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A Literature Review on the Availability of Phosphorus from Compost in Relation to the Nitrate Regulations SI 378 of 2006

Small-Scale Study Report

Prepared for the Environmental Protection Agency

by

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Executive Summary

The Statutory Instrument (SI) 378 of 2006 gives recommendations of nutrient input for a range of horticultural and agricultural crops. The recommended rates of phosphorus (P) are based on a soil phosphorous test. The availability of phosphorus from pig, poultry, cattle and other livestock manure, spent mushroom compost are accepted as from inorganic fertiliser (superphosphate). The SI has given the availability of phosphorus from compost the same availability of phosphorus from cattle manure. However, there is a possibility of special derogation if data can be provided regarding release rate from compost. This report reviewed literature and has determined the release rate of phosphorus from compost.

In order to define application rates and codes of practice for compost use to obtain optimum crop growth, it is essential to be able to predict the fertiliser effect of the compost and the availability of the nutrients contained relative to conventional inorganic fertilisers. There is an obvious problem where nutrient availability is underestimated in that this could result in nutrient overloading of the soil with the potential to pollute ground and surface water.

From the literature review of over 100 scientific publications and consultation with experts from Austria and the UK, the following may be concluded:

- There are limited publications available on the P availability from composts, as it has not been studied in great depth in comparison to the large number of publication available on the availability of N.
- The availability of phosphorus from compost was determined after reviewing publications on pot trials, incubation trials, field trials and leaching trials. Based on the information from the publications the author made a judgement on the approximate availability of phosphorus from different types of compost in Table 1.

Table 1. Proposed phosphorus availability from various composts made from different feedstock relative to superphosphate

Type of Compost	Relative availability when superphosphate is 100%
Spent Mushroom Compost	100
Manure	90
Sewage Sludge	85
SSBW	75
SSGW	60

- Phosphorus content of compost can vary considerably and can is dependent on feedstock.
- Phosphorus availability from compost is much higher than nitrogen availability from compost (Prasad, 2009) and is in the range of 60 to +100% as superphosphate equivalent.
- Release of compost P can be affected by feedstock. For example, the release of P from composted green waste is 60% of that of superphosphate, whilst composted poultry manure has the same availability as superphosphate.
- The release rate is affected by the biological stability of the compost, with stable compost having lower levels of water-soluble P. Water soluble P is the main pathway of P leaching in the environment.
- The release of P from compost is in a slow release form.

- The amount of P released as a percentage of total P can vary from 3% to 22% over two years.
- Information on the effect of compost application on soil test P (plant available P) is limited. The quantity of P that is extractable by different soil test extractants is also generally lacking.

Recommendations

- There is a need to emphasise the interdependency of P and N in compost in the SI 376. It is not nitrate leaching from compost that could be a potential problem from compost application; rather it is P that could be potential problem.
- Better characterisation of compost P is needed: including identification of organic P, inorganic P into different fractions which are inorganic P and organic P, water-soluble P and labile P.
- Routine laboratory tests need to be developed to predict compost P availability from different types of compost.
- The effect of the P content from compost on the soil test P (Morgan's[1] and Olsen's[2] extract methods) needs to be determined.
- There is a need to study the effect of composting on P availability from composts made from different feedstocks and the effect of stability on P availability.
- Long-term field trials (>5 years) on different soils using compost are needed to establish the P availability from compost.
- In view of lack of data on P availability from composts and to stay on the side of caution it is strongly recommend that when compost is applied to land soil test P levels should be measured every year. If the soil test value goes up by one unit, application of compost should be terminated on that part of land.
- Beside compost as a source of nutrients, it also has other properties which other organic fertilisers do not have as a source of stabilised organic matter, disease suppression properties, improved water retention. As such all types of compost should be given as separate classification as a 'soil conditioner' as opposed to being just a fertiliser source.
- Up to 1 January 2011, there is a temporary rule in which more phosphorus can be applied on land than crops require, as long as it comes from manure produced by pigs, poultry or from spent mushroom compost and that the 170kg nitrogen is not exceeded. This rule should be extended to include all types of source-separated compost.
- This report must be read in conjunction with "*A Literature Review on the Availability of Nitrogen from Compost in Relation to the Nitrate Regulations SI 378 of 2006*" (Prasad, 2009), as the available of nitrogen and phosphorus are required for compliance with SI 378 of 2006.

