. Ash content was determined by incinerating pre-dried samples in a furnace at 550 ^{o}C for 5 h (Tiquia, 2005). Organic matter was calculated as the difference between the dried and ash weights. The overall loss of OM (OM_{loss}) was calculated according to Nolan et al. (2011).

2.4 Maturity and stability analyses

Two tests were conducted to evaluate the compost as a growth medium. An OUR test (Nolan et al., 2011) was undertaken on day 0 and day 56 samples to determine the aerobic biological activity of the compost. Briefly, 2 g OM of each compost sample was mixed with distilled water in 1-L Duran bottles (DURAN Group Gmbh, Mainz, Germany). Samples were left on a stirring platform incubated at 30 ^{o}C for 5 d. A pressure transducer system (Oxitop Control System OC110, WTW Gmbh, Weilheim, Germany) was used to determine the OUR (mmol O_2 kg $OM^{-1}h^{-1}$) by measuring the pressure drop in the headspace (Nolan et al., 2011). The OUR test is an accurate test to measure compost stability and is one of the proposed tests for Irish compost standards (Prasad and Foster, 2006).

A cress seed germination test was undertaken on day 56 samples to determine the GI on a mixture of 50 % compost and 50 % peat moss (Prasad et al., 2010). Ten cress seeds were sown in each compost and peat mixture in a 10 mm x 10 mm Petri dish. Each treatment was undertaken in triplicate. Approximately 0.5 ml of water was added to each seed. The dishes were inclined at a 70 – 80 ° angle to the horizontal with the seeds on the underside and incubated at 25 ± 2 ^{o}C in the dark. After 72 h, the number of germinated seeds was counted and the root length measured. Germination index was calculated according to Tiquia and Tam (1998).

2.7 Statistical analysis

Data were analyzed using the Statistical Analyses System (SAS Institute, 2004) with each tumbler as the experimental unit. Water content, pH, bulk density, OM, N, C and H contents, C:N ratio and OUR, were analysed as repeated measures using the MIXED procedure of SAS with Tukey-Kramer adjustment for multiple comparisons. The dependent variables were: WC, pH, bulk density, OM, N, C and H contents, C:N ratio and OUR. For all the above analyses, the fixed effects were: treatment, day and tumbler. Day was the repeated measure and day 0 was included as a random variable.

Comparison of GI at day 56 was performed using the MIXED procedure in SAS. Germination index was the dependent variable. Treatment was included as a fixed effect and start day included as a random effect. For all analyses, significance was given as $p<0.05$.

3 Results and discussion

3.1 Physico-chemical analyses

3.1.1 Physical changes

From day 0 to approximately day 7, all treatments in both trials were malodorous. This was particularly noticeable when the tumblers were opened for sampling. However, by day 14 the pungent odour could no longer be detected. Water was observed to be leaching out of the tumblers in Treatment A for both trials. There was no leaching recorded from Treatments B and C in either trial.

On day 0, when the tumblers were filled, the separated pig manure had the flaky appearance of peat. However, for both trials, conglomerates (spheres of manure) were formed during the turning of the tumblers in Treatment A. The occurrence of large conglomerates was not evident in Treatments B and C. In these treatments, particle sizes were small, well mixed, and were peat-like in appearance throughout the composting process. The turning of the composting tumblers may influence the formation of conglomerates, which may not occur in a large-scale operation, where windrows and mechanical turning are used.

For T1, the mean bulk density for Treatment A increased from 389 ± 52.8 kg m^{-3} to 460 ± 66.3 kg m^{-3} from day 0 to day 56 ($p<0.01$), while for T2, it increased from 467 ± 26.1 kg m^{-3} to 589 ± 19.1 kg m^{-3} ($p<0.0001$). For T1, the bulk density of Treatment B was 296 ± 51.5 kg m^{-3} and 278 ± 20.7 kg m^{-3} ($p > 0.05$) on day 0 and day 56, respectively, while for Treatment C, it was 226 ± 17.8 kg m^{-3} and 210 ± 10.6 kg m^{-3} ($p > 0.05$), respectively. For T2, the bulk density of Treatment B was 309 ± 43.1 kg m^{-3} and 337 ± 16.4 kg m^{-3} ($p > 0.05$) on Day 0 and Day 56, respectively, while for Treatment C, it was 243 ± 16.7 kg m^{-3} and 231 ± 10.5 kg m^{-3} ($p > 0.05$), respectively. The bulk density of Treatments B and C were lower than Treatment A in both trials on both sampling days ($p<0.05$). Decreasing bulk density is linearly proportional to increasing FAS and decreasing WC (Agnew et al., 2003; Iqbal et al., 2010). Bulk density, WC, and FAS all play an important role in achieving the optimum aerobic conditions during the composting process, which, in turn, affects the efficiency of the process (Iqbal et al., 2010).

