



Effect of rainfall interval on runoff losses of biosolids and meat and bone meal when applied to a grassland soil

Title	Effect of rainfall interval on runoff losses of biosolids and meat and bone meal when applied to a grassland soil
Author(s)	Lucid, Joseph D.;Healy, Mark G.
Publication Date	2014
Publisher	Springer

1 *Published as: Lucid, J.D., Fenton, O., Grant, J., Healy, M.G. 2014. Effect of rainfall interval on*
2 *runoff losses of biosolids and meat and bone meal when applied to a grassland soil. Water, Air and*
3 *Soil Pollution 225(8): 2042. DOI 10.1007/s11270-014-2042-6*

4

5 **Effect of rainfall time interval on runoff losses of biosolids and meat and**
6 **bone meal when applied to a grassland soil**

7 Joseph D. Lucid¹, Owen Fenton^{2*}, Jim Grant³, Mark G. Healy¹

8

9 ¹Civil Engineering, National University of Ireland, Galway, Co. Galway, Rep. of Ireland.

10 ²Teagasc, Johnstown Castle, Environmental Research Centre, Co Wexford, Rep. of Ireland

11 ³ Teagasc, Ashtown, Dublin 15, Co. Dublin, Rep. of Ireland.

12 *Corresponding author. Tel: +353 53 9171271. E-mail address: owen.fenton@teagasc.ie

13

14 **Abstract**

15 This study assessed runoff losses following laboratory rainfall simulation on a grassland soil
16 at two time intervals (48 and 216 h) after a single application of biosolids and meat and bone
17 meal (MBM). The treatments were: a soil-only control, three types of biosolids (lime-
18 stabilised (LS), thermally dried (TD) and anaerobically digested (AD)) and two types of
19 MBM (low ash and high ash content) all applied at two rates (the maximum and double the
20 maximum legal application rate currently permitted in Ireland). Results showed that
21 treatment, time interval and their interactions all had significant effects on dissolved reactive
22 P (DRP), total P (TP) and total dissolved P (TDP) concentrations. Time interval had the
23 greatest effect for DRP and TP concentrations, while treatment was more significant for TDP.
24 All treatments released DRP concentrations in excess of 30 µg DRP L⁻¹. Anaerobically
25 digested biosolids released the least amount of DRP into surface runoff for both application

26 rates at both time intervals. Low ash-content MBM, applied at the maximum legal rate,
27 released the most DRP at both time intervals, and the TD biosolids released the most DRP
28 when applied at double the maximum rate. Lime-stabilised biosolids released the most TP in
29 runoff at both application rates. Runoff comprised > 50% particulate P for all treatments.
30 Besides TD biosolids, all treatments, applied at both rates, released lower concentrations of
31 suspended solids (SS) during the second time interval than the first. Soil-specific effects were
32 also evident; although the soil was non-calcareous and had a low pH and high amounts of
33 available aluminium and iron, high organic matter ensured low levels of P adsorption.

34

35 *Keywords:* biosolids, meat and bone meal, phosphorus, agriculture, runoff

36

37 **1. Introduction**

38 Biosolids, derived from the wastewater treatment process, and meat and bone meal (MBM),
39 the by-products of the rendering industry, may be used as agricultural fertilisers, as they
40 contain organic matter (OM) and inorganic elements (Ylivainio et al., 2008). When spread on
41 tilled land or grassland, they supply nutrients and metals required for plant and crop growth,
42 and may also be used as an aid in the development of a soil's physical and chemical
43 characteristics (Meyer et al., 2001; Mondini et al., 2008). A large amount of sewage sludge
44 and MBM are produced in Europe. Annual production of MBM in Ireland peaked in 2003
45 (150,000 tonnes p.a.; Inter Departmental/Agency Committee on Disposal Options for MBM,
46 2003), but declined due to a decrease in herd sizes (SEI, 2004). Quantities of sewage sludge
47 produced at urban waste water treatment plants in 2009 was approximately 106,000 tonnes,
48 with 62% (down from 70% in 2007) of this being reused on agricultural land (EPA, 2012).
49 The drive to reuse sewage sludge has been accelerated by the Landfill Directive, 1999/31/EC
50 (European Commission (EC), 1999) and the Renewable Energy Directive (2009/28/EC; EC,

51 2009), which places an increased emphasis on the production of biomass-derived energy. One
52 such means of reuse is landspreading, although potential hazards associated with their
53 application to land, such as excessive nutrient release, needs to be evaluated.

54

55 To dispose of treated sewage sludge (biosolids) in Ireland, farmers must abide by the
56 European Union (EU) (**Good Agricultural Practice for Protection of Waters) Regulations**
57 **2014 (Statutory Instrument (SI) 31 of 2014)**. Compliance with the regulations requires
58 protection of waters against pollution from agricultural sources and management of manures
59 and fertilisers. In addition, the application of biosolids to agricultural land is governed in
60 Europe by EU Directive 86/278/EEC (EEC, 1986), and within Ireland, is enacted by the
61 “Codes of Good Practice for the Use of Biosolids in Agriculture” (Fehily Timoney and
62 Company, 1999).

63

64 The handling (and disposal) of MBM is subject to strict enforcement in many European
65 states. For example, in Ireland, S.I. 551 of 2002 requires possession of a licence for the
66 manufacture, sale or supply of MBM. In addition, strict guidelines govern its reuse as a
67 bioenergy resource (SEI, 2004). Land application of various categories of MBM is permitted
68 within the EU member states, provided certain criteria are adhered to (EC, 2002; EC, 2006).
69 These criteria include handling and processing procedures, and the prevention of land
70 application of fertilisers consisting of Category 1 MBM. However, EC Regulation No. 181 of
71 2006 (EC, 2006) provides for stricter national rules to be implemented by each individual
72 member state (EC, 2000), and this has resulted in the prohibition of the land application of
73 organic fertilisers composed of Category 2 and 3 MBM materials in certain member states
74 (for example, the Republic of Ireland has banned the land application of MBM under S.I. No.
75 253 of 2008).

76

77 In the EU, land application of biosolids and MBM are typically based on their nutrient and
78 metal contents. This approach results in phosphorus (P) becoming the limiting factor in
79 determining the application rates. This is in contrast to the United States (US), where
80 biosolids are applied based on their nitrogen (N) content (US EPA, 1993). Such a discrepancy
81 means that land application rates of biosolids in the US tend to be far greater than the EU,
82 resulting in less land required for the application of biosolids – but potentially greater
83 environmental losses.

84

85 Phosphorus losses to a surface waterbody originate from either the soil (chronic) or in runoff
86 where a storm event follows land application of fertilizer (incidental sources) (Brennan et al.,
87 2012). Such losses to a surface waterbody occur *via* direct discharges, surface and near
88 surface pathways, and/or groundwater discharge. Where there is a hydrological continuum
89 between a nutrient source (chronic or incidental) and surface water receptor, dissolved
90 reactive phosphorus (DRP) and particulate P (PP) can be delivered to a receptor and, where
91 loads are significant, may adversely affect water quality (Wall et al., 2011). Biosolids and
92 MBM application to soils may also contribute to soil test phosphorus (STP) build-up in soils,
93 thereby contributing to chronic losses of P, metal and pathogen losses in runoff (Gerba and
94 Smith, 2005). Dissolved reactive P losses may also be leached from an agricultural system to
95 shallow groundwater (Galbally et al., 2013) and, where a connectivity exists, may affect
96 surface water quality for long periods of time (Domagalski and Johnson, 2011; Fenton et al.,
97 2011).

