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5
6 **Effect of sawdust addition on composting of separated raw and anaerobically digested**
7 **pig manure**

8
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11
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27 A B S T R A C T

28 Manures need the addition of carbon-rich bulking agents to conserve N during
29 composting, which increases the cost of the composting process. The recommended
30 proportion of manure / sawdust, based on a carbon (C): nitrogen (N) ratio, is approximately
31 3:2. Two composting experiments were conducted to determine the impact of varying the
32 proportion of sawdust to either separated raw, or separated anaerobically digested pig
33 manures. To determine stability and maturity of the final compost, oxygen uptake rate (OUR)
34 and germination index (GI) tests were conducted. For both experiments, three treatments were
35 employed: manure-only (Treatment A), manure / sawdust mixed 4:1, fresh weight (Treatment
36 B), and manure / sawdust mixed 3:2, fresh weight (Treatment C). The mixtures were
37 composted in tumblers for 56 d with regular turning. The composting material was tested over
38 the study duration for temperature, pH, water content, organic matter, C:N ratio and bulk
39 density. For both Treatments B and C, the GI indicated low levels of phytotoxicity, and OUR
40 values were lower than the recommended Irish threshold of $13 \text{ mmol O}_2 \text{ kg OM}^{-1} \text{ h}^{-1}$,
41 indicating that a high quality compost was produced. The proportion of sawdust to separated
42 manure used can be reduced to make a cost saving, while still producing a stable end-product:
43 60 % less sawdust is required to compost at a manure-to-sawdust ratio of 4:1 compared to the
44 previously recommended ratio of 3:2.

45

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

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52 **1 Introduction**

53 Thirty percent of sows in the European Union (EU) are located in a major pig
54 production basin which stretches from Denmark, through north western Germany and the
55 Netherlands to Vlaams Gewest in northern Belgium (Marquer, 2010). Other important regions
56 include Cataluña and Murcia in Spain, Lombardia in Italy, and Brittany in France. In the
57 Republic of Ireland, 38 % of the national sow herd is concentrated in counties Cork and
58 Cavan (Boyle, 2010). Pig manure in these concentrated pig farming areas must be transported
59 to less animal dense areas for landspreading, thereby increasing the cost of manure handling.
60 As a result of the EU Nitrates Directive (91/676/EEC; EEC, 1991), the amount of livestock
61 manure which can be applied to land has been limited to 170 kg of nitrogen (N) per hectare
62 per yr. In Ireland, the land available for landspreading will further be restricted, starting in
63 2013, and culminating in 2017, when land spreading of pig manure can no longer exceed the
64 crop's phosphorus (P) requirements for growth (S.I. 610 of 2010). The implication of this will
65 be that an additional ~50 % land area will be required for manure application than is the case
66 in 2012. The resulting increase in manure transport costs for farmers, along with the potential
67 of surface and groundwater pollution from the landspreading of manure, has resulted in the
68 need to examine practical and economical on-farm solutions for swine wastewater treatment.
69 Recently, anaerobic digestion (AD) has become topical as a means of producing energy from
70 farmyard by-products, including pig manure. However, AD does little to reduce the nutrient
71 content of pig manure, which still needs to be recycled in the same way as undigested manure.
72 One option may be to compost pig manures to produce a high quality, marketable product.

73 Composting of manures requires separation of the liquid manure to produce a solid
74 and liquid fraction. The solid fraction concentrates the P and can be composted. Composting
75 has the potential to stabilise the organic N fraction of manure and increase its fertiliser value,
76 while, at the same time, reducing its volume and odour, making it cheaper and easier to

77 transport (Bernal et al., 2009). The stabilisation of the OM in the composting materials
78 determines the effectiveness of the composting process. For stabilisation to occur, key factors,
79 such as temperature, aeration, water content (WC), pH and structure must be at an optimum
80 level both initially and throughout the composting process. The C:N ratio is one of the most
81 important factors influencing the quality of compost produced (Zhu, 2007). Sweeten and
82 Auvermann (2008) recommend a C:N ratio of 20-30, while Rynk (1992) recommended 25-30.
83 Since the C:N ratio of separated pig manure is reported to be 11.3 (Huang et al., 2006), the
84 addition of C-rich bulking agents is required to provide optimum C:N conditions. Previous
85 studies have looked at the effect of C:N ratio on composting of manures; however,
86 composting of manure after AD has not been investigated.