3.1.2 Temperature

Temperature is an excellent indicator of the microbial activity in a composting pile (Bernal et al., 2009). Temperatures in the tumblers went through three distinct phases: an initial heating phase, a thermophilic phase, and cooling/maturing phase (Figure 1(a) and (b)). The patterns of compost temperature change have been used to monitor the stabilization of the composting process (Tiquia et al., 1996; Huang et al., 2004; Tiquia, 2005). Temperatures rose very quickly in all reactors during the heating phase, indicating a rapid establishment of microbial activity. During this phase, readily degradable simple organic compounds are broken down (de Bertoldi et al, 1983). Bernal et al. (2009) identified an optimum temperature range of 40-65 ^{o}C for composting. Average temperatures of >50 ^{o}C were achieved by day 2 across all treatments, indicating a thermophilic phase. During this phase, more complex compounds such as fats, cellulose and lignin are degraded by thermophilic microorganisms (Bernal et al., 2009). The thermophilic phase was relatively short, due to the small scale of these composting tumblers, when compared with large-scale windrow composting, for example.

The thermophilic phase for Treatment A for both trials was much shorter than that of Treatments B and C. In T1, Treatment A dropped below 50 ^{o}C after day 6 compared to days 10 and 8 for Treatments B and C, respectively. For T2, Treatment A dropped below 50 ^{o}C after day 4 compared to day 11 for both Treatments B and C. The shorter thermophilic phase in Treatment A may be attributed to its lower C:N ratio and higher WC due to the absence of any C-rich bulking agent in this treatment. The insufficient supply of C likely caused unfavourable conditions for the growth and activity of the thermophilic microorganisms (Haung et al., 2004). The higher WC in this treatment caused the formation of conglomerates. Reduced oxygen movement within these wet conglomerates may have given rise to anaerobic conditions (Das and Keener, 1997), further causing a shorter thermophilic phase.

Treatments B and C had similar temperature profiles in both trials. Treatment B had the higher maximum temperature for both T1 and T2 - 68.8 ^{o}C and 70.1 ^{o}C, respectively - compared to 64.2 ^{o}C and 66.2 ^{o}C, respectively, for Treatment C. This could indicate higher initial microbial activity in Treatment B, or it could also be due to the increased porosity caused by the larger amount of added sawdust in Treatment C. This increased porosity allows for increased air movement that may have reduced the temperatures. However, Treatment C did remain above ambient temperatures for a longer period of time than Treatment B, indicating that elevated microbial activity continued for longer in this treatment. The average daily ambient temperatures are given in Figure 1(a) and (b). These show that during T1, average ambient temperatures were lower (min 6 ^{o}C, max 16 ^{o}C) than that during T2 (min 13 ^{o}C, max 23 ^{o}C), which may account for the slightly lower composting temperatures and shorter thermophilic phases observed in T1.

3.1.3 pH

The pH values followed a similar pattern for all treatments (Figure 2 (a) and (b)). It increased significantly after day 0 to a maximum value during the thermophilic phase. There was no significant difference in pH between any treatment on any particular sampling day ($p>0.05$). For T1, the pH was initially 8.0, 7.9 and 7.6 for Treatments A, B and C, respectively, and increased significantly to reach respective peak values of 8.6, 8.6 and 8.3 ($p<0.001$), respectively, on day 21. This was followed by a significant decrease to final values of 7.3, 7.5 and 7.1 ($p<0.001$), respectively, on day 56. For T2, the pH was initially 8.2, 8.1 and 7.8 for Treatments A, B and C, respectively. This quickly increased to respective peak values on day 3 of 8.6, 8.6 and 8.2 ($p<0.001$), respectively. Unlike T1, there was then a slow decrease in pH until day 21. This was followed by a significant decrease in pH until the final values of 6.7, 6.6 and 6.6 ($p<0.001$), respectively, were achieved on day 56.

