



2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation

Paper Number: 12-1340682

Nitrogen and Phosphorus Availability Following Topsoil Application of Mineral and Organomineral Fertilisers (OMF)

D.L. Antille

Cranfield University, School of Applied Science, Cranfield, Bedfordshire, MK43 0AL, UK.
Present address: Teagasc Johnstown Castle, Environmental Research Centre, Wexford, Co. Wexford, Ireland. Email: d.l.antille@gmail.com

R. Sakrabani

Cranfield University, School of Applied Science, Cranfield, Bedfordshire, MK43 0AL, UK.
Email: r.sakrabani@cranfield.ac.uk

R.J. Godwin

Harper Adams University College, Newport, Shropshire, TB10 8NB, UK.
Email: dickjillgodwin@waitrose.com

Written for presentation at the
2012 ASABE Annual International Meeting
Sponsored by ASABE
Hilton Anatole
Dallas, Texas
July 29 – August 1, 2012

Abstract. *The aim of this study was to determine the availability of N and P resulting from the soil application of a novel organomineral fertiliser (OMF₁₅ – 15:4:4) reported in earlier studies, in comparison with urea (46% N) and single superphosphate (SSP – 0:18:0). A sandy loam and a clay loam soils were incubated over a period of 90 days at 25 degrees Celsius. N and P (as P₂O₅) were applied at rates equivalent to 0 (control), 150 and 300 kg ha⁻¹ and the soils maintained near field capacity. The majority of the N was released from OMF₁₅ within 30 from application (range 40%-72% of total OMF-N applied) with a further 10% to 28% in the following 60 to 90 days. OMF₁₅ required an accumulated thermal time of 2250 d°C to release between 68% and 79% of the total OMF-N applied. From this, it was suggested that mineralisation of the organic-N fraction in the OMF would progress beyond the harvest of winter cereal crops in-field conditions in the UK. The availability of P from OMF₁₅ was low throughout the experiment ranging from -5.6% to 6.4% (% of total OMF-P applied). Despite this, a change in soil-P index from 5 to 6 was observed after the 90 days incubation period but the overall increase in soil-P status was marginal in both soils. For SSP, P-availability ranged from 16% to 46% (% of total SSP-P applied). The application of SSP induced a significant (p<0.001) increase in soil-P levels compared with the controls which led to an overall increase in soil-P index from 5 to 6. The results of this study aided the development of a strategy for the use of OMF in winter cereal crops.*

Keywords. Organomineral fertilisers (OMF), soil N, soil P, soil P index, fertiliser N and P availability.

The authors are solely responsible for the content of this technical presentation. The technical presentation does not necessarily reflect the official position of the American Society of Agricultural and Biological Engineers (ASABE), and its printing and distribution does not constitute an endorsement of views which may be expressed. Technical presentations are not subject to the formal peer review process by ASABE editorial committees; therefore, they are not to be presented as refereed publications. Citation of this work should state that it is from an ASABE meeting paper. EXAMPLE: Author's Last Name, Initials. 2012. Title of Presentation. ASABE Paper No. 12----. St. Joseph, Mich.: ASABE. For information about securing permission to reprint or reproduce a technical presentation, please contact ASABE at rutter@asabe.org or 269-932-7004 (2950 Niles Road, St. Joseph, MI 49085-9659 USA).

Introduction

In England and Wales, the disposal of sewage sludge (biosolids) follows a number of routes which include, most importantly, recycling to farmland (72%), incineration (18%), land reclamation and restoration (6%), and landfill (1%) with a total production (dry solids basis) estimated at 1.6 million tonnes per year (Defra, 2007). This amount is set to increase in response to the growth of the population, the adoption of cleaner technology for the treatment of effluents and stringent legislation which restricts the opportunities for disposal. In most circumstances, the disposal route to farmland appears to be the least expensive available option, and it is widely accepted in Europe that recycling of organic materials, including biosolids, to land is the best practicable environmental practice (Edge, 1999). Recycling aims to complete the natural nutrients and carbon cycles (Taylor et al., 2009) while it mitigates the demand for finite resources such as rock phosphate (Weikard and Seyhan, 2009). A novel technique was proposed by United Utilities PLC in the UK for the production of organomineral fertilisers (OMF) from biosolids granules which adds additional nitrogen, in the form of urea (46% N), and potash (60% K₂O) to the biosolids' nutrients to form a balanced NPK fertiliser. This new product concept appears to be a sustainable approach to recycling biosolids to land; it has the potential to contribute significantly to overcome some of the problems commonly faced by land managers with regards to the use of organic materials in crop production; e.g. nutrients availability and concentration, fertiliser value, handling and storage, and the issues associated with field-spreading of bulky materials. A previous study (Antille, 2011) reported the use of this technique for the production of two OMF formulations; namely, OMF₁₀ (10:4:4) and OMF₁₅ (15:4:4). Following soil application of OMF, urea-N is released relatively rapidly whereas the organic-N fraction (biosolids-N) releases N at a slower rate. The content of phosphorus in the OMF corresponds to that of the biosolids-P which is mostly inorganic; i.e. Fe, Al, and Ca phosphates (Antille, 2011). The amounts of N and P released following soil application of OMF have not been quantified yet. There is, therefore, a need for a better understanding of the nutrients release characteristics following topsoil application of OMF which can contribute to improve nutrient management practices from organic-based fertiliser materials and mitigate unwanted effects on the environment. Earlier studies (Bowden and Hann, 1997; Cordovil et al., 2007) had also highlighted the need for a clearer understanding of the nutrients availability following application of organic materials to agricultural land. Soil incubation techniques have been extensively used for the assessment of nutrients availability from organic-based materials applied in crop production (e.g. Chescheir et al., 1986; Smith et al., 1998; Cordovil et al., 2005). Garau et al. (1986) highlighted that a possible disadvantage of these methods may be the occurrence of large concentrations of inorganic-N in non-leached systems which can disrupt the mineralisation process. This, in turn, can result in potentially mineralisable N content of organic amendments being underestimated. Fangueiro et al. (2008) employed an anaerobic incubation technique to determine the potential N mineralisation of fresh slurry samples and estimated the N balance on the basis of the NH₄⁺-N in the system. The aim of the study reported herein was to determine the availability of N and P from OMF₁₅ (15:4:4) following fertiliser application to the soil under controlled laboratory conditions. A key aspect of this study was to determine whether the application of OMF₁₅ induced significant changes in soil-P indexes while acknowledging the experimental conditions used. The development of a strategy for the application of OMF₁₅ to grass and arable crops will benefit from the results reported in this work. The objectives of this research are summarised below:

- To determine the release characteristics of OMF-N and -P under controlled laboratory conditions of temperature and soil moisture content, and
- To determine the effects of the soil application of OMF on soil P-index under the same environmental conditions indicated above.