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[1] Exactrant made of 0.54M acetic acid + 0.7M sodium acetate pH 4.8.

[2] Exactrant made of 0.5M sodium bicarbonate pH 8.5

1. Introduction

This was carried out as part of the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme 2007–2013. The project, titled *A Literature Review on the Availability of Phosphourus from Compost in Relation to the Nitrate Regulations SI 378 of 2006* (Ref. 2006--SS-55), was a desktop literature review study. The project titled *A Literature Review on the Availability of Phosphorus from Compost in Relation to the Nitrate Regulations SI 378 of 2006* (Ref 2006-SS-56) was a desktop literature review study. This study provides information which would useful for drawing plans for Nutrient Management. Nutrient Management provides information on crop requirement in relation to the application of fertilisers to promote the growth of a crop which means the amount and type of fertilisers which are reasonable to apply to soil for the purpose of promoting growth of the crop having regard to foreseeable nutrient supply available to the crop from the fertilisers, the soil and from other sources.

The Nitrates Directive (91/676/EEC) – Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources was adopted in 1991 and has the objective of reducing water pollution caused or induced by nitrates from agricultural sources. The Directive has been implemented in Ireland since 1991 by way of extensive monitoring of nitrate levels in waters, the assessment of the trophic status of waters, the development and dissemination in 1996 of a Code of Good Agricultural Practice to Protect Waters from Pollution by Nitrates and a range of other measures which operate to protect water quality from pollution by agricultural sources.

Ireland's national Nitrates Action Programme was given statutory effect by the European Communities (Good Agricultural Practice for Protection of Waters) Regulations (SI 378 of 2006) 2006 which were made on 19 July 2006. These Regulations provide strengthened statutory support for the protection of waters against pollution from agricultural sources e.g. by phosphorus or nitrogen. The Regulations require the avoidance of careless practices by farmers, which create a risk of causing pollution and provide for inspections by local authorities.

New Nitrates Regulations (SI 101 of 2009) have been signed into law by the Minister for the Environment, Heritage and Local Government. The European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2009 revise and replace the previous Regulations made in 2006 and 2007.

1.1 Background

Phosphorus and Forms

Phosphorus is an essential element for plant growth and its input has long been recognised as essential to maintain economically viable levels of crop production. In agricultural systems P is needed for the accumulation and release of energy associated with cellular metabolism, seed and root formation, maturation of crops (especially cereals), crop quality and strength of straw in cereals. In natural (i.e. non-agricultural) systems, P is recycled to soil in litter, plant residues and animal remains (Brogan *et al.*, 2001).

However, in agricultural systems P maybe removed in the crop or animal product. Chemical P fertilisers, crops and feed supplements are imported into agricultural systems to increase and maintain productivity (Haygarth, 1997). The need to supplement soils with water-soluble P fertilisers arises because the relatively small pool of native soil P is unable to supply and maintain adequate amounts of soluble orthophosphate (H_2PO_{4-} and HPO_4^{2-}) to soil solution for satisfactory crop growth.

Phosphorus exists in soils either in the dissolved (i.e. solution) or solid form (particulate P), with the solid form being dominant. Dissolved P is typically less than 0.1 percent of the total soil P and usually exists as ortho-phosphate ions, inorganic polyphosphates and organic P (Magette and Carton, 1996). Phosphorus must be in solution before it can be absorbed by plant roots. After absorption into the plant, much of the phosphate reacts very quickly to form organic compounds (Wild, 1988). In a mineral soil, typically 20% to 80% the total soil P is in the organic form (Dalal, 1977).

Organic P compounds undergo ineralization (into inorganic forms) and immobilisation with the aid of soil bacteria and growing plants (Magette and Carton, 1996).