98

99 Issues surrounding the potential ‘edge-of-field’ nutrient concentration and load losses arising
100 from land application of biosolids and MBM may be effectively investigated using low-cost

101 laboratory rainfall simulation studies, as they provide for more control over the variability of
102 the soils' physical and chemical characteristics and surface slope, and allow comparison to be
103 made between treatments (Regan et al., 2010).

104

105 The aims of this study were to determine chronic (study control) and incidental flow
106 weighted mean concentrations (FWMCs) and loads (mass release) of DRP, PP, total
107 dissolved phosphorus (TDP), total phosphorus (TP) and suspended solids (SS) in runoff from
108 a grassland soil following application of three types of biosolids (lime-stabilised (LS),
109 thermally dried (TD) and anaerobically digested (AD)) and two types of MBM (low ash and
110 high ash content) applied at two rates (the maximum and double the maximum legal
111 application rate currently permitted in Ireland) over two successive rainfall events (at the 48-
112 h period outlined in S.I. 31 of 2014 and after 216 h) to see the lasting effects of potential
113 losses of 11 mm h⁻¹-intensity rainfall events.

114

115 **2. Materials and Methods**

116 **2.1 Biosolids and MBM characterisation**

117 Three types of biosolids – AD, TD and LS - were collected from three wastewater treatment
118 plants in Ireland. Two types of MBM, one with low ash (MBM LA) and one with high ash
119 (MBM HA), were collected from a slaughterhouse in Co. Mayo, Ireland. **All results with
120 respect to the characterisation of biosolids and MBM were presented previously in
121 Lucid et al. (2013). Briefly, AD, TD, and LS biosolids, and MBM (high ash) and MBM
122 (low ash) had total P (mg kg⁻¹) contents of 6916, 7600, 6332, 27.9 and 31.1, respectively,
123 and AD, TD and LS biosolids, and MBM (high ash) and MBM (low ash) had total N
124 (mg kg⁻¹) contents of 6.8, 30.8, 3.1, 39.7, and 59.1, respectively. Metal content and
125 release was presented in Lucid et al. (2013).**

126

127 **2.2 Soil Collection and Analysis**

128 The soil used in this study was collected from a grassland field in Co. Galway, Ireland (ITM
129 reference 528060, 727322) **and was from the same site as in Lucid et al. (2013)**. Intact soil
130 sods measuring 0.7 m in length, 0.4 m in width and 0.1 m in depth, were collected from site
131 for use in the rainfall simulation study. A separate set of soil samples ($n = 3$), 0.1 m in depth
132 and 0.1 m in diameter, were collected from the same site for classification studies. A 2:1 ratio
133 of deionised water-to-soil was used to determine the soil pH. The soil samples were then air
134 dried at 40°C for 72 h, crushed to pass a 2-mm sieve and analysed for Morgan's P (P_m; the
135 national test used for the determination of plant available P in Ireland) using Morgan's
136 extracting solution after Morgan (1941). To determine the particle size distribution (PSD) of
137 the soil, a sieving and pipette technique was used (BSI, 1990b). The OM of the soil was
138 determined by LOI after BSI (1990a). **Soil characteristics are presented in Table 1.**

139

140 **2.3 Phosphorus desorption study and rainfall simulator test**

141

142 A P desorption study was conducted on each of the five media used in this study to determine
143 the time over which DRP may be released to surface water. This involved placing 6 g of
144 either biosolids or MBM into 120-ml-capacity plastic cups, overlaying them with 100 ml of
145 distilled water, sealing the containers, and placing them into an end-over-end shaker for a
146 period of 24 h. All tests were carried out in triplicate ($n=3$). At time intervals of 1, 4, 8, and
147 24 h, 2.5 ml of water was removed, filtered through 0.45- μm filters, and stored at 4°C until
148 testing (normally conducted within 1 d of collection). The water samples were tested for DRP
149 in accordance with the standard methods (APHA, 1995) by a nutrient analyser (Konelab 20,
150 Thermo Clinical Labsystems, Finland).

151

152 The following treatments were examined in a laboratory rainfall simulator (n=3): grassed
153 soil-only treatment (the study control) and grassland onto which either TD, LS and AD
154 biosolids, or MBM HA and MBM LA were spread. Each type of biosolids and MBM was
155 applied to the soil at two different rates based on a soil with a P Index of 1 (after Lucid et al.,
156 2013; Table 2): the maximum legal application rate and double the maximum legal
157 application rate.

158

159 Laboratory runoff boxes, 0.1 m-long, 0.225 m-wide and 0.075 m-deep and inclined at a 5-
160 degree slope and with the side-walls 0.025 m higher than the grassed sods, were used in this
161 experiment. Each runoff box had 0.005-m-diameter drainage holes, located at 0.3-m-centres
162 in the base, after Regan et al. (2010) and Brennan et al. (2011), to allow for drainage of water
163 at the base. Muslin cloth was placed at the base of each runoff box, covering these drainage
164 holes, before packing the soil in order to prevent soil loss. Immediately prior to the start of
165 each experiment, the soil sods were trimmed and packed into the runoff boxes. The runoff
166 boxes were then positioned under the rainfall simulator. The rainfall simulator consisted of a
167 single 1/4HH-SS14SQW nozzle (Spraying Systems Co., Wheaton, IL) attached to a 4.5-m-
168 high metal frame. The rainfall simulator was calibrated to achieve an intensity of 10.85 ± 0.14
169 mm h^{-1} with a droplet impact energy of $260 \text{ kJ mm}^{-1} \text{ ha}^{-1}$ at 86% uniformity after Regan et al.
170 (2010) and Brennan et al. (2011). The source of the water that was used for the rainfall
171 simulations was potable tap water, which had a DRP concentration of less than 0.005 mg L^{-1} ,
172 a pH of 7.73 ± 0.2 and an electrical conductivity (EC) of 0.494 dS m^{-1} .

173

174 The packed sods were then saturated using a rotating disc, variable-intensity rainfall
175 simulator (after Williams et al., 1997), and left to drain for 24 h by opening the 5-mm-

176 diameter drainage holes at the base of the runoff box before continuing with the experiment.
177 After this time elapsed, the grassed sods were assumed to be at field capacity (after Regan et
178 al., 2010). The biosolids and MBM were spread over the surface of the sods and the drainage
179 holes were sealed for the remainder of the experiment. In accordance with S.I. No. 31 of
180 2014, the laboratory runoff boxes were then left in this state for a period of 48 h. The first
181 rainfall event (RE 1) was applied at $t = 48$ h (after the application of the treatments). To
182 investigate the breakdown, if any, of the treatments with time and the lasting effects that this
183 may have on surface runoff, the second rainfall event (RE 2) occurred at $t = 216$ h (on the
184 same sod).

185

186 Rainfall was applied to each runoff box until consistent, continuous droplets of water flowed
187 from the runoff box; once this state had been achieved, each rainfall event lasted for a 30-min
188 duration. Surface runoff samples for each event were collected in 5-min intervals over 30
189 min, with a final sample collected in the period after rainfall had completed and runoff had
190 ceased.