Materials and Methods

Description of the soils

The experiment used two soil types; a sandy loam – *Cottenham series* (World Reference Base equates this to Arenosol), and a clay loam – *Holdenby series* (World Reference Base equates this to Cambisol) (King, 1969). Both soils had been under arable cropping with similar crop rotations and have had standard fertilisation regimes. Soil moisture content corresponding to field capacity was determined based on BS 7755 Section 5.5 (1999). Table 1 shows the results of the textural analysis, field capacity (% w w⁻¹) and soil bulk density (SBD) encountered for the soils in their natural state. SBD was required to estimate the amount of fertiliser added to the incubation pots.

Table 1: Soil textural analysis, moisture content corresponding to field capacity (mass basis) and soil bulk density for the two soils used in the incubation studies (Soil depth 0 – 300 mm).

Determination	Soil type and series	
	Clay loam (<i>Holdenby</i>)	Sandy loam (<i>Cottenham</i>)
Soil textural analysis		
% Sand	46	67
% Clay	25	13
% Silt	29	20
Field capacity (% w w ⁻¹ @0.05 bar)	30.4	26.6
Soil bulk density (t m ⁻³)	1.22	1.34

Fertiliser materials

The availability of N and P in OMF₁₅ (15:4:4) were compared with urea (46% N) and single superphosphate (0:18:0) respectively. The fertilisers were applied at rates equivalent to 0 (unfertilised control), 150 and 300 kg [N] ha⁻¹, and 150 and 300 kg [P₂O₅] ha⁻¹ for the study of N and P release characteristics respectively. The actual quantities of fertiliser applied to individual pots are shown in Tables 2a-b. All treatments, including the controls, were replicated four times.

Table 2a: Fertiliser quantities added to the incubation pots for the study of N availability from OMF₁₅.

Equivalent rate (kg [N] ha ⁻¹)	Fertiliser material (mg of product per pot)					
	Clay loam			Sandy loam		
	OMF ₁₅	OMF ₁₅	Urea	OMF ₁₅	OMF ₁₅	Urea
	Pilot study	1 st & 2 nd runs	-	Pilot study	1 st & 2 nd runs	-
0 (Control)	0	0	0	0	0	0
150	125.1	76.6	26.7	113.9	69.7	24.3
300	250.2	153.2	53.5	227.8	139.5	48.7

Table 2b: Fertiliser quantities added to the incubation pots for the study of P availability from OMF₁₅ [SSP: single super-phosphate (0:18:0)].

Equivalent rate (kg [P ₂ O ₅] ha ⁻¹)	Fertiliser material (mg of fertiliser product per pot)			
	Clay loam		Sandy loam	
	OMF ₁₅	SSP	OMF ₁₅	SSP
0 (Control)	0	0	0	0
150	340	68.3	309	62.2
300	680	136.6	618	124.4

The differences in the quantities of OMF₁₅ reported in the tables were due to the concentration of total-N in the two fertiliser batches produced and the differences in the amount of total fertiliser applied on the clay and the sandy loam soils were due to the values of soil bulk density encountered in each of the two soil types.

Soil incubation

Incubation pots of 0.25 litres capacity were filled with 200 g of air-dried soil previously ground to pass a 2 mm sieve, mixed with fertiliser and wetted-up with de-ionised water to reach field capacity. Subsequently, they were placed in an incubator in the absence of light and the temperature in the chamber adjusted to 25°C (Smith et al., 1998; Leytem, et al., 2004). Soil moisture content (SMC) was regularly replenished by adding de-ionised water on a mass basis (Smernik et al., 2004), and the soil maintained between field capacity (FC) and 75% of FC throughout the experiment. This technique has been satisfactorily used in earlier studies (e.g. Flavel and Murphy, 2006). The study was conducted for a period of 90 days following the guidelines given by OECD (2002).

Measurements and analyses

Soil sampling was conducted at the start of the experiment (before the application of the fertilisers), and every 30 days thereafter. This was non-destructive as the same pot and soil were used throughout the experiment over the 90 days period. For the study of N, the soil was analysed for determination of total-N (BS EN 13654-2, 2001) prior to the fertiliser application and at the end of the incubation period, and soil mineral nitrogen (MAFF, 1986) prior to the fertiliser application and every 30 days thereafter. For the study of P, only soil extractable phosphorus (BS 7755 Section 3.6, 1995) was determined every 30 days. The percentage N-available was calculated in relation to the total-N applied (Equation [1]) at 30, 60 and 90 days based on the approach of Kokkora et al. (2008). The same procedure was used to estimate availability of phosphorus (Equation [2]).

$$\% N_{available} = \frac{Mineral\ N\ fertilised\ soil - Mineral\ N\ control\ soil}{Total\ N\ applied} \times 100 \quad [1]$$

Where:

% *N_{available}* : Net nitrogen available in the soil determined at 30, 60, and 90 days after the fertiliser application.

Soil mineral nitrogen (SMN) includes NH₄⁺-N and NO₃⁻-N (Batey, 1988) for which both N fractions were computed for the calculation of total mineral N at any given time.

$$\% P_{available} = \frac{\text{Extractable P fertilised soil} - \text{Extractable P control soil}}{\text{Total P applied}} \times 100 \quad [2]$$

Where:

$\% P_{available}$: Net soil extractable phosphorus determined at 30, 60, and 90 days after fertiliser application. Soil extractable P was determined according to Olsen et al. (1954).

Summary of experimental design

The experiments comprised the use of two soil types (sandy loam and clay loam), two fertiliser types (OMF₁₅ vs. urea or OMF₁₅ vs. single superphosphate), and three fertiliser application rates (0 [control], 150 and 300 kg [N] or [P₂O₅] ha⁻¹ respectively). All treatments were replicated four times.

Statistical analyses

Statistical analyses were undertaken using GenStat Release 10.1 (2007) by applying repeated measurement of analysis of variance and the least significant differences to compare the means (LSD 5% level). The analyses conducted were graphically verified by means of residual plots; normalisation of the data was not required.

Results and Discussion

Initial soil analyses

Table 3 shows the results of the soil chemical analyses conducted prior to the start of the experiment which correspond to the baseline level.

Table 3: Soil analyses conducted prior to the start of the experiments in the laboratory (n=3)

Determination	Sandy loam	SD	Clay loam	SD
¹ Soil pH	6.9	0.24	6.2	0.19
² SOM (% w w ⁻¹)	3.8	<0.01	5.9	0.02
C:N ratio	11.4	0.35	10.6	0.17
³ SMN (mg kg ⁻¹)	14.6	0.14	31.1	0.58
⁴ Extractable P (mg kg ⁻¹)	72.4	1.18	79.9	0.98
⁴ Extractable P (mg l ⁻¹)	96.9	1.59	97.5	1.20
⁵ P-index	5	-	5	-
⁶ Total C (% w w ⁻¹)	1.80	0.14	1.83	0.01
⁷ Total N (% w w ⁻¹)	0.14	0.01	0.16	<0.01
⁸ Total P (mg kg ⁻¹)	1070.1	-	1326.3	-

Methods used: ^{1,2,3}MAFF (1986); ⁴BS 7755 Section 3.6 (1995), Olsen et al. (1954); ⁵MAFF (2000); ⁶BS 7755 Section 3.8 (1995); ⁷BS EN 13654-2 (2001); ⁸US EPA (____) Method No.: 3051 [Note: SD – standard deviation].