87 Studies have found that the solid fraction from mechanically-separated pig manure
88 was too wet to be composted alone and, therefore, required the use of low-moisture bulking
89 agents (Georgacakis et al., 1996; Nolan et al., 2011). Bulking agents generally have low water
90 and high C contents (Bernal et al., 2009) and, when added to manure before composting, act
91 to increase the C:N ratio, decrease the WC, and improve the structure, porosity and free air
92 space (FAS) of the composting mix. Nolan et al. (2011) investigated the composting of
93 separated pig manure using chopped straw, sawdust, greenwaste and woodchip as bulking
94 agents. Sawdust appeared to be the bulking agent which resulted in the most stable compost.
95 However, the addition of sawdust adds an extra cost to the composting process (Nolan et al.,
96 2012).

97 There are many different methods used to test compost quality including: germination
98 index (GI) (Tiquia, 2005; Zhu, 2007), oxygen uptake rate (OUR) or CO₂ production rate
99 (Wang et al., 2004), water soluble organic C: total organic N ratio (Hue and Liu, 1995; Bernal
100 et al., 1998) and degree of OM humification (Hue and Liu, 1995). Industry-led quality
101 standards for biodegradable material-derived compost are currently being developed for

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

115

116

117 **2 Materials and methods**

118 **2.1 *Raw materials for composting***

119 Two composting trials were conducted to determine the effect varying the proportion
120 of sawdust to either separated raw or separated anaerobically digested pig manures. In trial 1
121 (T1), raw pig manure was collected from an uncovered over-ground manure storage tank at
122 the Teagasc Pig Development Department, Moorepark, Fermoy, Co. Cork, Ireland, and was a
123 mixture of pig manure from all stages of pig production. In trial 2 (T2), anaerobically digested
124 pig manure was collected from another pig farm and transferred to the study site before
125 separation. This manure also came from all stages of production and was aerated prior to AD.
126 Since the pig manure from each trial was taken from different pig farms, with different diets

127 and manure management systems, it was not possible to compare the composts from T1 and
128 T2.

129 A decanter centrifuge (GEA Westfallia Separator UCD 205, Bönen, Germany) was
130 used to perform the mechanical separation of both the raw pig manure and the anaerobic
131 digestate. A coagulant, aluminium salt in liquid form (PC31, Celtic Water Care, Cork,
132 Ireland), and a flocculent, a water soluble polyacrylamide (C1900P, Celtic Water Care, Cork,
133 Ireland), were used to increase the efficiency of separation. The coagulant was added at 3 L
134 per m³ and the flocculent was diluted with water to 0.4 % by volume and added to the manure
135 at approximately 17 % by volume. Approximately 10 m³ of liquid feedstock was separated for
136 each trial. Ten samples for each the liquid pig manure before separation, solid fraction after
137 separation, and liquid fraction after separation were analysed for dry matter in T1 and T2. The
138 results obtained were 1.5 ± 0.71 %, 32.7 ± 2.66 % and 0.3 ± 0.14 %, respectively, in T1. For
139 T2, the results obtained were 2.3 ± 0.68 %, 30.6 ± 3.09 % and 0.6 ± 0.07 %, respectively.
140 Sitka spruce (*Picea sitchensis*) sawdust was added as a bulking agent to adjust the C:N ratio
141 and to reduce the WC. The sawdust and separated manure were thoroughly mixed to ensure
142 homogeneity. Samples were taken from the raw and anaerobically digested pig manures
143 before separation and the separated solid and liquid fractions after separation. The WC, pH,
144 bulk density, C:N ratio and OM of the separated solids and of the sawdust were determined
145 before mixing (Table 1).

146

147 **2.2 Compost preparation and sampling**

148 Fifteen insulated tumblers (Jora 270 Organic waste composters, Mjölby, Sweden)
149 were used to compost the swine manures and sawdust mixtures. Each tumbler had a working
150 volume of 270 L. Three sawdust rates were added to the manures: Treatment A consisted of
151 40 kg (fresh weight) of separated manure solids and no sawdust. Treatment B consisted of 40

152 kg of separated solids and 10 kg of sawdust (to provide an initial C:N ratio of ~16). Treatment
153 C consisted of 30 kg of separated solids and 20 kg of sawdust (to provide an initial C:N ratio
154 of ~ 30). Each treatment was replicated five times except for Treatment A in T2, which
155 consisted of only four replications. One replication of each treatment commenced on each day
156 over 5 d until all 5 replicates were commenced.