The highest pH values occurred during the thermophilic phase when temperatures were at their highest. High temperatures are indicative of higher microbial activity (Tiquia, 2005). This high rate of microbial activity caused increased pH due to the production of NH_3 during ammonification and mineralisation of organic nitrogen (Eklind and Kirchmann, 2000). At lower C:N ratios, NH_3 emissions can occur if the amount of N in the compost is greater than that needed for microbial growth. Ekinci et al. (2000) found that NH_3 loss depends on both initial pH and initial C:N ratio, and that by increasing the initial C:N ratio from 18 to 30, NH_3 losses were reduced by 50 %. This indicates that NH_3 volatilisation may have been higher for Treatment B than Treatment C due to the lower initial C:N ratios. Compost pH fell when the temperature in the compost had decreased during the maturing phase. The decrease in pH likely resulted from NH_3 volatilisation and the release of H^+ during nitrification (Eklind and Kirchmann, 2000). Some of this decrease may also have been caused by the production of organic acids in the compost (Sweeten and Auvermann, 2008).

3.1.4 Water content

The optimum WC for efficient composting is between 40 % and 60 % (Sweeten and Auvermann, 2008). When the WC exceeds the 60 % limit, oxygen movement is inhibited in the compost pile and the process becomes anaerobic (Das and Keener, 1997). Increased WC also results in a decrease in FAS within the composting pile (Iqbal et al., 2010). In both trials, Treatment A was above this 60 % limit for the duration of the composting process, while Treatments B and C were within the limits. Tiquia et al. (1996) found that a WC of 70 % caused premature cooling and decreased microbial activity during composting of pig manure sawdust litter in comparison to WCs of 50 % and 60 %. These results are reflected in this study where Treatment A - with the higher WC - achieved lower temperatures in both trials (Figure 1(a) and (b)).

The initial WCs for T1 were 70.7, 60.5 and 48.4 for Treatments A, B and C, respectively. For T2, these values were 68.4, 57.7 and 45.0, respectively. For both trials, Treatment A had a higher WC than Treatments B and C on every sampling day ($p<0.001$). In both trials, all three treatments showed no decrease in WC over the duration of the trials ($p=0.93$ for T1, $p=0.62$ for T2). The final WCs for T1 were 68.4, 59.3 and 47.1 for Treatments A, B and C, respectively. For T2, these values were 69.5, 58.1 and 49.1, respectively. The limited change in WC over time was due to the type of composting process used in these experiments. The enclosed nature of the tumblers caused some of the water vapour lost from the compost through evaporation to condense on the inside of the tumbler walls and drop back into the compost. This caused the WC to remain relatively stable throughout the composting process. This would not have occurred in large-scale windrow composting where the water vapour would have been lost to the atmosphere.

3.1.5 Elemental analysis and C:N ratio

The elemental analysis and C:N ratios of all treatments on day 0 and day 56 are given in Table 2 (standard error and p values for changes over time not shown).The C content increased with each incremental addition of sawdust to the manure, and was significant in T1 but not in T2 (Table 2). Increasing the sawdust addition significantly decreased N contents in both trials (Table 2). All treatments in both trials showed increases in N content, decreases in C and H contents, and noticeable reductions in the C:N ratio from the beginning to the end of the composting process, except for Treatment A in T2. Carbon losses are caused by the degradation of carbohydrates, fats and amino acids in the first stage of the composting process and the partial degradation of cellulose, hemicelluloses and lignin during the later stages (Bernal et al., 2009).