In general, the amounts of NH₄⁺-N recorded in the analyses were negligible compared with NO₃⁻-N which was an indication that the conversion of NH₄⁺ to NO₃⁻ occurred rapidly under the prevailing experimental conditions.

Nitrogen release characteristics

The results are presented in the form of soil mineral nitrogen (SMN) recorded at the time corresponding to the sampling event at 0, 30, 60 and 90 days respectively. Figures 1 and 2 show the mean values of SMN ($n=12$) recorded for each sampling event for the controls, urea- and OMF₁₅-amended soils respectively. These were obtained from a series of three incubation studies conducted in parallel and under the same experimental conditions. As expected, there were significant differences in SMN between the control and the fertilised soils ($p<0.001$). The statistical analysis showed that the interaction soil type \times time was not significant ($p=0.39$) which suggested that the soil type did not have a significant effect on the formation of SMN with respect to the time given the conditions of the study. The differences observed between the sandy loam and the clay loam soils ($p<0.001$) can be explained by the differences recorded initially in the overall fertility status of the two soils; in particular, the SOM levels (Table 3). Overall, there were significant differences with respect to the fertiliser type and the N application rate (p -values <0.001) which were not observed when factoring in the soil type (p -values >0.05). This suggested that the changes recorded in SMN as a result of the fertiliser type or the N application rate were of the similar order of magnitude in both soil types. The interaction fertiliser type \times N rate showed a significant effect ($p=0.009$) which was mainly due to the use of urea-N applied at 300 kg ha^{-1} . This effect was not observed when the incubation time, the soil type or the interaction time \times soil type were factored in (p -values >0.05). Overall, the effect of the fertiliser type was also significant with respect to the time ($p<0.001$); the soils treated with urea showed consistently larger SMN values than those that received OMF₁₅ throughout the experiment. This was more evident at 30 and 60 days respectively (*c.*17%-26% higher) than at 90 days when SMN levels in both treatments were approximately the same (*c.*165 mg [N] kg⁻¹ [soil] – mean values for the two soil types and N rates; $n=16$).

Gaseous losses of N by denitrification and/or volatilisation can result in errors when providing estimates of N availability of organic amendments determined by laboratory incubation techniques (Smith et al., 1998). However, Terry et al. (1981) indicated that these losses of N are usually low when biosolids are thoroughly mixed with the soil which was the case in this study. In agreement with Terry et al. (1981), and despite the nature of the fertiliser materials used in the experiment (containing urea-N), it is reasonable to assume that N losses by volatilisation were negligible given the conditions of the experiment and the soil incorporation of the fertilisers.

The accumulated thermal time (d°C; base temperature =0°C) can provide a link between data obtained in laboratory conditions and the patterns of mineral N formation that may be expected in-field conditions (Honeycutt et al., 1991; Smith et al., 1998). Based on the work of Smith et al. (1998), it was possible to correlate the data obtained in the incubation studies with that from the field. Soil temperatures reported by Antille (2011) at the College Farm at Cranfield University (Silsoe, UK) indicated that the accumulated thermal time for the period between 1st March and 30th June, which coincides approximately with the main growth period of winter cereal crops, was equivalent to 1593 d°C. This value was estimated based on the mean monthly soil temperatures recorded in 2008 and 2009 at a depth of 0.2 m. Taking a base temperature equivalent to 0°C, the incubated soils reached this accumulated thermal time approximately 60 days from the start of the experiment.

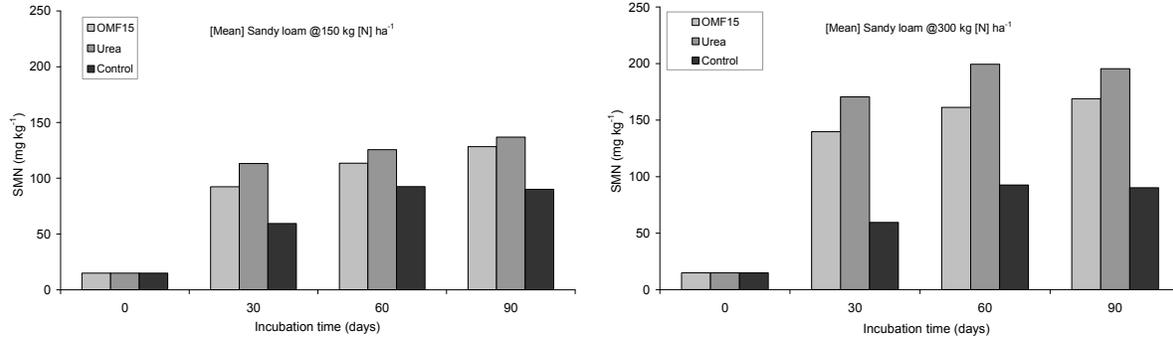


Figure 1: Mean soil mineral nitrogen content over the 90 days incubation period following application of urea and OMF₁₅ to the sandy loam soil; (*left*) 150 kg [N] ha⁻¹ and (*right*) 300 kg [N] ha⁻¹ (LSD_[5% level] =18.2; p=0.43; n=12).

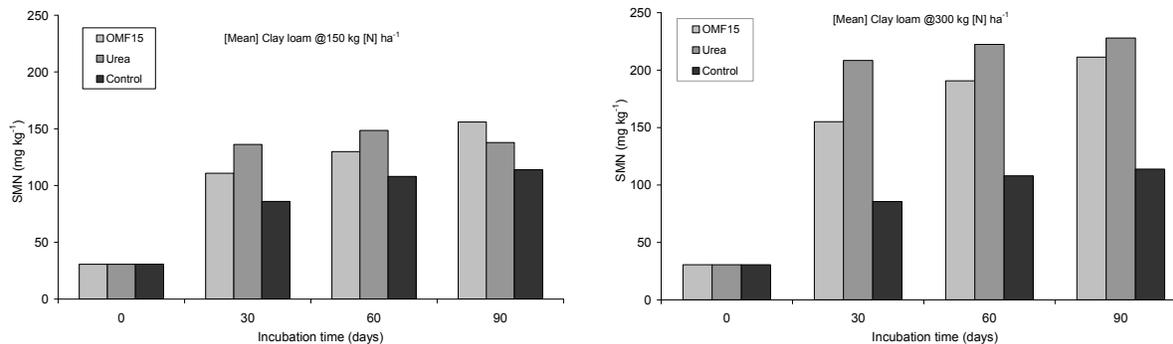


Figure 2: Mean soil mineral nitrogen content over 90 days incubation period following application of urea and OMF₁₅ to the clay loam soil; (*left*) 150 kg [N] ha⁻¹ and (*right*) 300 kg [N] ha⁻¹ (LSD_[5% level] =18.2; p=0.43; n=12).