157 Aeration was provided by manually rotating the tumblers twice daily (morning and
158 afternoon) during the first week of the trial and once-a-day for the remainder of the trial. The
159 tumblers were rotated fully around their axis 3 times for each turning event. The addition of
160 water during composting was not required because the WC did not fall below 40 % for any
161 treatment at any time during the process. The temperature of each compost pile was recorded
162 daily before turning, using long stemmed thermometers (Control Company, Friendswood,
163 TX, USA). Two thermometers were inserted 0.15 m into the pile at different positions. The
164 higher temperature was recorded. Samples (0.5 kg) were taken from the compost piles at 0, 3,
165 7, 14, 21, 28, 42 and 56 d. Each sample consisted of 6 small sub-samples, half from the top
166 200 mm of the compost pile and half from the bottom 200 mm.

167

168 **2.3 *Physico-chemical analyses***

169 Fresh samples collected from the compost piles were tested for pH and WC on all
170 sample days. Bulk density was measured on fresh samples collected on day 0 and 56. Ash
171 content, OM, C, N, and H contents were determined from dried samples collected on day 0
172 and 56. Bulk density was determined according to Nolan et al. (2011). The WCs were
173 determined by drying the samples in an oven at 60°C for 24 h to a constant weight (Hao et al.,
174 2004). Measurement of pH was performed in water solution using a bench top meter
175 (SevenEasy, Mettler-Toledo, Switzerland) at a compost/distilled water ratio of 1:10 (w/v)
176 (Tiquia et al., 2002). Carbon and N content was determined using a CHNOS Elemental

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

182

183 **2.4 Maturity and stability analyses**

184 Two tests were conducted to evaluate the compost as a growth medium. An OUR test
185 (Nolan et al., 2011) was undertaken on day 0 and day 56 samples to determine the aerobic
186 biological activity of the compost. Briefly, 2 g OM of each compost sample was mixed with
187 distilled water in 1-L Duran bottles (DURAN Group GmbH, Mainz, Germany). Samples were
188 left on a stirring platform incubated at 30 °C for 5 d. A pressure transducer system (Oxitop
189 Control System OC110, WTW GmbH, Weilheim, Germany) was used to determine the OUR
190 ($\text{mmol O}_2 \text{ kg OM}^{-1} \text{ h}^{-1}$) by measuring the pressure drop in the headspace (Nolan et al., 2011).
191 The OUR test is an accurate test to measure compost stability and is one of the proposed tests
192 for Irish compost standards (Prasad and Foster, 2006).

193 A cress seed germination test was undertaken on day 56 samples to determine the GI
194 on a mixture of 50 % compost and 50 % peat moss (Prasad et al., 2010). Ten cress seeds
195 were sown in each compost and peat mixture in a 10 mm x 10 mm Petri dish. Each treatment
196 was undertaken in triplicate. Approximately 0.5 ml of water was added to each seed. The
197 dishes were inclined at a 70 – 80 ° angle to the horizontal with the seeds on the underside and
198 incubated at 25 ± 2 °C in the dark. After 72 h, the number of germinated seeds was counted
199 and the root length measured. Germination index was calculated according to Tiquia and Tam
200 (1998).

201

202 **2.7 Statistical analysis**

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

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

213

214 **3 Results and discussion**

215 **3.1 Physico-chemical analyses**

216 **3.1.1 Physical changes**

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

222 On day 0, when the tumblers were filled, the separated pig manure had the flaky
223 appearance of peat. However, for both trials, conglomerates (spheres of manure) were formed
224 during the turning of the tumblers in Treatment A. The occurrence of large conglomerates
225 was not evident in Treatments B and C. In these treatments, particle sizes were small, well
226 mixed, and were peat-like in appearance throughout the composting process. The turning of

227 the composting tumblers may influence the formation of conglomerates, which may not occur
228 in a large-scale operation, where windrows and mechanical turning are used.