In Treatment A in T2, the C:N ratio increased significantly from 10.1 to 25.0 from day 0 to 56 ($p<0.001$). This unexpected increase was caused by the large reduction in the N content of the pile, from 4.5 % on day 0 to 1.9 % on day 56 (Table 2). In all other treatments, there was an increase in N content over time due to the loss of CO_2 and also water loss through evaporation. Losses of N during the composting of manure can occur due to volatilisation of NH_3 (Tiquia and Tam, 2000). Also, when the WC of the compost is high, leaching of nitrate (NO_3^-) may occur (Tiquia et al., 1998). As described previously, there was some leachate lost from this treatment, due to its high WC, which may have resulted in the higher loss of N from this treatment.

In Treatment C, the initial C:N ratios were 29.6 and 30.3 for T1 and T2, respectively. When the initial C:N ratio is between 25 and 30, the final value for a stable compost should be at or below 20 (Hiria et al., 1983). This was the case in T2, where the final C:N ratio was 15.2. However, the C:N ratio in T1, at 24.9, surpassed this upper limit, indicating that the composting process was more efficient in T2. This result was supported by the longer thermophilic period observed in T2 in comparison to T1, and by the GI and OUR values (discussed later), which, for Treatment C, were better in T2 than T1.

The initial C:N ratio of Treatment B was 17.5 and 16.0 in T1 and T2, respectively, while the final C:N ratio was16.0 and 10.0, respectively. However, it is not appropriate to use final C:N ratio as an indicator of compost maturity when the initial C:N ratio is low (Huang et al., 2004). Therefore, in this case, another method, such as GI, may be used to test the maturity of the compost (Huang et al., 2004; Nolan et al., 2011).

3.1.6 Organic matter

It has been recommended that the minimum OM content for compost in Ireland be set at 20 % (Prasad and Foster, 2006). All of the treatments in both trials easily exceeded this, as final OM values for all composts treatments were above 70 %. The OM of all treatments is given in Table 3. Treatment C had the highest OM in both trials due to the high levels of sawdust added to this treatment, while Treatment A had the lowest OM as no C-rich bulking agent had been used as an addendum in this treatment. In both trials, all three treatments were different from each other (Table 3, $p<0.001$).

The total loss of OM may be used as an indicator of compost biodegradation. However, the dry weight reduction was not measured as part of this experiment; therefore, it was not possible to measure the total loss of OM. The OM losses were calculated as the differences in concentrations of OM only (Huang et al., 2004; Nolan et al., 2011). The OM content of the piles decreased from day 0 to day 56 for all treatments (p=0.001). This was caused by the degradation of the OM by the microorganisms during composting. For T1, the losses of OM from the beginning to the end of the composting process were 22.5 %, 19.2 % and 14.8 % for Treatments A, B and C, respectively. For T2, these losses were 20.6 %, 17.5 % and 9.6 % for Treatments A, B and C, respectively. The loss in OM was greatest in Treatment A, followed by Treatment B and then Treatment C. These reduced rates of change in OM content were due to the addition of lignin-rich sawdust in Treatments B and C. Lignin is extremely resistant to chemical and enzymatic degradation. Michel et al. (2004) also found a lower decomposition in the compost substrate and decreased amounts of organic C lost during the composting process when using lignin-rich bulking agents.

3.2 Maturity and stability analysis

3.2.1 Germination index (GI)

Results for the GI tests for both trials are shown in Table 3. The GI for Treatment C was significantly higher than Treatment A ($p<0.05$) for both treatments. Zucconi et al. (1981) reported that GI values below 50 % indicated the presence of phytotoxic compounds in the compost. Jodice (1989) reported that a GI of 50 - 70 % indicated low levels of phytotoxins present, while Tiquia and Tam (1998) suggest that phytotoxic free compost is indicated when GI is above a threshold of 80 %. Other studies have followed this latter threshold (Huang et al., 2004, 2006; Tiquia, 2005). Using these results, Treatment C in both trials could be classified as phytotoxin free, while Treatments A and B in both trials had low levels of phytotoxins.