From Figures 1 and 2, it is derived that the net amounts of SMN determined at this stage (60 days) in the incubated soils were equivalent to 19.5 mg [N] kg⁻¹ [soil] (or 48 kg [N] ha⁻¹), and 82.7 mg [N] kg⁻¹ [soil] (or 202 kg [N] ha⁻¹) for the clay loam soil fertilised with OMF₁₅ at 150 and 300 kg [N] ha⁻¹ respectively. For the sandy loam soil, the OMF₁₅ after 60 days from the fertiliser application yielded 21.1 mg [N] kg⁻¹ [soil] (or 56 kg [N] ha⁻¹) and 68.8 mg [N] kg⁻¹ [soil] (or 184 kg [N] ha⁻¹) when applied at 150 and 300 kg [N] ha⁻¹ respectively. This simple analysis of the data provides an indication that OMF₁₅ has, overall, some potential to supply relatively high amounts of N to the crop; in particular, when the fertiliser was applied at the highest N rate used in this study. In both soil types, OMF₁₅ required an accumulated thermal time of 2250 d°C to yield the percentages N available reported in Tables 4a-b at 90 days. As can be read off the tables, the majority of the N that was released from the OMF₁₅ became available within 30 days from the start of the experiment which was attributed to the rapid release of N from the OMF₁₅ fraction carrying urea. At this point in time (30 days from the fertiliser application), the accumulated thermal time was 750 d°C. Typically, the application of N to winter cereal crops in the UK is conducted during March and April. Based on the same temperatures records indicated earlier, the accumulated thermal time for these two months was 585 d°C. Unfortunately, it was not possible to produce accurate estimates of N available from the incubated soils corresponding to this thermal time with the information available as this falls earlier than the first sampling event conducted at 30 days. It is therefore acknowledged that soil sampling at shorter time intervals as well as immediately after the start of the experiment; e.g. days 0 to 7, would have provided a valuable indicator of the N transformations in the field.

The accumulated thermal time of 2250 d°C is likely to be reached in early August in-field conditions in Bedfordshire (UK) suggesting that mineralisation of OMF-N will continue beyond the senescence of the crop which has implications upon N management. On one hand, subsequent crops sown in early autumn may benefit from the residual N mineralised between pre- and post-harvest of wheat which could result in reduced N requirements for establishment of some crops in soils with relatively low soil N supply (SNS); e.g. SNS ≤ 2 (MAFF, 2000). On the other hand, unused N up until harvest is prone to leaching during the autumn; for example, for late sown crops or second winter wheat crops. Hence, the logistics of applying OMF₁₅ in early spring may be considered as part of a fertilisation strategy which should take account not only the N requirements of current crop but also the following in the rotation. Based on these results, it may be advisable to apply OMF₁₅ early in the spring to maximise the amount of fertiliser-N utilised by the current crop. When the total N rate is to be split into two applications; i.e. fertilisation rates in excess of 120 kg [N] ha⁻¹ (MAFF, 2000), the second N dressing may be done with a mineral N source and by adjusting it accordingly to the N requirement by the crop and the overall fertility of the soil at the time of the fertiliser application. Due to the scale and the characteristics of this experiment, this set of recommendations need to be validated with data obtained in real field conditions. Antille et al. (2009) reported that a first winter wheat crop fertilised with OMF₁₅ benefited from the combined application of mineral N and OMF in the first and second dressings respectively since the levels of grain yield obtained in OMF-treated crop were of similar order of magnitude to those that received mineral N only. The percentages available N (% of the total N applied with the fertiliser) obtained on average from the incubation studies are shown in Tables 4a and 4b for the clay loam and the sandy loam soils respectively. Despite the initial differences recorded in the levels of SOM (Table 3), the mean values of soil available N for the sandy loam soil over the 90 days incubation period were found to be comparable to those recorded for the clay loam soil. The incubation studies conducted by Cordovil et al. (2005) demonstrated that a sandy loam soil amended with organic materials initially underwent intense N mineralisation but after approximately 30 days from the start of the experiment the N mineralisation rate decreased significantly. This pattern of mineralisation had also been reported by El-Gharous et al. (1990) and it helps to explain the relatively high levels of N available encountered in the sandy loam soil. This soil was therefore able to sustain higher N mineralisation rates than the clay loam soil. Serna and Pomares (1992) reported values of N available (% of total N applied) in the range of c.14% to 46% for soils amended with air-dried sludge at rates of 28 g kg⁻¹ [soil] and maintained in incubators at 25°C (N-contents in the sludge in the range of 0.85% to 4.7% by weight and C:N ratios in the range of 6 to 13.5).

Table 4a: Percentage available N (% of total N applied with the fertiliser) for OMF₁₅ and urea treated soil recorded over time for the clay loam soil [*SD*: standard deviation].

Soil type	----- %N _{available} (% w w ⁻¹) -----			
	Clay loam			
	OMF ₁₅		Urea	
Fertiliser type				
Time/N-rate	150 kg [N] ha ⁻¹	300 kg [N] ha ⁻¹	150 kg [N] ha ⁻¹	300 kg [N] ha ⁻¹
30 days	40.5	56.6	81.6	99.9
60 days	35.6	67.3	65.8	93.0
90 days	68.4	79.4	39.3	93.0
Mean	48.2	67.7	62.2	95.2
<i>SD</i>	17.7	11.4	21.4	4.1

Table 4b: Percentage available N (% of total N applied with the fertiliser) for OMF₁₅ and urea treated soil recorded for the sandy loam soil [*SD*: standard deviation].

----- %N _{available} (% w w ⁻¹) -----				
Soil type	Sandy loam			
Fertiliser type	OMF ₁₅		Urea	
Time/N-rate	150 kg [N] ha ⁻¹	300 kg [N] ha ⁻¹	150 kg [N] ha ⁻¹	300 kg [N] ha ⁻¹
30 days	58.6	71.6	96.1	99.1
60 days	37.4	61.3	59.1	95.4
90 days	68.3	70.3	83.8	94.0
Mean	54.8	67.8	79.7	96.2
<i>SD</i>	15.8	5.6	18.7	2.6

Phosphorus release characteristics

Based on the values reported in Table 3, it is expected that soil extractable P to be unaffected by soil pH (Troeh and Thompson, 1993). The results of the incubation study for phosphorus are shown in Figures 3 and 4 for the sandy loam and the clay loam soils respectively. The values of soil extractable P, as reported from the soil laboratory, needed conversion from [w v⁻¹] to [w w⁻¹] which was done by multiplying by the corresponding value of soil bulk density given in Table 1 (Johnston, 1975). The statistical analysis showed that, after an incubation period of 90 days, the application of fertiliser to the soil significantly increased ($p < 0.001$) soil extractable P levels with respect to the unfertilised control soils. Significant differences in soil extractable P ($p < 0.001$) were found with respect to the soil type which was attributable to the overall higher fertility status of the clay loam compared with the sandy loam soil (mean values were 86.3 and 80.5 mg [P] kg⁻¹, respectively – $LSD_{[5\% \text{ level}]} = 0.95$). When the values were expressed in mg [P] L⁻¹, the sandy loam soil showed a statistically higher value of soil extractable P compared with the clay loam soil (mean values of 107.8 and 105.3 mg [P] l⁻¹; respectively – $LSD_{[5\% \text{ level}]} = 1.25$). This was due to the higher soil bulk density encountered in the sandy loam despite the relatively higher soil phosphorus status and SOM encountered initially in the clay loam soil. Significant differences in soil extractable P were found for the control and the treatments with respect to the fertiliser type ($p < 0.001$) and the phosphorus application rate ($p < 0.001$). Although the application of OMF₁₅ resulted in soil extractable P being marginally increased compared with the control, the overall effect of the fertiliser application was due to the use of single super-phosphate (SSP).