191

192 **2.4 Water sample collection and analysis**

193 Runoff samples were collected in 1-L containers (covered to prevent rain water entering the
194 container) at the bottom of the runoff box. Immediately after collection, a sub-sample of the
195 runoff water was passed through a 0.45- μm filter and analysed colorimetrically for DRP
196 using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland). A second
197 filtered sub-sample was removed and TDP was measured using potassium persulphate and
198 sulphuric acid digestion (Hach Lange, Germany). An unfiltered sub-sample was removed and
199 analysed for the TP in the same manner as for TDP analysis. The DRP of every sample was
200 measured, while the TDP and TP was measured for the 10, 20 and 30-min interval samples,

201 as well as for the last sample removed after the rainfall had stopped. The DRP was subtracted
202 from the TDP to give the dissolved unreactive phosphorus (DUP). Particulate phosphorus
203 was calculated by subtracting TDP from TP. In order to determine the SS concentration, a
204 well-mixed, unfiltered sample of runoff water was passed through Whatman GF/C (pore size:
205 1.2 μm) filter paper by vacuum filtration. All water samples were tested in accordance with
206 standard methods for the examination of water and wastewater (APHA, 2005). Flow-
207 weighted mean concentrations for nutrients and SS in runoff were determined by dividing the
208 total mass load for the runoff event by the total flow volume for the same period.

209

210 Measurements of pH and dissolved oxygen (DO) were also conducted using a pH probe
211 (WTW SenTix 41 probe with a pH 330 meter, WTW, Germany) and a DO probe (WTW Oxi
212 315i meter with a Cellox 325 oxygen sensor, WTW, Germany), respectively. The time to
213 runoff was also recorded and the runoff ratio for each flume was determined. The runoff ratio
214 is defined as the ratio of the volume of surface runoff to the amount of rainfall applied over
215 the duration of the rainfall simulation.

216

217 **2.5 Statistical Analysis**

218 The analysis was carried out as a rainfall interval (time 48 h or 216 h after application) by
219 treatment (biosolids or MBM type and rate) factorial experiment with the non-randomised
220 times modelled with a repeated measures structure. As there were only two time intervals, all
221 correlation models gave the same result. The rainfall simulator data was analysed using the
222 GLIMMIX Procedure of the Statistical Analyses System (SAS Institute, 2004) with each
223 flume as the experimental unit. For all analyses, significance was given as $p < 0.05$. Dissolved
224 reactive phosphorus, DUP, PP, TDP, TP, SS, DO, pH and runoff ratio were analysed as
225 repeated measures using the MIXED procedure of SAS with Tukey-Kramer adjustment for

226 multiple comparisons with a covariance structure to account for correlations between the
227 repeated measures. The dependent variables were: DRP, DUP, PP, TDP, TP, SS, DO, pH and
228 runoff ratio for this experimental analysis. For all the above analyses, the fixed effects were:
229 treatment, time, treatment \times time, and flume. Time and treatment were the repeated measures.
230 Where interactions were significant, the comparisons within the means for the time by
231 treatment combinations were examined. Where interactions were not significant, the main
232 effects were interpreted and comparisons within each main effect were examined.

233

234 **3. Results and Discussion**

235 **3.1 Soil analysis and rainfall simulator test**

236 The soil used in this study was a non-calcareous soil with a low pH. This could lead to high
237 amounts of available Al and Fe, which can bind with P, rendering it unavailable. However,
238 the soil had high OM levels (18%; Table 1), and given that ~12-14% is the threshold between
239 a mineral and organic soil type, the Al and Fe in biosolids may be complexed in OM and
240 would be unavailable. Therefore, this soil had limited capacity to bind the added P and the
241 high OM may have worked against the amendments by complexing the Al or Fe in them. The
242 OM content of the soil is an important parameter, which determines soil suitability of
243 receiving MBM and biosolids.

244

245 Treatment, time and their interactions all had significant effects on DRP, TP and TDP
246 concentrations. Time had the greatest effect for DRP and TP concentrations, while treatment
247 was more significant for TDP. Treatment and a treatment \times time interaction were significant
248 for DUP and PP, but not time on its own. The average FWMCs and load (mass release) of
249 DRP, DUP and PP in the surface runoff for the two rainfall events, at both application rates,
250 are shown in Figures 1 and 2. Anaerobically digested biosolids released the least amount of

251 DRP into surface runoff for both application rates and both rainfall events. There was no
252 significant difference in DRP losses between the control and all treatments when compared
253 for the maximum legal application rate ($p < 0.05$). All treatments, at both application rates, and
254 the study control, released DRP in excess of the $30 \mu\text{g L}^{-1}$, the concentration over which
255 significant deterioration of rivers and other surface water bodies may occur (Clabby et al.,
256 2008). However, owing to the buffering capacity of receiving waters, it is likely that these
257 concentrations would be considerably reduced in receiving watercourses.

258

259 Low ash-content MBM, applied at the maximum legal rate, released the most DRP for both
260 rainfall events, and the TD biosolids released the most DRP when applied at double the
261 maximum legal rate ($p < 0.05$). These results followed the same general trend as the desorption
262 study. Of the five materials examined in the desorption test, at the 24-h period, the AD (0.013
263 g kg^{-1}) and LS (0.015 g kg^{-1}) biosolids released the least amount of DRP (Figure 3); this was
264 followed by MBM (HA) (0.446 g kg^{-1}), TD biosolids (0.569 g kg^{-1}) and MBM (LA) (0.713 g
265 kg^{-1}), the latter of which produced DRP concentrations 70 times larger than the AD and LS
266 biosolids. With the exception of the TD biosolids, all the treatments released 90% of their
267 DRP after 1 h of continuous mixing with water.

268

269 Lime-stabilised biosolids released the most TP into the surface runoff at both application
270 rates ($p < 0.05$). The main purpose of the lime addition to biosolids is to remove pathogens
271 (Epstein, 2002). However, liming is sometimes associated with an initial flush of soluble OM
272 and dissolved organic P, which can increase P losses in runoff (Murphy, 2007). With the
273 exception of the LS biosolids, at both application rates, there was no statistical difference
274 between the TP concentrations during both rainfall events. Although there was no significant
275 difference in pH between treatments, at an elevated pH similar to the range measured in the

276 current study (pH 6 – 8), organic P can be more soluble due to desorption or dispersion of
277 OM (Hannapel et al., 1964). With the exception of three cases (RE 2 of the control and RE 1
278 of the TD biosolids applied at both rates), the surface runoff comprised mainly PP throughout
279 all of the treatments, with less than 50% present as DRP (Figure 4). The relatively small
280 amount of highly mobile P means that measures such as buffer zones would trap most of the
281 P in surface runoff.