Phytotoxins produced by the microorganisms in the less stable composts inhibit growth (Zucconi et al., 1981) and lead to lower GI values. High copper, zinc, organic acids and NH_4 concentrations and high electrical conductivity (EC) have also been shown to inhibit seed germination in manure-based composts (Tiquia and Tam, 1998; Huang et al., 2004). Sawdust addition to manure will dilute the concentration of these inhibitors and reduce EC in the mixture. The GI values for both trials compared favourably with those from Huang et al. (2004), who studied composting of pig manure and sawdust at initial C:N ratios of 30 and 15. After 63 d of composting, Huang et al. (2004) reported a GI of 85 % for a C:N ratio of 30, and 46 % for a C:N ratio of 15. The lower GI was attributed to a higher EC in the treatment which received the lower sawdust inclusion.

3.2.2 Oxygen Uptake Rate (OUR)

Results for the OUR tests for both trials are shown in Table 3 (standard errors and p values for changes over time not shown). For both trials, day 0 OUR values were significantly higher than those on day 56 for all treatments ($p<0.001$). This indicates that the compost was more stable at the end of the process than at the beginning. For both trials, d 56 OUR values for Treatment A were higher compared to Treatments B and C ($p<0.05$) (Table 3). This indicates that Treatment A underwent less biological decomposition than Treatments B and C, thereby producing a less stable end-product. This was confirmed by the lower microbial activity and lower temperatures observed for this treatment (Figure 1(a) and (b)) as a consequence of the treatment's initially high WC and low C:N ratio. Tiquia et al. (1996) studied the effect of water contents (50 %, 60 % and 70 %) on the decomposition rate of spent pig litter. They found that the decomposition process was slower for the 70 % WC pile, due to the cooling effect of the water and the restriction of oxygen from the microbial mass.

The proposed OUR threshold value in Ireland for stable compost is 13 mmol O_2 kg OM^{-1} h^{-1} (Prasad and Foster, 2006). This value is similar to that used in Belgium and The Netherlands, where this test is commonly used. In these countries, values above 15 mmol O_2 kg OM^{-1} h^{-1} are considered unstable (Prasad and Foster, 2006). Treatment B and C in both trials reached stability values below the recommended Irish threshold by day 56. However, Treatment A was higher than this value and could not be considered stable at day 56. There was no difference in day 56 OUR values between Treatments B and C in either of the trials ($p=0.94$ for T1, $p=1.00$ for T2).

There was generally a good correlation between the results of both tests for compost quality. The OUR test was used to test the stability of the compost, while the GI measured the presence of phytotoxicity which indicates compost maturity. This relationship was expected since the phytotoxins measured in the GI test are produced by the microorganisms present in the unstable compost (Zucconi et al., 1985). In both trials, the treatments with the highest OUR values corresponded to the treatment with the lowest GI values. However, this relationship may not always be present, hence the need for the two separate tests to determine compost quality. Other parameters important in determining compost quality are pathogen load and heavy metal (especially Cu and Zn) content, but these were not determined in the current study.

4 Conclusions

Composts with manure to sawdust ratios of 4:1 and 3:2 (fresh weight) were found to be stable after 56 d of aerobic composting. Both treatments met the proposed stability standard for composts in the Republic of Ireland. No differences between these two treatments were found for the stability test (oxygen uptake rate) and the maturity test (germination index).

It is concluded that co-composting either separated raw or separated anaerobically digested pig manures with sawdust at a manure-to-sawdust ratio of 4:1 (w/w) and a C:N ratio of 18 or 16, respectively, can produce stable compost. Using this lower ratio reduces the quantity of sawdust required and hence the cost to produce stable compost; 60 % less sawdust is required to compost at a manure-to-sawdust ratio of 4:1, compared to 3:2. Using this lower ratio may make composting pig manure more financially attractive to farmers, and persuade them to implement on-farm composting as a means of nutrient recycling.