The application of OMF₁₅ did not induce a significant increase ($p > 0.05$) in soil extractable P levels compared with the unfertilised control soil (on average across the whole experiment). Mean values of soil extractable P across the whole experiment were 79.6, 80.1, and 88.6 mg [P] kg⁻¹ [soil] for the control, OMF₁₅ and SSP amended soils respectively ($LSD_{[5\% \text{ level}]}$ values of 1.29 for comparisons between the treatments and the control, and 1.06 for comparisons between the treatments respectively).

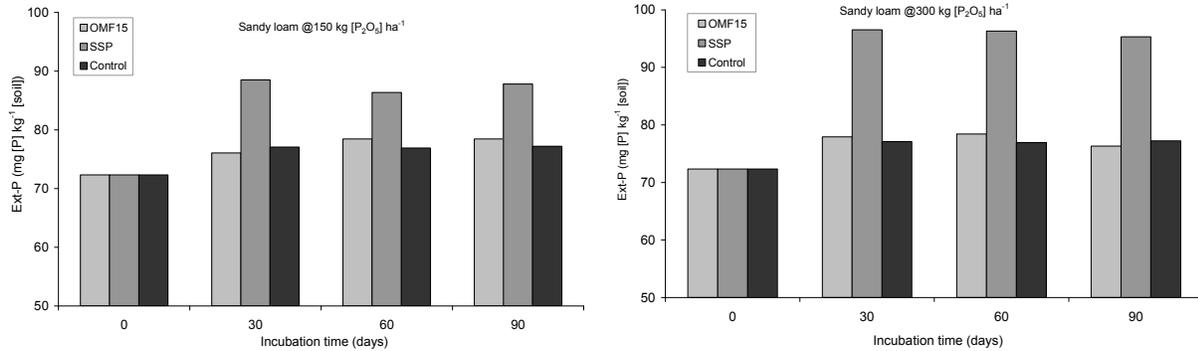


Figure 3: Soil extractable-P following application of single superphosphate (SSP) and OMF₁₅ to the sandy loam soil; (*left*) 150 kg [P₂O₅] ha⁻¹ and (*right*) 300 kg [P₂O₅] ha⁻¹ (LSD_[5% level] =3.46; p=0.70; n=4).

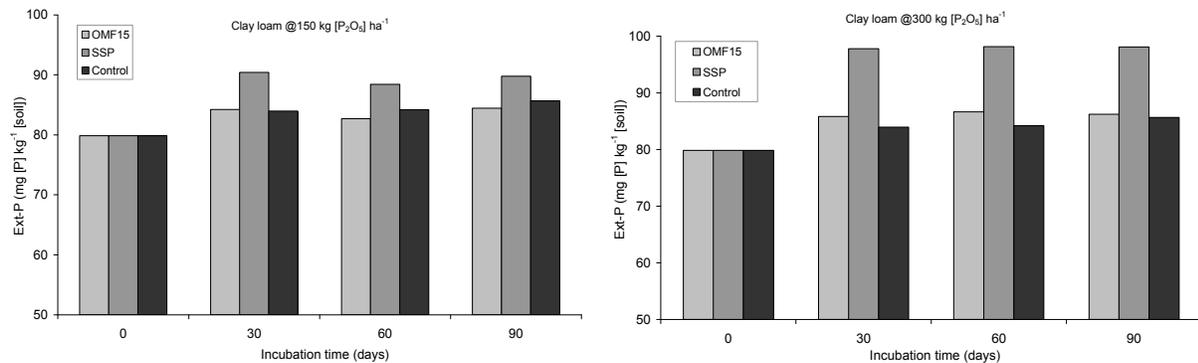


Figure 4: Soil extractable-P following application of single superphosphate (SSP) and OMF₁₅ to the clay loam soil; (*left*) 150 kg [P₂O₅] ha⁻¹ and (*right*) 300 kg [P₂O₅] ha⁻¹ (LSD_[5% level] =3.46; p=0.70; n=4).

The values of soil extractable P encountered in OMF₁₅-treated soil reflected the relatively low solubility of inorganic-P fractions present in the biosolids granules; hence, in the OMF₁₅. These are associated with the chemical removal of P from the wastewater effluent during the tertiary treatment. A commonly used process for phosphorus removal is by means of precipitation using FeCl₃ with phosphorus being subsequently incorporated into the sludge (Farrant et al., 2008). This process results in the formation of Fe-phosphates which are largely unavailable for plant up-take. Previous studies (de Haan, 1980; Lu and O'Connor, 2001) had also highlighted the effect of P removal by precipitation on the bioavailability of P as insoluble inorganic-P compounds are not readily available for plant up-take. These phosphorus fractions cannot be detected by routine soil analyses such as Olsen-P (Olsen et al., 1954); hence, the application of OMF₁₅-P to the soil did not induce an immediate change in soil extractable-P levels. Chemical analysis performed on samples of biosolids granules (Antille, 2011) indicated that the amount of water soluble-P was c.0.2% P₂O₅ (% w w⁻¹) which confirms that the majority of the phosphorus in the OMF₁₅ is therefore not readily available. Taylor et al. (1978) highlighted that the net availability of P following application of biosolids to the soil is controlled by chemisorption and precipitation reactions of P and mineralisation of organic-P. Similarly, following application of P fertilisers to the soil, phosphorus is dissolved in the soil-water and rapidly immobilised undergoing this type of reactions with the various soil constituents (Morgan, 1997).