Phosphorus in solid form can be classified as:

- inorganic P (i.e. bound to Al, Fe, and Ca); and
- organic P (P bound to organic material. Such as dead and living plant material and micro-organisms, soil organic matter etc). Organic P compounds are largely phosphate esters. About half of the organic P fractions consists of unidentified compounds.

P exists in soils as an extremely active chemical element and up to 170 different phosphate-supplying minerals have been identified in soils. These vary greatly in their reactivity and solubility (Finkl and Simonson, 1979). Different forms of P are also partitioned between soluble P, labile soil P and non-labile soil P. Soluble P represents P in the soil solution which is readily extracted with either water or a weak salt solution. Labile P describes forms of P which are chemically mobile, exchangeable and reactive in soil and water. Labile P can replenish the soil solution P concentrations for uptake of P by the crop. The soluble P fraction measures the concentration of ortho-phosphate ions in solution, i.e. ($H_2PO_4^-$ and HPO_4^{2-}) and it is generally believed that plants take up P as HPO_4^{2-} .

The generally small quantity of P in soils, its immobility, and its tendency to form relatively insoluble forms causes P fertilisation practices to differ somewhat from those for Nitrogen (N) and Potassium (K) fertilisation. Upon dissolving in the soil, fertiliser P reacts with soil components to form a variety of compounds which may be only slowly available to plants. The identification of some of these soil applied P application products (e.g. $AlPO_4.2H_2O$, $FePO_4$. $2H_2O$,$Ca_8H_2(PO_4)_6$ $Ca_8H_2(PO_4)_65H_2O$) have helped to provide a better understanding of the fate of P added to soils (Lindsay and Vlek, 1977).

There has been a huge increase in the use of phosphorus fertilisers in Ireland since 1960, and this has resulted in a ten-fold increase in concentration of P detected in soil test P in the past 50 years (Kiely *et al.*, 2007). Uncontrolled application of compost will result in a further deterioration of the situation.

Movement of Phosphorus

Transport of soil P occurs primarily via surface flow, although the background levels of P entering streams and lakes via sub surface flow certainly reflect the impact of landuse. Water flowing across the soil surface can dissolve and transport soluble P, or erode and transport particulate P. Soluble P can be either inorganic or organic, while particulate P generally consists of finer sized soil particles e.g. clay and lighter organic matter. If however excessive P is applied, the level of soluble P is of great importance. There is general acceptance that diffuse leakage of P from soils can occur and may be contributing to water quality deterioration in Ireland (Brogan *et al.,* 2001).

Phosphorus and Compost

Phosphorus added to soil in organic wastes or crop residues, represent an important source of P for plant growth, as well as a potential source of soluble P which may be lost in runoff or leaching. Fresh plant residues may quickly release P in soil, where as more stable forms of organic matter (such as composts) generally act as long-term slow release sources of P. Accurate determination of compost mineralization is necessary for users to comply with a nutrient management plan. Nutrient management plans require that fertiliser equivalents of manures and composts be used when determining the total nutrient application to soils. For years, N was the only nutrient of concern but in recent years, soil P levels, especially in Ireland, have risen greatly and information on P availability from compost is thus necessary. There are few studies done to unravel the availability of phosphorus in composts.

The loading, solubility, mobility, and plant availability of P from compost applied to land is a growing environmental concern to regulators and planners of nutrient management plans. P has been identified as an uncontrolled pollutant from animal agriculture (Magette *et al.,* 2007).

The type of organic wastes composted and the method of composting may affect the P availability in compost to plants. Accurate prediction of P availability and plant P recovery may help tailor compost applications to plant needs and minimize the build-up of bioavailable P which can contribute to eutrophication of sensitive water courses (Magette *et al.,* 2007).

Other Benefits Attributed to Compost Use in Soils

Recently the European Commission Joint Research Centre published a report "End of Waste Criteria"[3]. In this report it outlines the many other benefits attributed to the use of compost in soils. These comments are summarised as follows;

Ongoing decline of organic matter in soils as a result of agricultural activities is a well-known phenomenon and is depicted as one of the main threats to soil within the documents of the European Soil Strategy[4]. In many sections of the EU Soil Strategy papers, the need of combating EU soil's organic matter depletion also by adding organic matter in form of compost is stated.