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Table 1. Physiochemical properties (means ± SD) for pig manure and sawdust

	Pig manure (T1)	AD Pig manure (T2)	Sawdust
pH	8.03 ± 0.14	8.19 ± 0.22	4.85 ± 0.09
Water content (%)	67.3 ± 2.7	69.5 ± 2.4	14.4 ± 2.7
C:N ratio	10.6 ± 1.4	10.1 ± 0.9	466.5 ± 58.6
Bulk density (kg/m^3)	389 ± 53	467 ± 26	40 ± 2
Organic Matter (%)	75.2 ± 3.30	77.8 ± 1.08	99.7± 0.02

SD: Standard deviation; Trial 1 (n=5), Trial 2 (n=4), Sawdust (n=10)

Table 2. C, N, H and C:N for compost piles

	Trial 1					Trial 2				
	A	B	C	s.e.	p	A	B	C	s.e.	p
C D0	47.0^{a}	50.1^{ab}	51.3^{b}	0.94	<0.01	45.2	47.6	49.0	1.27	0.26
C D56	42.0^{a}	47.3^{b}	48.8^{b}	0.94	<0.01	47.6	41.5	44.2	1.27	0.26
N D0	4.5^{a}	2.9^{b}	1.7^{c}	0.27	<0.01	4.5^{a}	3.0^{b}	1.6^{c}	0.23	<0.01
N D56	4.5^{a}	3.0^{b}	2.0^{c}	0.27	<0.01	1.9^{a}	4.2^{b}	2.9^{c}	0.23	<0.01
H D0	5.8	5.8	5.9	0.18	0.06	5.1	5.3	5.2	0.22	0.60
H D56	5.0	5.5	5.5	0.18	0.06	4.7	4.7	5.1	0.22	0.60
C:N D0	10.4^{a}	17.5^{b}	29.6^{c}	1.76	<0.01	10.1^{a}	16.0^{b}	30.3^{c}	2.49	<0.01
C:N D56	9.3^{a}	16.0^{b}	24.9^{c}	1.76	<0.01	25.0^{a}	10.0^{b}	15.2^{c}	2.49	<0.01

^{abc} Means were separated using the Tukey-Kramer adjustment for multiple comparisons. Means without a common superscript, in a row, for the same Trial, differ by $p<0.05$.
For Trial 1 the separated solid fraction of raw pig manure was used. For Trial 2 the separated solid fraction of anaerobically digested pig manure was used.
A: 40kg manure only; B: 40kg manure and 10kg sawdust; C: 30kg manure and 20kg sawdust. D56: day 56

Table 3. OUR (mmol O_2/kg organic solids/h), OM (%) and GI (%) for compost piles

	Trial 1					Trial 2				
	A	B	C	s.e.	p	A	B	C	s.e.	p
OUR D0	53.0^{a}	42.6^{b}	35.9^{b}	1.85	<0.001	42.4^{a}	28.7^{b}	22.9^{b}	1.58	<0.001
OUR D56	26.4^{a}	11.8^{b}	8.0^{b}	1.85	<0.001	16.2^{a}	8.3^{b}	8.0^{b}	1.58	<0.001
OM D0	75.2^{a}	85.2^{b}	91.1^{c}	0.75	<0.001	77.8^{a}	86.8^{b}	91.8^{c}	0.45	<0.001
OM D56	70.1^{a}	82.4^{b}	89.8^{c}	0.75	<0.001	73.6^{a}	83.4^{b}	91.0^{c}	0.45	<0.001
GI D56	59^{a}	63^{ab}	83^{b}	8.59	<0.05	61^{a}	70^{ab}	95^{b}	11.2	<0.05