The availability of P to crops is governed by the release of P from these reaction products to the soil solution (Morgan, 1997). This process appeared to have occurred following application of SSP resulting in some immobilisation of P which is supported by the fact that, despite SSP-P being 92%-94% water soluble-P (MAFF, 2000) not all the P added with SSP was subsequently detected in the soil analyses. The effect being more obvious in the clay loam soil (values of available-P in soil, as percentage of total-P added in the form of SSP, were c.15%-25% and 37%-46% for the clay loam and the sandy loam soil respectively). The phosphorus application rates used in this experiment were sufficiently high to allow this process to take place and also to increase significantly the concentration of phosphorus in the soil solution compared with both the control and the OMF₁₅ amended soils, as highlighted earlier. With regards to the phosphorus present in biosolids, EC (2003) stated that a small amount of organic-P in the form of organic phosphates, generally not exceeding 6% (w w⁻¹), may be found in sludges. This organic-P can contain organic-P species in the form of orthophosphate, pyrophosphate and polyphosphate (Hinedi et al. 1989; Cade-Menun and Preston, 1996; Smith et al., 2006). Although the organic-P in the OMF₁₅ was not quantified for this experiment, to some extent, it could have contributed to increase marginally soil extractable-P levels in OMF₁₅-amended soils compared with the unfertilised controls. Johnston and Syers (2006) suggested that when phosphorus is applied to the soil it is rapidly distributed between the various soil-phosphorus pools and, as a result, not all the P added with the fertiliser can be detected by standard soil analyses. According to the authors, the movement of phosphorus between the pools is a reversible process which is mainly driven by plant up-take. Based on their study, the application of SSP to the soil increased the concentration of P in the soil solution and the readily available pool, both of which are measured by standard soil analyses. In the absence of plant up-take, as it is the case in this experiment, the excess P in these pools is likely to move to the less readily available and the very slowly available pools. This occurs as a result of the high concentration in the soil solution and the readily available pools respectively following the application of SSP to the soil. There appeared to be an indication of this process taking place as some of the values of soil extractable-P encountered at days 60 and 90 were lower compared with those at day 30 from the start of the experiment. This, however, cannot be fully supported as they were not statistically different (p=0.70) and it could be due to differences derived from the analyses. In addition, P dynamics is relatively slow which makes it difficult to provide a clear understanding of this process in such a short experiment. Replenishment of P to the soil solution occurs through mechanisms involving dissolution and desorption reactions which include reaction products from recent phosphorus applied with fertilisers (mainly soluble-P) as well as soil phosphorus compounds from previous fertiliser-P applications (Morgan, 1997). Therefore, it is possible that solubilisation of Fe-phosphates can occur in the longer term which would allow to replenish the more readily available pools until the equilibrium between the pools is re-established. As highlighted earlier, the values of soil extractable-P as expressed in mg [P] L⁻¹ were used to determine soil-P indexes (MAFF, 2000). Overall, soil-P index was found to increase from 5 (initial level) to 6 in all treatments, including the control soils, after the 90 days incubation period. For all treatments, except for the sandy loam soil receiving SSP at 300 kg [P₂O₅] ha⁻¹, the change in soil P index was found to occur from the upper limit of index 5 to the lower limit of index 6, as shown in Table 5. The use of SSP resulted in soil extractable P being significantly increased (p<0.001) after 90 days from the application compared with the controls. The majority of the P released from SSP was available during the first 30 days from the start of the experiment. In-field conditions, this immediate increase in soil extractable P levels (following application of fertilisers containing P) may be counter-balanced by crop up-take in addition to the complex precipitation and adsorption reactions discussed earlier. Therefore, significant changes in the level of soil extractable P and soil-P index may be difficult to notice in the short term following fertiliser application; particularly, if P is not applied in excess of the crop requirement.

From the results of this experiment, it also appears that the availability of P derived from the use of OMF₁₅ may be sustained for several years following application. Wise (1999) stated that on this basis, the use of sludges is better justified to meet crop requirements for P of the whole crop rotation and not for individual years providing soil-P status was already satisfactory. With respect to the residual effect of fertilisers containing P, there is evidence (e.g. Kamprath, 1967; Spratt, 1978; Halvorson and Black, 1981-82; Morgan, 1997) which suggests that phosphorus from applied fertiliser can be utilised by crops in subsequent seasons following application; e.g. up 8 to 10 years post-application, that is, in the absence of losses of this applied phosphorus by mechanisms such as run off.

Table 5: Changes in soil-P index following application of OMF₁₅ and single super-phosphate (SSP) to the soil under controlled laboratory conditions ($p=0.61$; $LSD_{[5\% \text{ level}]} = 4.51$; $n=4$ except initial level $n=3$). Soil-P indexes 5 and 6 (range 71-100 and 101-140 mg [P] L⁻¹, respectively; MAFF, 2000). T: time in days from the application of the fertiliser. ^(*)Olsen-P (Olsen et al., 1954).

Soil type	Clay loam		Sandy loam	
	P (mg L ⁻¹) ^(*)	P index	P (mg L ⁻¹) ^(*)	P index
Initial level (T=0)	97.5	5	96.9	5
Control (T=90)	104.5	6	103.4	6
OMF ₁₅ @150 kg [P ₂ O ₅] ha ⁻¹ (T=90)	103.0	6	105.1	6
SSP @150 kg [P ₂ O ₅] ha ⁻¹ (T=90)	109.6	6	117.7	6
OMF ₁₅ @300 kg [P ₂ O ₅] ha ⁻¹ (T=90)	105.2	6	102.3	6
SSP @300 kg [P ₂ O ₅] ha ⁻¹ (T=90)	119.7	6	127.8	6

Tables 6a-b show the amount of phosphorus available in the soil as percentage of the total phosphorus applied with the fertiliser. The values presented in the tables were calculated by applying Equation 2. For the conversion of P into P₂O₅ a factor of 2.291 was used (MAFF, 2000). The net value was obtained by subtracting the value of soil extractable P corresponding to the control soil to that of the treatment.

Table 6a: Phosphorus available in the soil as percentage of the total phosphorus applied with the fertiliser for the clay loam soil [SSP: single super-phosphate].

Soil type	----- %P ₂ O ₅ (% w w ⁻¹) -----			
	Clay loam			
	OMF ₁₅		SSP	
Fertiliser type				
Time/P-rate	150 kg [P ₂ O ₅] ha ⁻¹	300 kg [P ₂ O ₅] ha ⁻¹	150 kg [P ₂ O ₅] ha ⁻¹	300 kg [P ₂ O ₅] ha ⁻¹
30 days	1.0	3.5	24.1	25.8
60 days	-5.6	4.6	15.7	26.0
90 days	-4.6	1.1	15.3	23.2

Table 6b: Phosphorus available in the soil as percentage of the total phosphorus applied with the fertiliser for the sandy loam soil [SSP: single super-phosphate].

----- %P ₂ O ₅ (% w w ⁻¹) -----				
Soil type	Sandy loam			
Fertiliser type	OMF ₁₅		SSP	
Time/P-rate	150 kg [P ₂ O ₅] ha ⁻¹	300 kg [P ₂ O ₅] ha ⁻¹	150 kg [P ₂ O ₅] ha ⁻¹	300 kg [P ₂ O ₅] ha ⁻¹
30 days	-4.1	1.7	46.8	39.8
60 days	6.4	3.1	38.7	39.7
90 days	5.0	-1.8	43.4	37.1

As can be read from the table, the application of OMF₁₅-P to the soil resulted in relatively low percentages of phosphorus available (relative to the total-P applied). This effect was observed in both soil types to approximately the same extent. For SSP-P, the percentage of phosphorus available was found to be higher in the sandy loam soil compared with the clay loam soil which was expected due to the higher SOM and clay contents. O'Connor et al. (2004) indicated that biosolids that had undergone biological phosphorus removal but that had been supplemented with Fe and Al showed low phytoavailability (<25% of the phytoavailability of that encountered with triple superphosphate) which appears to be in agreement with the results shown in the table for OMF₁₅-P.