229 For T1, the mean bulk density for Treatment A increased from $389 \pm 52.8 \text{ kg m}^{-3}$ to
230 $460 \pm 66.3 \text{ kg m}^{-3}$ from day 0 to day 56 ($p < 0.01$), while for T2, it increased from 467 ± 26.1
231 kg m^{-3} to $589 \pm 19.1 \text{ kg m}^{-3}$ ($p < 0.0001$). For T1, the bulk density of Treatment B was $296 \pm$
232 51.5 kg m^{-3} and $278 \pm 20.7 \text{ kg m}^{-3}$ ($p > 0.05$) on day 0 and day 56, respectively, while for
233 Treatment C, it was $226 \pm 17.8 \text{ kg m}^{-3}$ and $210 \pm 10.6 \text{ kg m}^{-3}$ ($p > 0.05$), respectively. For T2,
234 the bulk density of Treatment B was $309 \pm 43.1 \text{ kg m}^{-3}$ and $337 \pm 16.4 \text{ kg m}^{-3}$ ($p > 0.05$) on
235 Day 0 and Day 56, respectively, while for Treatment C, it was $243 \pm 16.7 \text{ kg m}^{-3}$ and $231 \pm$
236 10.5 kg m^{-3} ($p > 0.05$), respectively. The bulk density of Treatments B and C were lower than
237 Treatment A in both trials on both sampling days ($p < 0.05$). Decreasing bulk density is linearly
238 proportional to increasing FAS and decreasing WC (Agnew et al., 2003; Iqbal et al., 2010).
239 Bulk density, WC, and FAS all play an important role in achieving the optimum aerobic
240 conditions during the composting process, which, in turn, affects the efficiency of the process
241 (Iqbal et al., 2010).

242

243 3.1.2 Temperature

244 Temperature is an excellent indicator of the microbial activity in a composting pile
245 (Bernal et al., 2009). Temperatures in the tumblers went through three distinct phases: an
246 initial heating phase, a thermophilic phase, and cooling/maturing phase (Figure 1(a) and (b)).
247 The patterns of compost temperature change have been used to monitor the stabilization of the
248 composting process (Tiquia et al., 1996; Huang et al., 2004; Tiquia, 2005). Temperatures rose
249 very quickly in all reactors during the heating phase, indicating a rapid establishment of
250 microbial activity. During this phase, readily degradable simple organic compounds are
251 broken down (de Bertoldi et al, 1983). Bernal et al. (2009) identified an optimum temperature

252 range of 40-65 °C for composting. Average temperatures of >50 °C were achieved by day 2
253 across all treatments, indicating a thermophilic phase. During this phase, more complex
254 compounds such as fats, cellulose and lignin are degraded by thermophilic microorganisms
255 (Bernal et al., 2009). The thermophilic phase was relatively short, due to the small scale of
256 these composting tumblers, when compared with large-scale windrow composting, for
257 example.

258 The thermophilic phase for Treatment A for both trials was much shorter than that of
259 Treatments B and C. In T1, Treatment A dropped below 50 °C after day 6 compared to days
260 10 and 8 for Treatments B and C, respectively. For T2, Treatment A dropped below 50 °C
261 after day 4 compared to day 11 for both Treatments B and C. The shorter thermophilic phase
262 in Treatment A may be attributed to its lower C:N ratio and higher WC due to the absence of
263 any C-rich bulking agent in this treatment. The insufficient supply of C likely caused
264 unfavourable conditions for the growth and activity of the thermophilic microorganisms
265 (Haung et al., 2004). The higher WC in this treatment caused the formation of conglomerates.
266 Reduced oxygen movement within these wet conglomerates may have given rise to anaerobic
267 conditions (Das and Keener, 1997), further causing a shorter thermophilic phase.