The current draft Soil Framework Directive (SFD), Member States will be obliged to establish programmes for combating organic matter decline in priority areas. Consequently, organic matter substitution by compost use will be one of the promoted and recognised measures.

Humus also stores some of the biomass carbon, contained in compost, in soil for longer periods of time. This carbon can be considered sequestered (locking up carbon in soils) from the atmosphere, which acts against global warming and climate change. Composting and the production and use of compost can have a major role in helping Ireland implement its Climate Change Strategy.

Other potential positive environmental effects which have been attributed to compost include:

- Reduced soil erosion
- Compost of a good quality (i.e. meets a quality standard) may help to control soil borne plant diseases and thus reduce the need for applying agricultural chemicals.
- Water retention is improved, reducing the need for irrigation and reducing the risk of flooding
- The improved soil structure reduces the need to work the soil with agricultural machinery and the related use of fuel.

When compost can be used instead of peat in growing media, there is also a lower global warming potential, mainly because peat degrades relatively quickly under the release of 'long cycle' CO_2 when exposed to oxygen.

[3] Anon. (2009) *End of Waste Criteria* Report. European Commission Joint Research Centre, Seville.
[4] http://ec.europa.eu/environment/soil/index.htm

Replacing peat also plays a part in the protection of the biodiversity and landscape of peatlands (Anon., 2009).

Separate Classification for Compost

SI 378 of 2006, it states that if compost is applied onto land for two years in a row, the nitrogen index[5] is reduced by 1. This means that a farmer gets penalised for using compost, even though it has lower availability of nutrients e.g. nitrogen compared to other ‘organic fertilisers’ such as manure.

Beside compost being a source of nutrients, it also has other benefits mentioned above which other organic fertilisers do not have. As such, compost should be given a separate classification as a ‘soil conditioner’ as opposed as a fertiliser source.

Extension of Phosphorus Rule for All Types of Compost

There is a temporary rule to help holdings producing pig manure, poultry manure and spent mushroom compost, and also for holdings using them. Up to 1 January 2011, more phosphorus may be put on land than crops require, as long as it comes from manure produced by pigs, poultry or from spent mushroom compost and that the 170kg nitrogen is not exceeded.

This temporary rule should be extended to include all types of source-separated composts.

[5] The soil nitrogen (N) index system indicates the soil's ability to supply N during the growing season and depends on the previous cropping history and previous organic manure applications. An estimation of soil reserves is not completed by taking and analysing a soil sample, unlike phosphorus and potash.

There are four N indices ranging from 1 to 4, index 1 soils containing small soil nitrogen reserves and index 4 soils having the largest soil nitrogen reserves. Where a crop is sown into a soil at index 1, then most of the crop requirements are supplied to the crop from chemical or applied organic nitrogen during the growing season.

1.2 Study Purpose and Objective

The specific objectives of this comprehensive desk study are therefore:

- To quantify the release/immobilisation of phosphorus made from different composts based on published and unpublished world-wide data, with emphasis on European and Irish data;
- To quantify any leaching losses of phosphorus;
- To determine if certain parameters can be used to predict the extent of P □ineralization or P immobilisation and thus estimate the potential for leaching or runoff of P when compost is applied to soil, and
- To produce a Standard Reference Document for use by all (composting sector, Local Authorities, EPA) in relation to SI 378 of 2006.

1.3 Methodology

Initially publications on the release of phosphorus from source-separated material derived compost were obtained from the following different sources; Cré Technical Committee members, online scientific databases (Science Direct, Web of Science), Commonwealth Agricultural Bureaux International (CABI) and the European Compost Network/ORBIT members. Contact was also made with a long-term crop trials research at the Agricultural Research Station in Stuttgart, Germany to obtain data. In addition to the literature available, a database of the phosphorus (total phosphorus, extractable phosphorus, carbon to phosphorus ratio) content of 300 Irish compost results were used in this report. Studies carried out in Ireland on P □ineralization or release from compost which has not been published or partially published will be examined.