Conclusions

- Nitrogen availability:
 - The greatest rate of N release from OMF₁₅ (% of the total-N applied), occurred in the first 30 days following soil application. It ranged between 59% and 72% in the sandy loam, and between 40% and 57% in the clay loam soil depending on the N application rate. A further 10% increase in the percentage N available, and between 23% and 28% were subsequently recorded in the sandy loam and the clay loam soils respectively.
 - The greatest rate of N release from urea (% of the total-N applied), also occurred in the first 30 days following soil application. It ranged between 96% and 99% in the sandy loam, and between 82% and 99% in the clay loam soil depending on the N application rate; SMN remained relatively constant thereafter. Overall, SMN was significantly higher in urea- compared with OMF₁₅-treated soils.
 - An accumulated thermal time of 2250 d°C was needed for OMF₁₅ to release between 68% and 70%, and between 68% and 79% of the total-N applied in the sandy loam and the clay loam soils respectively depending on the N application rate. This accumulated thermal time is likely to be reached in early August in-field conditions which suggested that mineralisation of the organic-N fraction in the OMF would progress after the harvest of winter cereal crops.
- Phosphorus availability:
 - Phosphorus availability from OMF₁₅ (% of the total-P applied) was low throughout the experiment. It ranged from -4.1% to 6.4% in the sandy loam and from -5.6% to 4.6% in the clay loam soil. The negative values recorded indicated that the availability of P was reduced in the treated soils compared with the control. The relatively low availability of OMF-P was attributable to the technique used for the removal of phosphorus during the wastewater treatment process.

- Despite the generally low availability of applied OMF-P, a change in soil-P index from 5 to 6 was observed but the overall increase in soil extractable-P was marginal and it remained close to the initial levels recorded in both soils. For single superphosphate, the availability of P (% of the total-P applied) was significantly higher than that of OMF₁₅-P. It ranged from 37% to 46% in the sandy loam, and from 16% to 26% in the clay loam soil. The application of SSP induced a significant increase in soil extractable P levels compared with the unfertilised soils. As a result, soil-P index changed from 5 to 6 in both soil types. This was expected given its high water solubility (92%-94% water soluble-P).

Acknowledgements

Acknowledgements are due to United Utilities PLC, The Engineering and Physical Science Research Council (EPSRC, UK), the Soil and Water Laboratory at Cranfield University (UK), and Teagasc Environmental Research Centre (Ireland). The contribution made by A E Johnston (Rothamsted Research, UK) and S T J Lalor (Teagasc Johnstown Castle) is much appreciated.

References

- Antille, D.L., 2011. Formulation, utilisation and evaluation of organomineral fertilisers. Unpublished Engineering Doctorate Thesis, School of Applied Science, Cranfield University, Cranfield, MK43 0AL, UK.
- Antille, D.L., Sakrabani, R., and Godwin, R.J., 2009. Organomineral fertilisers: nutrient dynamics and evaluation of agronomic characteristics. Proceedings of the American Society of Agricultural and Biological Engineers (ASABE) – Annual International Meeting, Reno, NV. [Paper No.: 095981]. St. Joseph, MI (49085-9659) 21-24 June 2009.
- Batey, T., 1988. Soil husbandry: a practical guide to the use and management of soils. Soil and Land Use Consultants Ltd., Aberdeen, AB9 8GF.
- Bowden, W., and Hann, M.J., 1997. The availability of nitrogen following digested sludge incorporation in arable land. *Nutrient Cycling in Agroecosystems* 47: 167-172.
- BS 7755 Section 3.6, 1995; British Standard 7755 Section 3.6, 1995. Determination of phosphorus-Spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution. Equivalent to ISO 11263:1994. BSI (The British Standards Institution), London, W4 4AL, UK.
- BS 7755 Section 3.8, 1995; British Standard 7755 Section 3.8, 1995. Soil quality. Chemical Methods. Determination of organic and total carbon after dry combustion (elementary analysis). Equivalent to ISO 10694:1995. BSI (The British Standards Institution), London, W4 4AL, UK.
- BS 7755 Section 5.5, 1999; British Standard 7755 Section 5.5, 1999. Determination of water retention characteristics – Laboratory methods. Equivalent to ISO 11274:1998. BSI (The British Standards Institution), London, W4 4AL, UK.
- BS EN 13654-2, 2001; British Standard EN, 2001. Soil improvers and growing media. Determination of nitrogen. Dumas method. Equivalent to ISO 5725:1994. BSI (The British Standards Institution), London, W4 4AL, UK.
- Cade-Menun, B.J., and Preston, C.M., 1996. A comparison of soil extraction procedures for ³¹P NMR spectroscopy. *Journal of Soil Science* 161: 770-785.

- Chescheir, G.M. III, Westerman, P.W., and Safley, L.M. Jr., 1986. Laboratory methods for estimating available nitrogen in manures and sludges. *Agricultural Wastes* 18: 175-195.
- Cordovil, C.M.D.S., Cabral, F., and Coutinho, J., 2007. Potential mineralization of nitrogen from organic wastes to ryegrass and wheat crops. *Bioresource Technology* 98: 3265-3268.
- Cordovil, C.M.d.S., Coutinho, J., Goss, M., and Cabral, F., 2005. Potentially mineralisable nitrogen from organic materials applied to a sandy loam soil: fitting the one-pool exponential model. *Soil Use and Management* 21: 65-72.
- Defra, 2007; Department for Environment, Food, and Rural Affairs, 2007. Waste strategy for England 2007. PB12596. Accessed 16 March 2010. <http://www.defra.gov.uk/environment/waste/strategy/strategy07/documents/waste07-strategy.pdf>
- de Haan, S., 1980. Sewage sludge as a phosphate fertiliser. In: Hucker, T.W.G., and Catroux, G., 1980 (Ed). Phosphorus in sewage sludge and animal waste slurries. Proceedings of the EEC Seminar organised jointly by the CEC (Commission of the European Communities) and the Institute for Soil Fertility (Haren, The Netherlands). 12-13 June 1980, GrÖningen, The Netherlands. D. Reidel Publishing Company, 149pp.
- EC, 2003; European Commission, 2003. Draft discussion document for the ad-hoc meeting on biowastes and sludges [Brussels, 15-16 January 2004]. Directorate General Environment. Directorate A- Communications, Governance, Production, Production, Consumption and Waste. E.N.V.A.2 - Production, Consumption & Wastes. DG ENV. A2/LM. Accessed 25 Sept. 2008. http://www.ewaonline.de/downloads/WD_sludge.pdf
- Edge, D., 1999. Perspectives for nutrient removal from sewage sludge and implications for sludge strategy. *Environmental Technology* 20: 759-763.
- El-Gharous, M., Westerman, R.L., Soltanpour, P.N., 1990. Nitrogen mineralisation potential of arid and semi-arid soils of Morocco. *Soil Science Soc. of America Journal* 54: 438-443.
- Fangueiro, D., Chadwick, D., and Bol, R., 2008. Assessment of the potential N mineralization of different particle-size fractions in two dairy cattle slurries. *Journal of Plant Nutrition and Soil Sciences* 171: 1-3. (Short communication).
- Farrant, L., Le, M.S., Phipps, D., and Al-Khaddar, R., 2008. A new carbon source from sewage sludge. Proceedings of the 13th European Biosolids and Organic Resources Conference, Workshop and Exhibition organised by Aqua-Enviro Technology Transfer. Manchester, UK, 10-12 November 2008.
- Flavel, T.C., and Murphy, D.V., 2006. Carbon and nitrogen mineralization rates after application of organic amendments to soil. *Journal of Environmental Quality* 35: 183-193.
- Garau, M.A., Felipó, M.T., and Ruiz de Villa, M.C., 1986. Nitrogen mineralization of sewage sludge in soils. *Journal of Environmental Quality* 15: 225-229.
- GenStat Release 10.1 [10th Edition PC/Windows XP] Copyright, 2007. Lewes Agricultural Trust (Rothamsted Experimental Station, Harpenden, AL5 2JQ, UK). Registered to Cranfield University-Silsoe, MK45 4DT, UK.
- Halvorson, A.D., and Black, A.L., 1981-82. Long-term benefits from a single application of P. *Better Crops Plant Food* 66: 33-35.
- Hinedi, Z.R., Chang, A.C., Lee, R.W.K., 1989. Characterisation of phosphorus in sludge extracts using phosphorus-31 nuclear magnetic resonance spectroscopy. *Journal of Environmental Quality* 18: 323-329.