268 Treatments B and C had similar temperature profiles in both trials. Treatment B had
269 the higher maximum temperature for both T1 and T2 - 68.8 °C and 70.1 °C, respectively -
270 compared to 64.2 °C and 66.2 °C, respectively, for Treatment C. This could indicate higher
271 initial microbial activity in Treatment B, or it could also be due to the increased porosity
272 caused by the larger amount of added sawdust in Treatment C. This increased porosity allows
273 for increased air movement that may have reduced the temperatures. However, Treatment C
274 did remain above ambient temperatures for a longer period of time than Treatment B,
275 indicating that elevated microbial activity continued for longer in this treatment. The average
276 daily ambient temperatures are given in Figure 1(a) and (b). These show that during T1,

277 average ambient temperatures were lower (min 6 °C, max 16 °C) than that during T2 (min 13
278 °C, max 23 °C), which may account for the slightly lower composting temperatures and
279 shorter thermophilic phases observed in T1.

280

281 3.1.3 pH

282 The pH values followed a similar pattern for all treatments (Figure 2 (a) and (b)). It
283 increased significantly after day 0 to a maximum value during the thermophilic phase. There
284 was no significant difference in pH between any treatment on any particular sampling day
285 ($p > 0.05$). For T1, the pH was initially 8.0, 7.9 and 7.6 for Treatments A, B and C,
286 respectively, and increased significantly to reach respective peak values of 8.6, 8.6 and 8.3
287 ($p < 0.001$), respectively, on day 21. This was followed by a significant decrease to final values
288 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
289 and 7.8 for Treatments A, B and C, respectively. This quickly increased to respective peak
290 values on day 3 of 8.6, 8.6 and 8.2 ($p < 0.001$), respectively. Unlike T1, there was then a slow
291 decrease in pH until day 21. This was followed by a significant decrease in pH until the final
292 values of 6.7, 6.6 and 6.6 ($p < 0.001$), respectively, were achieved on day 56.

293 The highest pH values occurred during the thermophilic phase when temperatures
294 were at their highest. High temperatures are indicative of higher microbial activity (Tiquia,
295 2005). This high rate of microbial activity caused increased pH due to the production of NH_3
296 during ammonification and mineralisation of organic nitrogen (Eklind and Kirchmann, 2000).
297 At lower C:N ratios, NH_3 emissions can occur if the amount of N in the compost is greater
298 than that needed for microbial growth. Ekinici et al. (2000) found that NH_3 loss depends on
299 both initial pH and initial C:N ratio, and that by increasing the initial C:N ratio from 18 to 30,
300 NH_3 losses were reduced by 50 %. This indicates that NH_3 volatilisation may have been
301 higher for Treatment B than Treatment C due to the lower initial C:N ratios. Compost pH fell

302 when the temperature in the compost had decreased during the maturing phase. The decrease
303 in pH likely resulted from NH₃ volatilisation and the release of H⁺ during nitrification (Eklind
304 and Kirchmann, 2000). Some of this decrease may also have been caused by the production
305 of organic acids in the compost (Sweeten and Auvermann, 2008).

306

307 *3.1.4 Water content*

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

318 The initial WCs for T1 were 70.7, 60.5 and 48.4 for Treatments A, B and C,
319 respectively. For T2, these values were 68.4, 57.7 and 45.0, respectively. For both trials,
320 Treatment A had a higher WC than Treatments B and C on every sampling day (p<0.001). In
321 both trials, all three treatments showed no decrease in WC over the duration of the trials
322 (p=0.93 for T1, p=0.62 for T2). The final WCs for T1 were 68.4, 59.3 and 47.1 for
323 Treatments A, B and C, respectively. For T2, these values were 69.5, 58.1 and 49.1,
324 respectively. The limited change in WC over time was due to the type of composting process
325 used in these experiments. The enclosed nature of the tumblers caused some of the water
326 vapour lost from the compost through evaporation to condense on the inside of the tumbler

327 walls and drop back into the compost. This caused the WC to remain relatively stable
328 throughout the composting process. This would not have occurred in large-scale windrow
329 composting where the water vapour would have been lost to the atmosphere.

330

331 3.1.5 *Elemental analysis and C:N ratio*

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

342 In Treatment A in T2, the C:N ratio increased significantly from 10.1 to 25.0 from day
343 0 to 56 ($p < 0.001$). This unexpected increase was caused by the large reduction in the N
344 content of the pile, from 4.5 % on day 0 to 1.9 % on day 56 (Table 2). In all other treatments,
345 there was an increase in N content over time due to the loss of CO_2 and also water loss
346 through evaporation. Losses of N during the composting of manure can occur due to
347 volatilisation of NH_3 (Tiquia and Tam, 2000). Also, when the WC of the compost is high,
348 leaching of nitrate (NO_3^-) may occur (Tiquia et al., 1998). As described previously, there was
349 some leachate lost from this treatment, due to its high WC, which may have resulted in the
350 higher loss of N from this treatment.