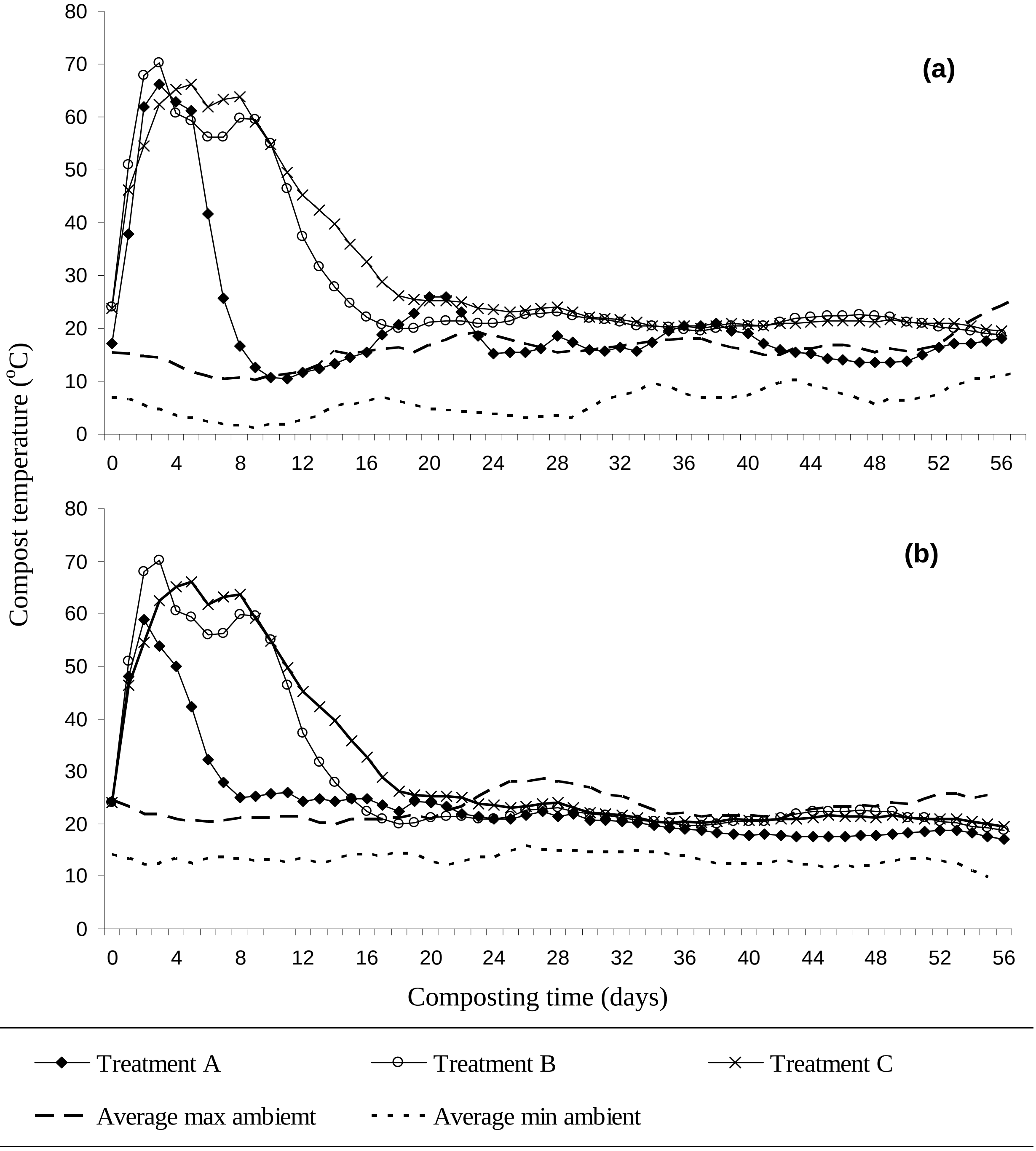
^{abc} Means were separated using the Tukey-Kramer adjustment for multiple comparisons. Means without a common superscript, in a row, for the same Trial, differ by $p<0.05$.
For Trial 1 the separated solid fraction of raw pig manure was used. For Trial 2 the separated solid fraction of anaerobically digested pig manure was used.
A: 40kg manure only; B: 40kg manure and 10kg sawdust; C: 30kg manure and 20kg sawdust, OUR: oxygen uptake rate, OM: organic matter content, GI: germination index, D56:day 56

Captions for Figures

Figure 1: Changes in temperature during composting for (a) Trial 1 – raw manure and (b) Trial 2 – AD manure. Treatment A = 40 kg manure only; Treatment B = 40 kg manure + 10 kg sawdust; Treatment C = 30 kg manure + 20 kg sawdust.

Figure 2: Changes in pH during composting for (a) Trial 1 – raw manure and (b) Trial 2 – AD manure. Treatment A = 40 kg manure only; Treatment B = 40 kg manure + 10 kg sawdust; Treatment C = 30 kg manure + 20 kg sawdust.