- Honeycutt, C.W., Potaro, L.J., and Halteman, W.A., 1991. Predicting nitrate formation from soil, fertilizer, crop residue, and sludge with thermal units. *Journal of Environmental Quality* 20: 850-856.
- Johnston, A.E., 1975. The Woburn Market Garden experiment, 1942-69. II: Effects of the treatments on soil pH, soil carbon, nitrogen, phosphorus and potassium. Rothamsted Experimental Station Report for 1974 Part 2; pp 102-131.
- Johnston, A.E., and Syers, J.K., 2006. Changes in understanding the behaviour of soil and fertiliser phosphorus: implications for their efficient use in agriculture. Proceeding No.: 589 of The International Fertiliser Society, York, YO32 5YS, UK.
- Kamprath, E.J., 1967. Residual effect of large applications of phosphorus on high phosphorus fixing soils. *Agronomy Journal* 59: 25-27.
- King, D.W., 1969. Soils of the Luton and Bedford Districts: a reconnaissance survey. The Soil Survey of England and Wales, Harpenden, UK.
- Kokkora, M.I., Hann, M.J., and Godwin, R.J., 2008. The use of vegetable and bio-waste compost: effects on forage maize production and soil properties. Proceedings of ASABE (American Society of Agricultural and Biological Engineers), St. Joseph, MI (49085-9659), US. [Paper No.: 083514].
- Leytem, A.B., Sims, J.T., and Coale, F.J., 2004. Determination of phosphorus source coefficients for organic phosphorus sources: laboratory studies. *Journal of Environmental Quality* 33: 380-388.
- Lu, P., and O'Connor, G.A., 2001. Biosolids effects on phosphorous retention and release in some sandy Florida soils. *Journal of Environmental Quality* 30: 1059-1063.
- MAFF, 1986; Ministry of Agriculture, Fisheries and Food, 1986. The analysis of agricultural materials. Reference book 427. 3rd Edition. The Stationery Office, London.
- MAFF, 2000; Ministry of Agriculture, Fisheries and Food, 2000. Fertiliser recommendations for agricultural and horticultural crops (RB209). 7th Edition. The Stationery Office, London.
- Morgan, M.A., 1997. The behaviour of soil and fertiliser phosphorus. Chapter 6. In: Tunney, H., Carton, O.T., Brookes, P.C., and Johnston, A.E., 1997 (Eds). Phosphorus loss from soil to water. CAB International, Oxon, OX10 8DE, UK.
- OECD, 2002; Organization for Economic Co-operation and Development, 2002. OECD guidelines for the testing of chemicals. Section 3: degradation and accumulation. Test No.: 307. Aerobic and anaerobic transformations in soil. 1-17pp. Accessed 30 Apr. 2009. <http://puck.sourceoecd.org/vl=1597167/cl=26/nw=1/rpsv/cw/vhosts/oecdjournals/1607310x/v1n3/contp1-1.htm>.
- O'Connor, G.A., Sarkar, D., Brinton, S.R., Elliot, H.A., and Martin, F.G., 2004. Phytoavailability of biosolids phosphorus. *Journal of Environmental Quality* 33 (2): 703-712.
- Olsen, S.R., Cole, C.V., Watanabe, F.S., and Dean, L.A., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular No.: 939.
- Serna, M.D., and Pomares, F., 1992. Nitrogen mineralization of sludge-amended soil. *Bioresource Technology* 39: 285-290.
- Smernik, R.J., Oliver, I.W., and McLaughlin, M.J., 2004. Changes in the nature of sewage sludge organic matter during a twenty one month incubation. *Journal of Environmental Quality* 33: 1924-1929.

- Smith, K., Dobbie, K., Thorman, R., Yamulki, S., 2006. WP2 The effect of N fertiliser forms on nitrous oxide emissions. Component report for Defra Project NT2605 (CSA 6579). February 2006. Accessed 05 April 2010. <http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=11983>
- Smith, R.S., Woods, V., and Evans, T.D., 1998. Nitrate dynamics in biosolids-treated soils: I. Influence of biosolids type and soil type. *Bioresource Technology* 66: 139-149.
- Spratt, E.D., 1978. Residual fertiliser P benefits wheat and oilseed rape production. *Better Crops Plant Food* 62: 24-26.
- Taylor, J.M., Newell-Price, J.P., and Chambers, B.J., 2009. Recycling organic resources to land: risk assessment for organic chemicals. Proceedings of the 14th European Biosolids and Organic Resources Conference and Exhibition. Aqua-Enviro Technology Transfer, Leeds, UK, 9-11 November 2009. [Paper No.: 033].
- Taylor, J.M., Sikora, L.J., Tester, C.F., and Parr, J.F., 1978. Decomposition of sewage sludge compost in soil: II. Phosphorus and sulphur transformations. *Journal of Environmental Quality* 7: 119-123.
- Terry, R.E., Nelson, D.W., and Sommers, L.E., 1981. Nitrogen transformations in sewage sludge-amended soils as affected by environmental factors. *Soil Science Society of America Journal* 45: 506-513.
- Troeh, F.R., and Thompson, L.M., 1993. *Soils and soils fertility*. 5th Edition. Oxford University Press, NY.
- US EPA, ____; US Environment Protection Agency, _____. Method 3051 – Microwave assisted acid digestion of sediments, sludges, soils and oils. (Equivalent to British Standard BS 7755: Section 3.13:1998 and ISO11047:1998). Accessed 18 May 2008. <http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/3051a.pdf>
- Weikard, H.P., and Seyhan, D., 2009. Distribution of phosphorus resources between rich and poor countries: the effect of recycling. *Ecological Economics* 68: 1749-1755.
- Wise, S.W., 1999. A systems approach to the recycling of wastewater sludge phosphorus in agriculture. Unpublished Engineering Doctorate Thesis, Cranfield University at Silsoe, Institute of Agri-Technology, Silsoe, MK45 4DT, UK.