282

283 The runoff ratio for each rainfall event is displayed in Figure 5. The addition of biosolids to
284 grass has been found in some cases to affect the volume of surface runoff from soil: Joshua et
285 al. (1998) applied a one-time application of AD biosolids at rates of 0, 30, 60 and 120 t DS
286 ha⁻¹ and, over a 3-y period, found that soil-only control plots produced more runoff than those
287 applied with biosolids, and that increasing biosolids application produced decreasing runoff
288 volumes for the biosolids-treated plots. However, Meyer et al. (2001) found that the
289 application of composted biosolids, at rates of 0, 40 and 80 t ha⁻¹, did not significantly affect
290 mean runoff, even though runoff values were smaller on biosolids-treated plots. In the current
291 study, when applied at the maximum legal application rate, LS biosolids and MBM (HA)
292 increased the volume of surface runoff. When the treatments were applied at double the
293 maximum legal application rate, all treatments increased the volume of surface runoff, but in
294 most cases, these increases were not significant ($p>0.05$). Although the rate of application
295 was low in comparison to other studies that examined surface runoff (Joshua et al., 1998;
296 Meyer et al., 2001), these results would suggest that higher applications of biosolids and
297 MBM could produce larger volumes of surface runoff, which would impede drainage through
298 the soil structure. There was no correlation between runoff ratio and total mass or
299 concentration of P released. The period between the rainfall events allowed both the soil and

300 biosolids to dry out, therefore when rainfall was applied during RE 2, there was water taken
301 in by both the biosolids and soil.

302

303 With the exception of TD biosolids, all treatments, applied at the maximum and twice the
304 maximum legal application rate, released lower concentrations of SS during the second
305 rainfall event than during the first rainfall event (Figure 6). The increase in SS for the TD
306 biosolids from RE 1 to RE 2 could be due to the breakdown of the biosolids over time. Lime-
307 stabilised biosolids exceeded the allowable discharge limit for the release of SS to surface
308 waters (35 mg L^{-1} ; S.I. 419 of 1994) at both application rates. Low ash MBM and TD
309 biosolids also exceeded the discharge limits on the legal and double the maximum legal
310 application rates, respectively. The incorporation of biosolids into the top layer of soil, as
311 opposed to a surface application, may assist in the reduction of SS. Meyer et al. (2001)
312 reported reductions in the SS lost to surface runoff compared to control plots (plots receiving
313 no biosolids) when biosolids were incorporated into the top 0.1 – 0.2 m soil layer.

314

315 **3.2 Time to Runoff**

316 The time to runoff for each amendment and application rate are presented in the on-line
317 supplementary data. For each treatment and application rate, the time to runoff increased
318 from RE 1 to RE2. The period between RE 1 and RE 2 allowed the grassed sods to dry out
319 which, in turn, increased the amount of time required during RE 2 for the sods to saturate and
320 for runoff to commence. With the exception of the AD biosolids applied at the maximum
321 legal rate and TD biosolids applied at both application rates, all other amendments decreased
322 the time to runoff compared to the corresponding control results.

323

324 **4. Conclusions**

325 This study showed that treatment, time interval and their interactions all had significant
326 effects on DRP, TP and TDP concentrations in surface runoff after application of biosolids
327 (lime-stabilised, thermally dried and anaerobically digested) and MBM (low ash and high ash
328 content) to a grassland soil. Time interval had the greatest effect for DRP and TP
329 concentrations, while treatment was more significant for TDP. All treatments released DRP
330 concentrations in excess of $30 \mu\text{g DRP L}^{-1}$ and runoff comprised $> 50\%$ particulate P for all
331 treatments. The study found that soil type influences the quality of runoff generated. Further
332 research is needed to further investigate this effect.

333

334 **Acknowledgements**

335

336 The first author gratefully acknowledges the award of the EMBARK scholarship from the
337 Irish Research Council to support this study. The authors would also like to thank Brian
338 Cloonan, Western Proteins, Ballyhaunis and David Gahan, SEDE Ireland, for their advice
339 and assistance. The authors would also like to thank Cornelius O'Flynn, Liam Gary Henry
340 and Ana João Serrenho.

341

342

343

344

345

346

347

348

349

350 **References**

351

352 APHA (1995). *Standard methods for the examination of water and wastewater*. Washington:

353 American Public Health Association.

354

355 Brennan, R.B., Fenton, O., Grant, J., & Healy, M.G. (2011). Impact of chemical amendment

356 of dairy cattle slurry on phosphorus, suspended sediment and metal loss to runoff from a

357 grassland soil. *Science of the Total Environment*, 409, 5111–5118

358

359 Brennan, R.B., Healy, M.G., Grant, J., Ibrahim, T.G., & Fenton, O. (2012). Incidental

360 phosphorus and nitrogen loss from grassland plots receiving chemically amended dairy cattle

361 slurry. *Science of the Total Environment*, 441, 132–140

362

363 British Standards Institution (1990a). *Determination of particle size distribution. British*

364 *standard methods of test for soils for civil engineering purposes. BS 1377: 1990:2*. London:

365 British Standards Institution.

366

367 BSI (1990b). *Determination by mass-loss on ignition. British standard methods of test for*

368 *soils for civil engineering purposes. Chemical and electro-chemical tests. BS 1377:1990:3*.

369 London: British Standards Institution.

370

371 Clabby, K.J., Bradley, C., Craig, M., Daly, D., Lucey, J., McGarrigle, M., O’Boyle, S.,

372 Tierney, D. & Bowman, J. (2008). *Water Quality in Ireland 2004-2006*. Environmental

373 Protection Agency, County Wexford.

374

375 Domagalski, J.L., & Johnson, H.M. (2011). Subsurface transport of orthophosphate in five
376 agricultural watersheds, USA. *Journal of Hydrology*, 409, 157-171.
377

378 Enterprise Ireland (2011) EnviroCentre.ie. Animal by-products legislation - An explanatory
379 guide. [http://www.envirocentre.ie/includes/documents/Animal%20By-](http://www.envirocentre.ie/includes/documents/Animal%20By-Products%20March%202011.pdf)
380 [Products%20March%202011.pdf](http://www.envirocentre.ie/includes/documents/Animal%20By-Products%20March%202011.pdf) Accessed 19 June 2013
381

382 Environmental Protection Agency. (2012). Monaghan, S., Shannon, D., Wall, B., O'Leary, G.
383 Focus on Urban Waste Water Discharges in Ireland.
384 http://www.epa.ie/downloads/pubs/water/wastewater/uww/UWW_Report.pdf
385

386 Epstein, E (2002) Land application of sewage sludge and biosolids. CRC Press.
387

388 European Commission (1999) Council Directive 1999/31/EC of 26 April 1999 on the landfill
389 of waste. Official Journal L 182, 16/07/1999. [http://eur-](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31999L0031:EN:HTML)
390 [lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31999L0031:EN:HTML](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31999L0031:EN:HTML) Accessed 7
391 October 2013
392

393 European Commission (2000) Council Decision of 4 December 2000 concerning certain
394 protection measures with regard to transmissible spongiform encephalopathies and the
395 feeding of animal protein (2000/766/EC). Official Journal of the European Communities
396 07.12.2000 (L 306/32). http://ec.europa.eu/food/food/biosafety/tse_bse/docs/d00-766.pdf
397 Accessed 7 December 2013.
398

399 European Commission (2009) Directive 2009/28/EC of the European Parliament and of the
400 Council of 23 April 2009 on the promotion of the use of energy from renewable sources and
401 amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC
402