Figure 1



(a)
(b)
Compost temperature (°C)
Composting time (days)
Treatment A
Treatment B
Treatment C
Average max ambiemt
Average min ambient

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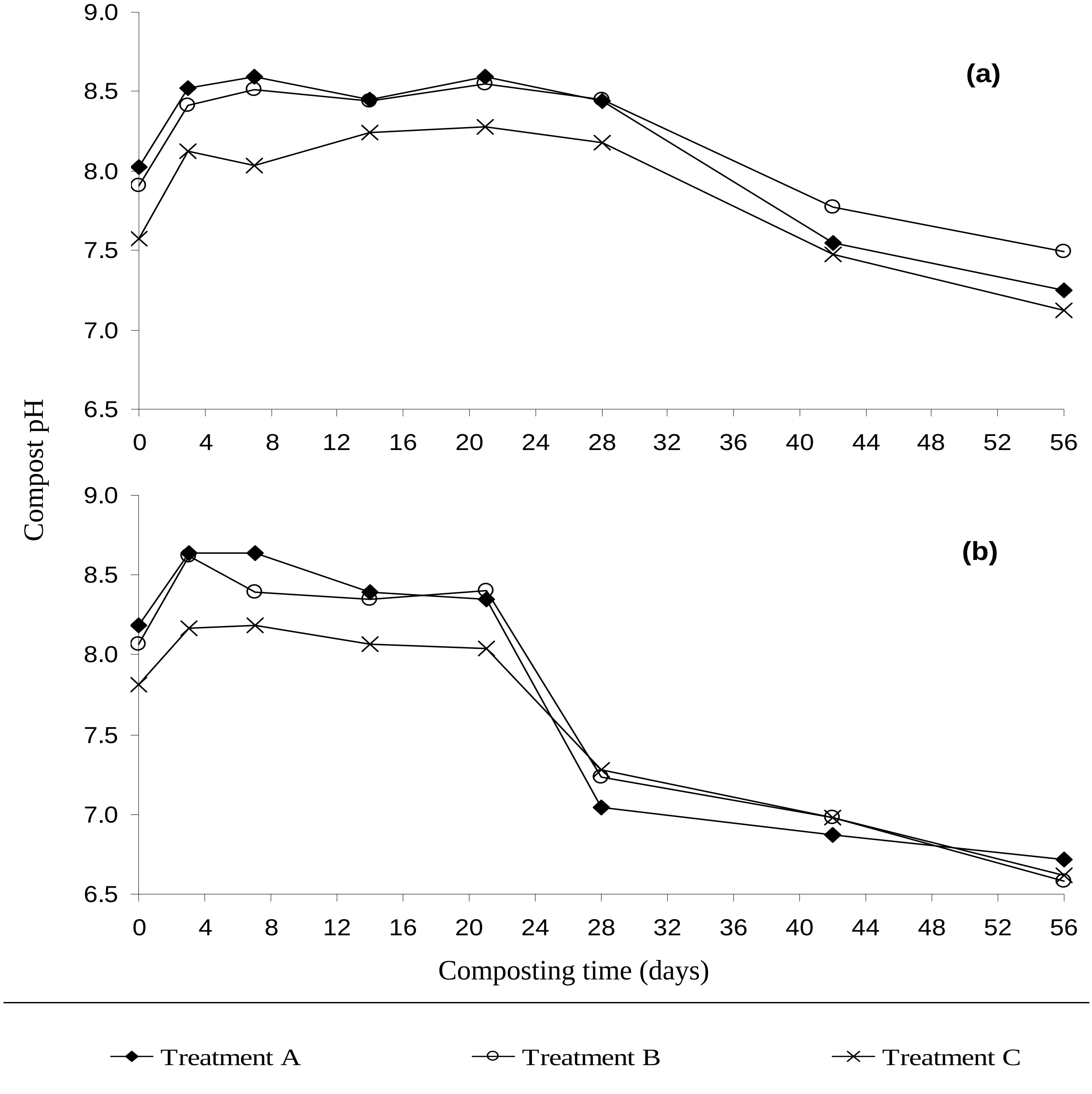

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