351 In Treatment C, the initial C:N ratios were 29.6 and 30.3 for T1 and T2, respectively.
352 When the initial C:N ratio is between 25 and 30, the final value for a stable compost should
353 be at or below 20 (Hiria et al., 1983). This was the case in T2, where the final C:N ratio was
354 15.2. However, the C:N ratio in T1, at 24.9, surpassed this upper limit, indicating that the
355 composting process was more efficient in T2. This result was supported by the longer
356 thermophilic period observed in T2 in comparison to T1, and by the GI and OUR values
357 (discussed later), which, for Treatment C, were better in T2 than T1.

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

363

364 3.1.6 *Organic matter*

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

372 The total loss of OM may be used as an indicator of compost biodegradation.
373 However, the dry weight reduction was not measured as part of this experiment; therefore, it
374 was not possible to measure the total loss of OM. The OM losses were calculated as the
375 differences in concentrations of OM only (Huang et al., 2004; Nolan et al., 2011). The OM

376 content of the piles decreased from day 0 to day 56 for all treatments ($p=0.001$). This was
377 caused by the degradation of the OM by the microorganisms during composting. For T1, the
378 losses of OM from the beginning to the end of the composting process were 22.5 %, 19.2 %
379 and 14.8 % for Treatments A, B and C, respectively. For T2, these losses were 20.6 %, 17.5
380 % and 9.6 % for Treatments A, B and C, respectively. The loss in OM was greatest in
381 Treatment A, followed by Treatment B and then Treatment C. These reduced rates of change
382 in OM content were due to the addition of lignin-rich sawdust in Treatments B and C. Lignin
383 is extremely resistant to chemical and enzymatic degradation. Michel et al. (2004) also found
384 a lower decomposition in the compost substrate and decreased amounts of organic C lost
385 during the composting process when using lignin-rich bulking agents.

386

387 **3.2 *Maturity and stability analysis***

388 **3.2.1 *Germination index (GI)***

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

398 Phytotoxins produced by the microorganisms in the less stable composts inhibit
399 growth (Zucconi et al., 1981) and lead to lower GI values. High copper, zinc, organic acids
400 and NH_4 concentrations and high electrical conductivity (EC) have also been shown to inhibit

401 seed germination in manure-based composts (Tiquia and Tam, 1998; Huang et al., 2004).
402 Sawdust addition to manure will dilute the concentration of these inhibitors and reduce EC in
403 the mixture. The GI values for both trials compared favourably with those from Huang et al.
404 (2004), who studied composting of pig manure and sawdust at initial C:N ratios of 30 and 15.
405 After 63 d of composting, Huang et al. (2004) reported a GI of 85 % for a C:N ratio of 30, and
406 46 % for a C:N ratio of 15. The lower GI was attributed to a higher EC in the treatment which
407 received the lower sawdust inclusion.

408

409 3.2.2 Oxygen Uptake Rate (OUR)

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

422 The proposed OUR threshold value in Ireland for stable compost is 13 mmol O₂ kg
423 OM⁻¹ h⁻¹ (Prasad and Foster, 2006). This value is similar to that used in Belgium and The
424 Netherlands, where this test is commonly used. In these countries, values above 15 mmol O₂
425 kg OM⁻¹ h⁻¹ are considered unstable (Prasad and Foster, 2006). Treatment B and C in both

426 trials reached stability values below the recommended Irish threshold by day 56. However,
427 Treatment A was higher than this value and could not be considered stable at day 56. There
428 was no difference in day 56 OUR values between Treatments B and C in either of the trials
429 ($p=0.94$ for T1, $p=1.00$ for T2).

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

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442 **4 Conclusions**

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

448 It is concluded that co-composting either separated raw or separated anaerobically
449 digested pig manures with sawdust at a manure-to-sawdust ratio of 4:1 (w/w) and a C:N ratio
450 of 18 or 16, respectively, can produce stable compost. Using this lower ratio reduces the

451 quantity of sawdust required and hence the cost to produce stable compost; 60 % less sawdust
452 is required to compost at a manure-to-sawdust ratio of 4:1, compared to 3:2. Using this lower
453 ratio may make composting pig manure more financially attractive to farmers, and persuade
454 them to implement on-farm composting as a means of nutrient recycling.