403 European Commission (2002) Regulation (EC) No 1774/2002 of the European parliament
404 and of the council of 3 October 2002 laying down health rules concerning animal by-products
405 not intended for human consumption, 2002, Available at: [http://eur-](http://eur-lex.europa.eu/LexUriServ/site/en/consleg/2002/R/02002R1774-20070101-en.pdf)
406 [lex.europa.eu/LexUriServ/site/en/consleg/2002/R/02002R1774-20070101-en.pdf](http://eur-lex.europa.eu/LexUriServ/site/en/consleg/2002/R/02002R1774-20070101-en.pdf). Accessed 7
407 December 2013.
408

409 European Commission (2006) Commission Regulation (EC) No 181/2006 of 1 February
410 2006 implementing Regulation (EC) No 1774/2002 as regards organic fertilisers and soil
411 improvers other than manure and amending that Regulation, 2006, Official Journal of the
412 European Union 02.02.2006 (L 29/31).
413

414 European Economic Community (1986) Council Directive of 12 June 1986 on the protection
415 of the environment, and in particular of the soil, when sewage sludge is used in agriculture
416 (86/278/EEC), 1986. [http://www.efma.org/PRODUCT-STEWARDSHIP-PROGRAM-](http://www.efma.org/PRODUCT-STEWARDSHIP-PROGRAM-10/images/86278EEC.pdf)
417 [10/images/86278EEC.pdf](http://www.efma.org/PRODUCT-STEWARDSHIP-PROGRAM-10/images/86278EEC.pdf) Accessed 7 December 2013.
418

419 Fehily Timoney and Company (1999) Codes of good practice for the use of biosolids in
420 agriculture - guidelines for farmers.
421 <http://www.environ.ie/en/Publications/Environment/Water/FileDownload,17228,en.pdf>
422 Accessed 7 December 2013.
423

424 Fenton, O., Healy, M.G., Rodgers, M., & O'hUallachain, D. (2009). Site-specific P
425 absorbency of ochre from acid mine-drainage near an abandoned Cu-S mine in the Avoca-
426 Avonmore catchment, Ireland. *Clay Minerals*, 44, 113-124.

427

428 Fenton, O., Schulte, R.P.O., Jordan, P., Lalor, S.T.J., & Richards, K.G. (2011). Time lag: a
429 methodology for the estimation of vertical and horizontal travel and flushing timescales to
430 nitrate threshold concentrations in Irish aquifers. *Environmental Science and Policy*, 14, 419-
431 431.

432

433 Galbally, P., Ryan, D., Fagan, C.C., Finnan, J., Grant, J., & McDonnell, K. (2013). Biosolid
434 and distillery effluent amendments to Irish short rotation coppiced willow plantations:
435 impacts on groundwater quality and soil. *Agriculture Water Management*, 116, 193 – 203.

436

437 Gerba, C.P., & Smith, J.E. (2005). Sources of pathogenic microorganisms and their fate
438 during land application of wastes. *Journal of Environmental Quality* 34, 42-48.

439

440 Hannapel, R.J., Fuller, W.H., Fox, R.H. (1964). Phosphorus movement in a calcareous soil:
441 II. Soil microbial activity and organic phosphorus movement. *Soil Science*, 97, 421 – 427.

442

443 Inter Departmental/Agency Committee on Disposal Options for MBM (2003)
444 http://www.lagangroup.co.uk/lagan_cement/downloads/report_inter_departmental_committe
445 e.pdf. Accessed 7 December 2013.

446

447 Joshua, W.D., Michalk, D.L., Curtis, I.H., Salt, M., & Osborne, G.J. (1998). The potential for
448 contamination of soil and surface waters from sewage sludge (biosolids) in a sheep grazing
449 study, Australia. *Geoderma* 84, 135-156.

450

451 Lucid, J.D., Fenton, O., & Healy, M.G. (2013). Estimation of maximum biosolids and meat
452 and bone meal application to a low P index soil and a method to test for nutrient and metal
453 losses. *Water, Air and Soil Pollution*, 224, 1464-1475.

454

455 Meyer, V.F., Redente, E.F., Barbarick, K.A., & Brobst, R. (2001) Biosolids applications
456 affect runoff water quality following forest fire. *Journal of Environmental Quality*, 30, 1528-
457 1532.

458

459 Mondini, C., Cayuela, M.L., Sinicco, T., Sánchez-Monedero, M.A., Bertolone, E., & Bardi,
460 L. (2008). Soil application of meat and bone meal. Short-term effects on mineralization
461 dynamics and soil biochemical and microbiological properties. *Soil Biology and*
462 *Biochemistry*, 40, 462-474.

463

464 Morgan, M.F. (1941). Chemical soil diagnosis by the universal soil testing system.
465 Connecticut Agricultural Experimental Station Bulletin 450. Connecticut, New Haven.

466

467 Murphy, P.N.C. (2007). Lime and cow slurry application temporarily increases organic
468 phosphorus mobility in an acid soil. *European Journal of Soil Science*, 58, 794 – 801.

469

470 O' Flynn, C.J., Fenton, O., & Healy, M.G. (2012a). Evaluation of amendments to control
471 phosphorus losses in runoff from pig slurry applications to land. *Clean Soil Air Water*,
472 40,164–170
473

474 O' Flynn, C.J., Fenton, O., Wilson, P., & Healy, M.G. (2012b). Impact of pig slurry
475 amendments on phosphorus, suspended sediment and metal losses in laboratory runoff boxes
476 under simulated rainfall. *Journal of Environmental Management*, 113, 78-84
477

478 Regan, J.T., Rodgers, M., Healy, M.G., Kirwan, L., & Fenton, O. (2010) Determining
479 phosphorus and sediment release rates from five Irish tillage soils. *Journal of Environmental*
480 *Quality*, 39, 1-8
481

482 SAS Institute (2004) SASV9.1. SAS/STAT® user's guide. Cary, NC. SAS Institute Inc.
483

484 Sustainable Energy Ireland (2004) Bioenergy in Ireland. Department of Communications,
485 Marine and Natural Resources. Dublin.
486

487 Statutory Instrument No. 419 of 1994, Environment Protection Agency Act, 1992 (Urban
488 waste water treatment regulations, 1994).
489 <http://www.irishstatutebook.ie/1994/en/si/0419.html> Accessed 7 January 2013
490

491 Statutory Instrument No. 551 of 2002. Diseases of Animal Act 1966 (Transmissible
492 spongiform encephalopathies) (meat and bone meal and poultry offal) Order 2002.
493 <http://www.irishstatutebook.ie/2002/en/si/0551.html> Accessed 7 December 2013.
494

495 Statutory Instrument No. 253 of 2008, Diseases Of Animals Act 1966 (Transmissible
496 Spongiform Encephalopathies) (fertilisers and soil improvers).
497 <http://www.attorneygeneral.ie/esi/2008/B26298.pdf> Accessed 7 December 2013.
498
499 Statutory Instrument 31. European Union (Good agricultural practice for protection of
500 waters) Regulations 2014. Statutory Instruments. SI No. 31 of 2014. Department of
501 Environment, Heritage and Local Government, The Stationary Office, Dublin, 54 p.
502
503 U.S. EPA (1993) Standards for the use or disposal of sewage sludge.
504 <http://water.epa.gov/scitech/wastetech/biosolids/upload/fr2-19-93.pdf> Accessed 7 December
505 2013.
506
507 Wall, D., Jordan, P., Melland, A.R., Mellande, P.-E., Buckley, C., Reaney, S.M., Shortle, G.
508 (2011) Using the nutrient transfer continuum concept to evaluate the European Union
509 Nitrates Directive National Action Programme. *Environmental Science Policy*, 14, 664-674
510
511 Williams, J.D., Wilkins, D.E., McCool, D.K., Baarstad, L.L., Klepper, B.L., Papendick, R.I.
512 (1997). A new rainfall simulator for use in low-energy rainfall areas. *Applied Engineering in*
513 *Agriculture*, 14, 243–247
514
515 Ylivainio, K., Uusitalo, R, Turtola, E (2008) Meat bone meal and fox manure as P sources for
516 ryegrass (*Lolium multiflorum*) grown on a limed soil. *Nutrient Cycling in Agroecosystems*,
517 81, 267-278.
518
519
520

521 **Captions for Figures**

522

523 **Figure 1** Average flow-weighted dissolved reactive phosphorus (DRP), dissolved unreactive
524 phosphorus (DUP) and particulate phosphorus (PP), which collectively make-up the total
525 phosphorus (TP), in runoff after each rainfall simulation event for the treatments applied at
526 both the maximum legal (a) and double the maximum legal (b) rate. The concentrations
527 measured for first rainfall event and the second rainfall event are denoted by '1' and '2',
528 respectively. Dashed line represents $30 \mu\text{g P L}^{-1}$ maximum admissible concentration for
529 surface waters (Clabby et al., 2008).

530

531 **Figure 2** Average flow-weighted dissolved reactive phosphorus (DRP), dissolved unreactive
532 phosphorus (DUP) and particulate phosphorus (PP), which collectively make-up the total
533 phosphorus (TP), in runoff after each rainfall simulation event for the treatments applied at
534 both the maximum legal (a) and double the maximum legal (b) rate. The concentrations
535 measured for first rainfall event and the second rainfall event are denoted by '1' and '2',
536 respectively.

537

538 **Figure 3** Phosphorus desorption from the treatments examined.

539

540 **Figure 4** The average % of dissolved reactive phosphorus (DRP), dissolved unreactive
541 phosphorus (DUP) and particulate phosphorus (PP), which comprise total phosphorus
542 (TP), in runoff for the first ('1') and second ('2') rainfall events.

543

544 **Figure 5** Runoff ratios from each rainfall simulation event for the treatments applied at both
545 the maximum legal (a) and double the maximum legal (b) rate.

546

547 **Figure 6** Average flow weighted mean concentrations of suspended solids in runoff after
548 each rainfall simulation event for the treatments applied at both the maximum legal (a) and
549 double the maximum legal (b) rate. The concentrations measured for first rainfall event and
550 the second rainfall event are denoted by '1' and '2', respectively. The dashed line represents
551 the 35 mg L⁻¹ standard (S.I. No 419 of 1994).

Table 1. Classification of soil used in this experiment. Standard deviations, where multiple sampling (n=3) was conducted, are in brackets.

Water extractable phosphorus (g kg ⁻¹)	0.00249 (0.00054)
pH	5.63
Lime requirement pH	5.90
Morgan's P (mg L ⁻¹)	1.12(0.09) (P Index 1)
K (mg L ⁻¹)	203.24
Mg (mg L ⁻¹)	239.5
Organic matter (%)	18.18 (1.19)

Table 2. Application rates of biosolids and meat and bone meal (MBM) to the soil in this study using a P Index 1 soil.

Nutrient Type	Maximum legal application rate ^a		Double the maximum legal application rate	
	Wet weight	Dry solids	Wet weight	Dry solids
	-----Tonnes ha ⁻¹ -----			
AD biosolids	14.8	3.3	29.6	6.6
TD biosolids	3.3	3.0	6.5	6.0
LS biosolids	18.0	5.2	36.0	10.4
MBM (HA)	0.9	0.8	1.7	1.6
MBM (LA)	0.8	0.7	1.5	1.4

^a Legal limits, estimated after Lucid et al. (2013).