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576 Table 1. Physiochemical properties (means \pm SD) for pig manure and sawdust

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

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

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597 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

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615 Table 3. OUR (mmol O₂/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

616 **Captions for Figures**

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

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

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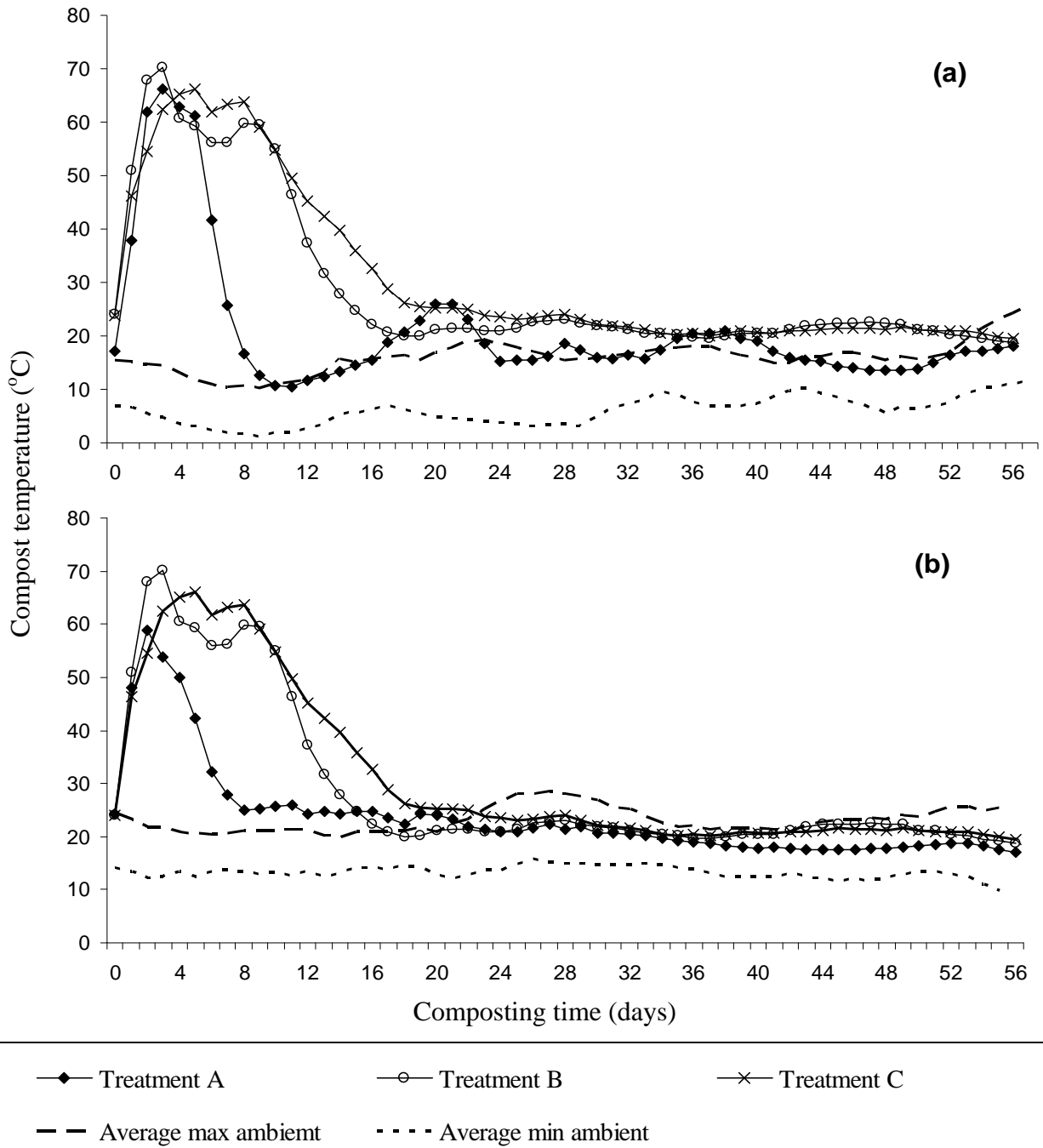
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641 Figure 1