Figure 1

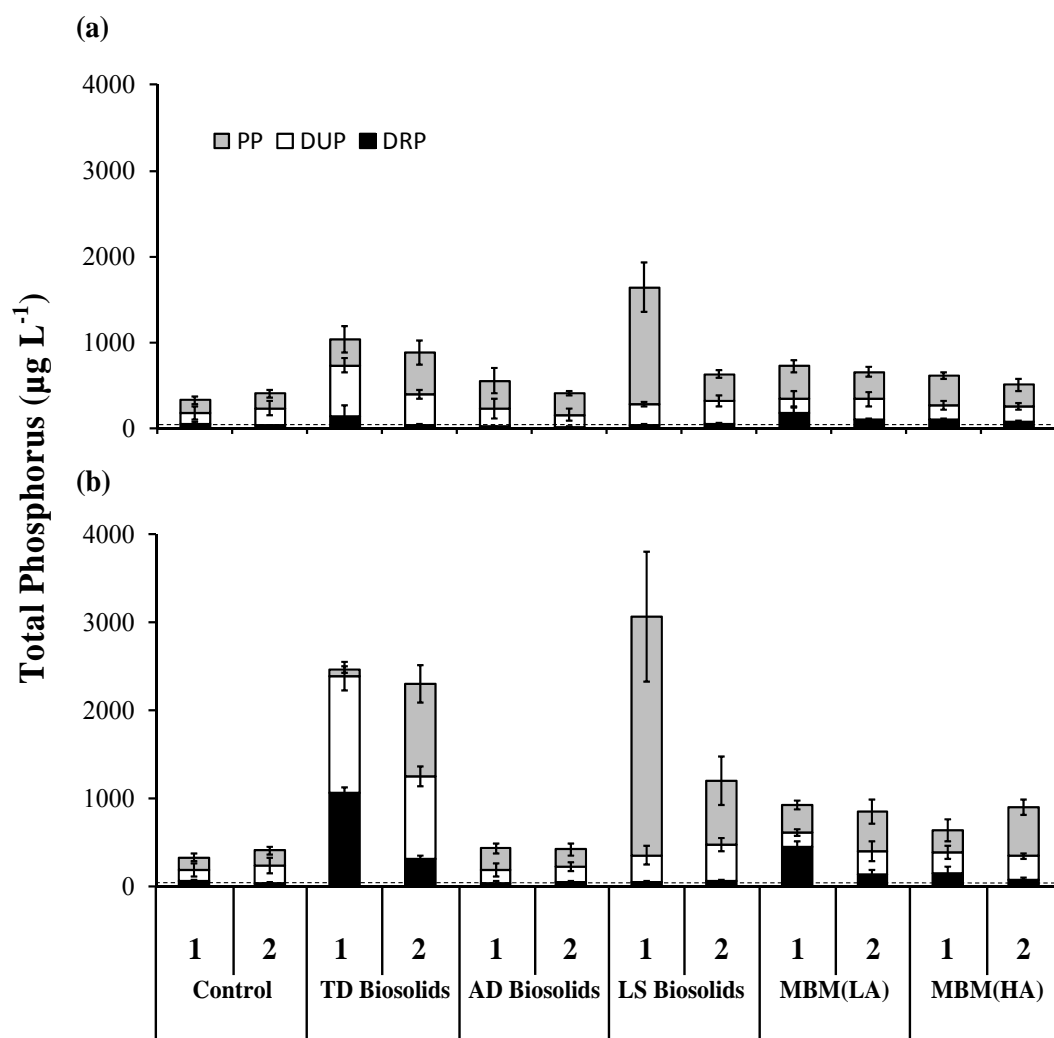


Figure 2

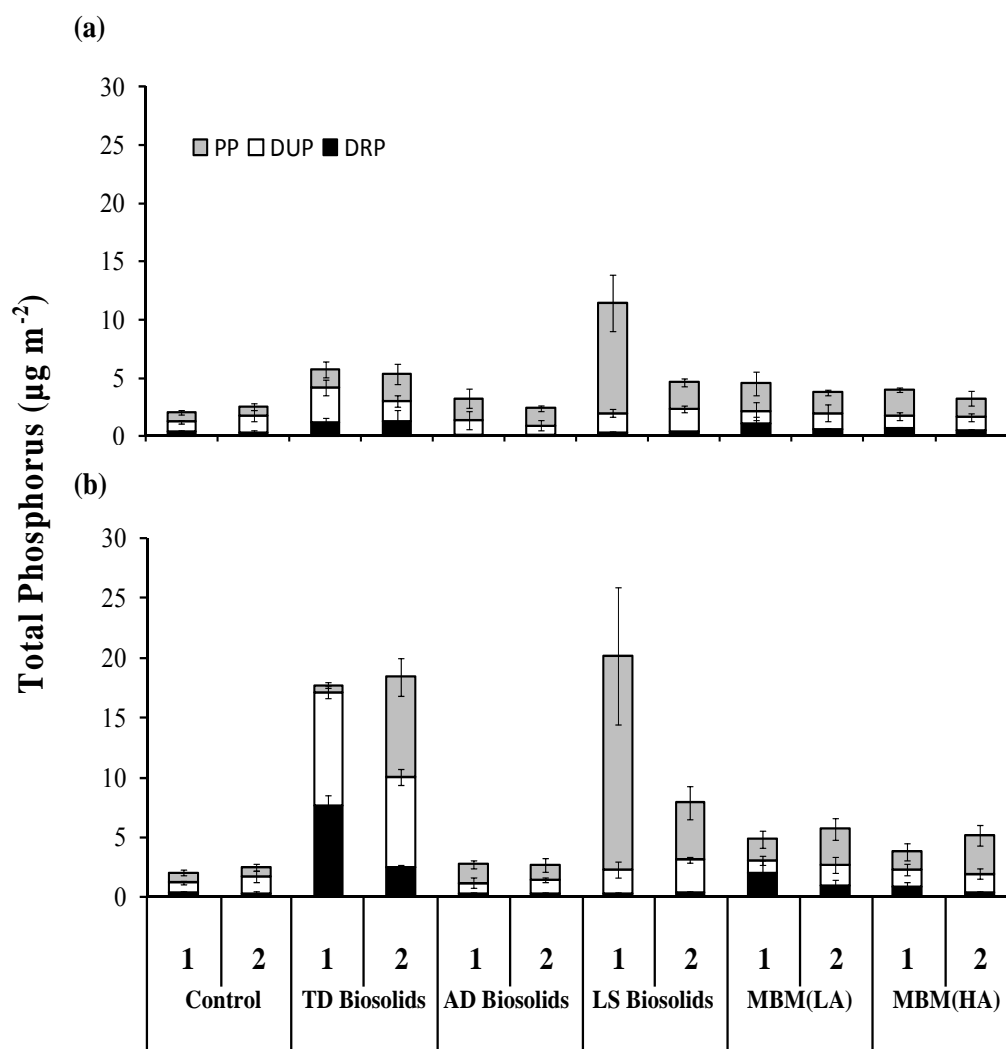


Figure 3

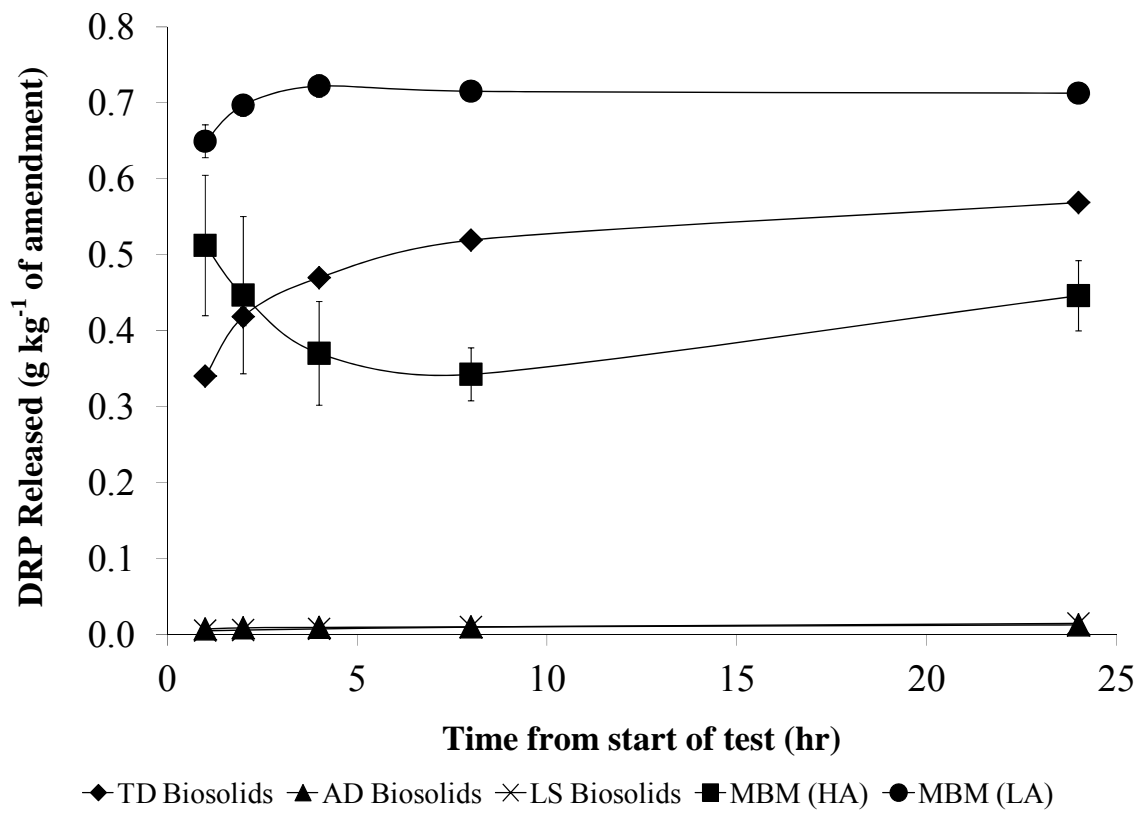