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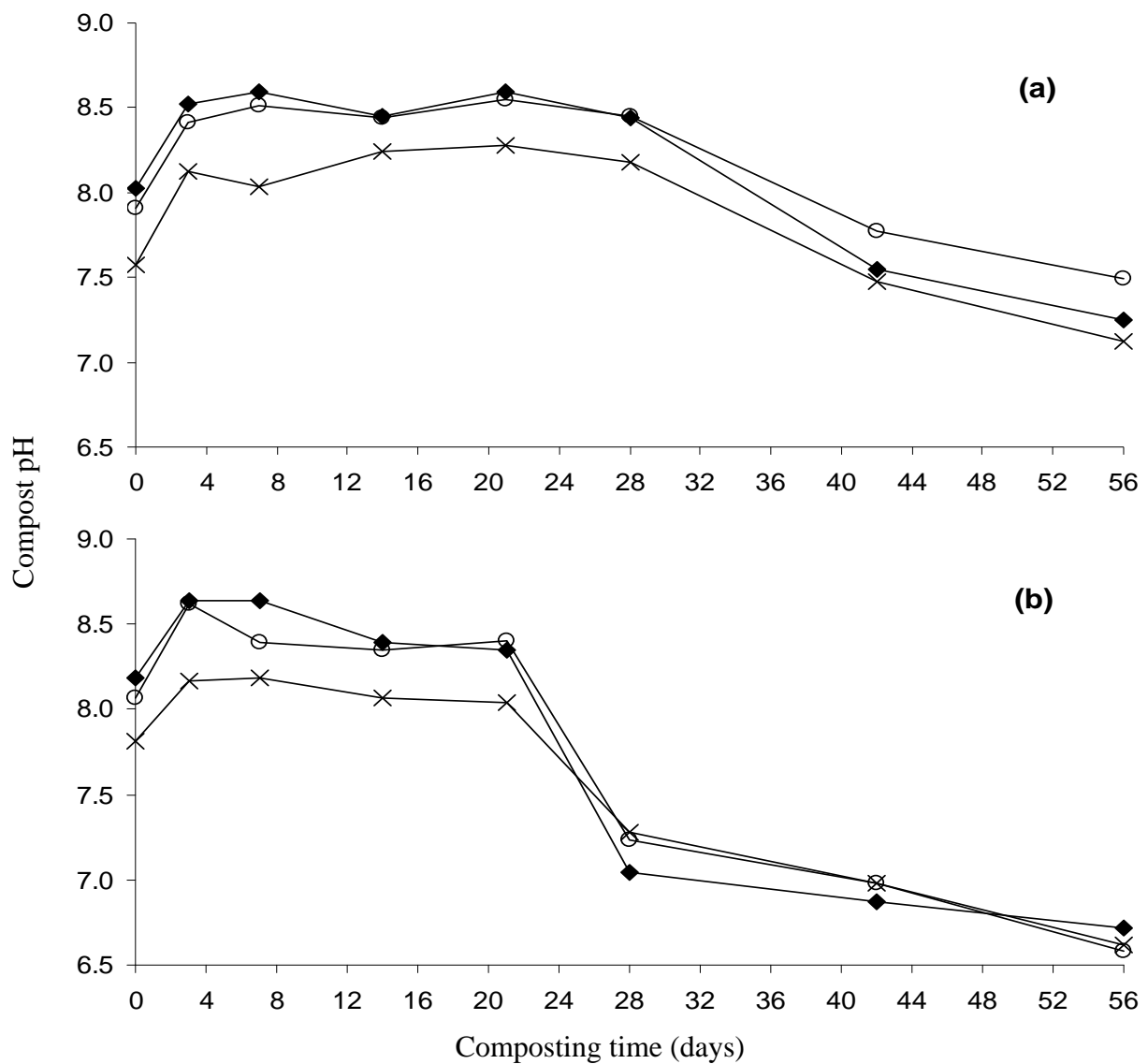
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647 Figure 2



◆ Treatment A ○ Treatment B × Treatment C

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