Figure 4

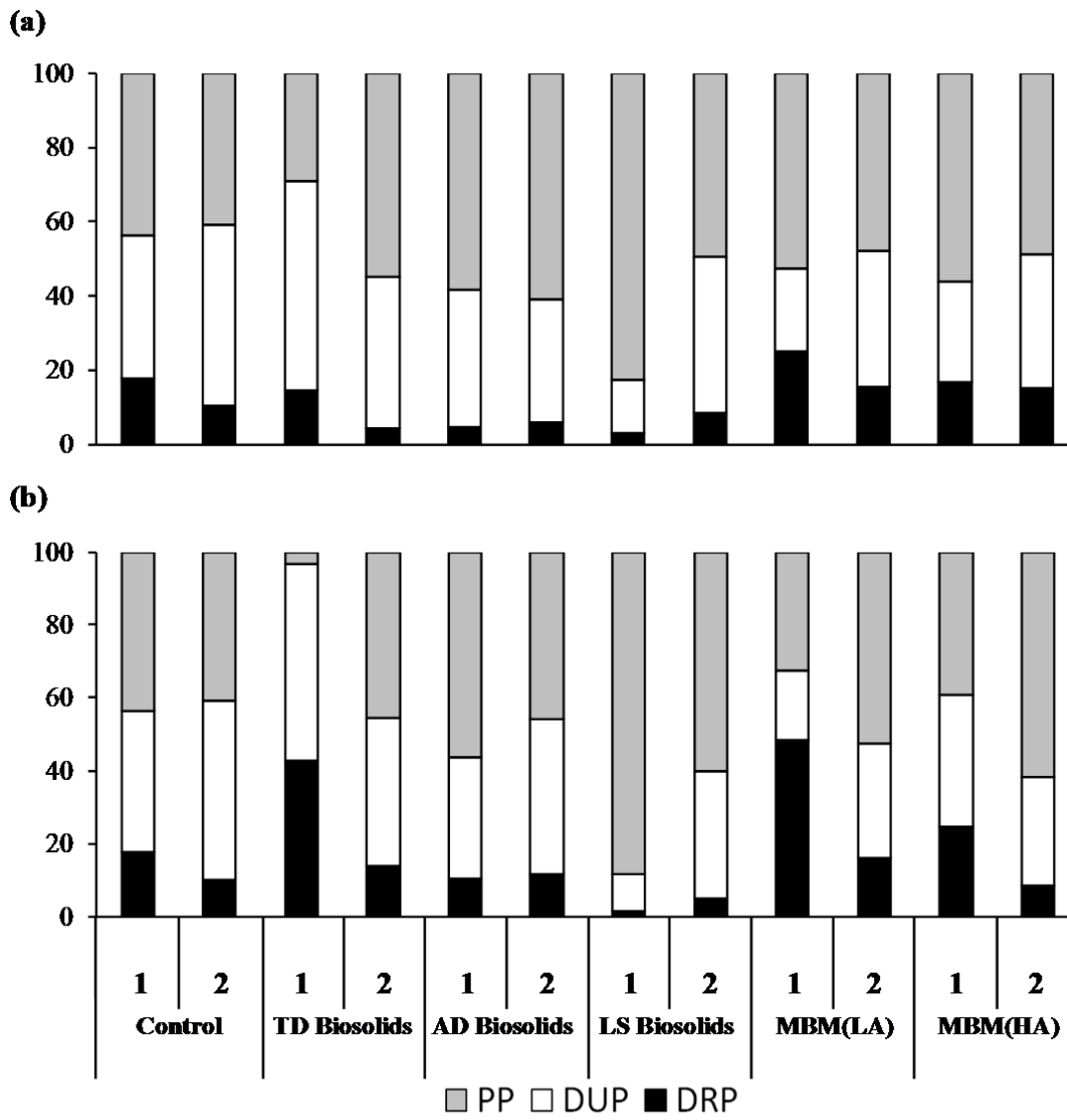


Figure 5

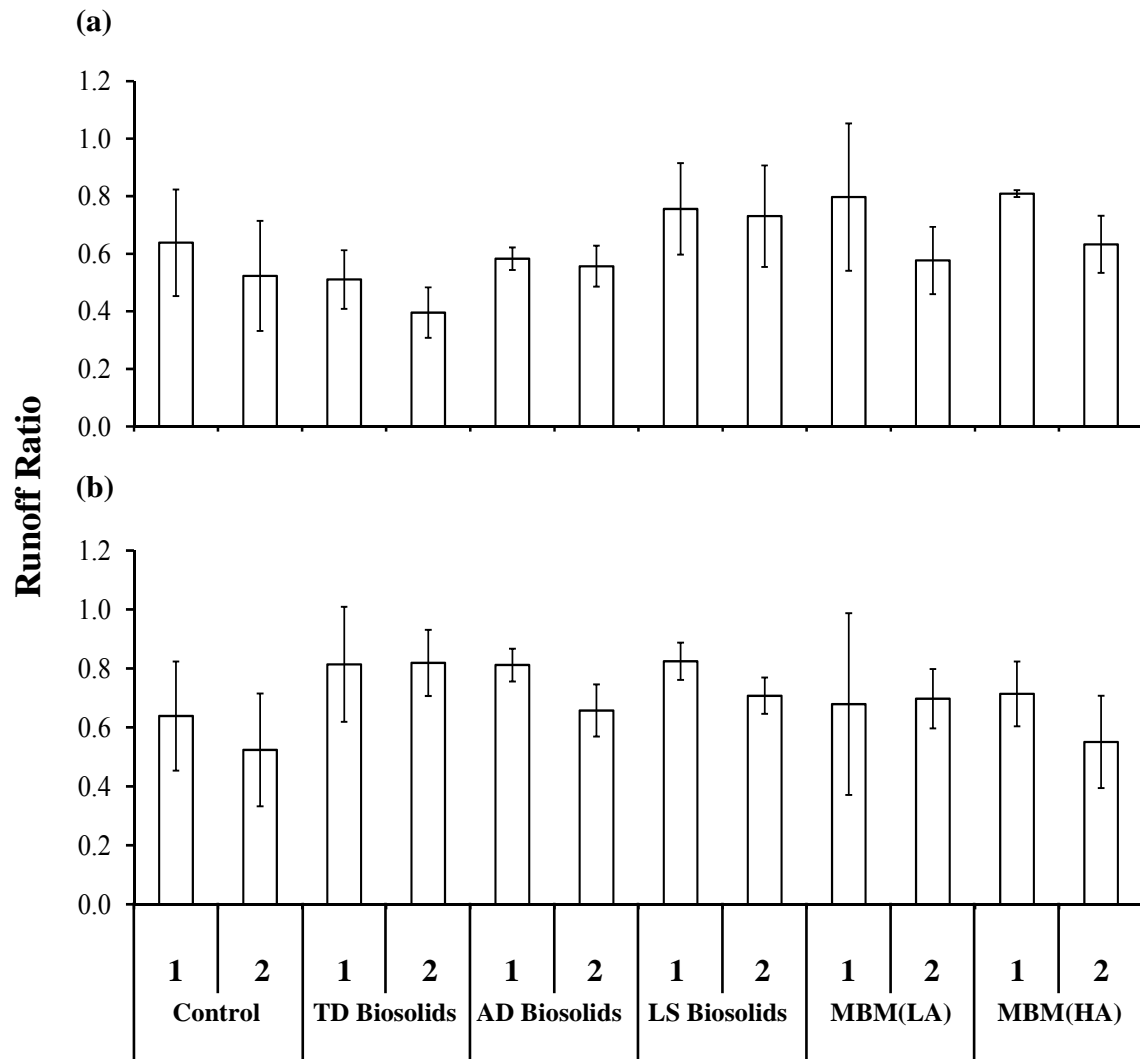


Figure 6