Approximately over 100 publications were reviewed. In this overview, the external factors such as soil microbial activity, soil moisture and temperature which can also affect the release of nutrients from all types organic matter were not considered. These factors have been reviewed in other publications.

After sourcing the literature, the literature publications were reviewed under the following headings;

- Amount of P and forms of P in compost, type of tests/trials i.e. laboratory tests, incubation trial (measures release of nutrients without plants under standard temperature and moisture), pot trial (pot trials have plants in them), and field trials.
- The source of compost has been highlighted as well as the availability which includes release/mineralisation as a percentage of total P added, P uptake by plant as a percentage of added P,
- Apparent phosphorus recovery of compost P in relation to superphosphate.
- Parameters (C:P ratio, and stability measurement e.g. CO_2 evolution) which can predict release or immobilisation of P from compost were also examined.

Publications in relation to field work were the primary focus; however data from pot trials and laboratory incubation were examined in relation to P release.

To summarise, the availability of phosphorus from compost was determined after reviewing publications on pot trials, incubation trials, field trials and leaching trials. Based on the information from the publications the author made a judgement on the approximate availability of phosphorus from different types of compost.

2. A Review of Incubation and Pot Trials Publications

A number of publications concerning source-separated green waste (SSGW), source-separated biowaste consisting of green waste, food and non-recyclable paper (SSBW), and other miscellaneous source-separated biodegradable materials (MISC) (food processing residuals, spent grain, *etc.*) manure and sewage sludge based composts are summarised in the following Section.

The papers have been reviewed for the phosphorus content in compost (Section 3.1), release of P in incubation trials (3.2) and pot trials (3.3).

At the end of the Section 4.3, Table 2 gives examples of phosphorous release from various composts from the pot, incubation and field trials reviewed.

2.1 P content and fractions of composts

Total P concentration in compost is important as it gives an idea of how much P is added into the soil when composts are applied to soils. At present, data on availability of compost P to plants is limited. Extractable P depending on extractant used can give an idea of immediate availability or short-term availability. Similarly, fractionation[6] of compost P into inorganic or organic P and other fractions can give an idea of immediate and long-term P availability.

Table 2 is of the database of the mean P content of Irish compost samples were collated as part of the development of a compost standard (Prasad and Foster, 2009). Table 2 also shows the mean P content in compost from the UK and other countries.

Table 3 shows the CAT content, C:P ratio and the CAT/Total P ratio for Irish composts.

CAT extractable P from the compost was only about 8% of the total P in compost (Wallace 2006a). This ratio probably indicates P which is immediately available and could be related to the leaching potential of these materials. If triple superphosphate was extracted with CAT, about 99% of the P would be extracted.

Table 2: P Mean content (& range) of compost in Ireland and other countries

P Content (% Dry Matter)			
Compost Type	**Ireland**	**UK**	**Other Countries**
SSGW	**0.25** (0.05-0.45)	**0.24-0.25**[1]	**0.34**[3]
SSBW	**0.45** (0.15-0.70)	**0.88**[2]	**0.27**[4]
Miscellaneous	**0.69** (0.08-2.53)		**0.60**[5]
			0.34[6]

1- Compost used in agriculture
2- Vegetable and manure compost
3- Solid waste compost (He *et al*., 1995)
4- Vogtmann *et al.,* 1993a, Petruzzelli, 1985.
5- Gonzalez-Vila *et al*., 1982.
6- De Haan, 1981.

Table 3: Amount of CAT extractable P and ratio of CAT extractable P to total P in Irish compost

Compost Type	CAT (mg/L) content of the compost	C/P ratio	CAT/Total P*
SSGW	**52** (5-196)	**84** (27-208)	**2.1**
SSBW	**57** (5-138)	**70** (13-291)	**1.3**
Miscellaneous	**66** (1-319)	**76** (16-336)	**1.0**

6 Fractionation is a separation process in which a certain quantity of a mixture (solid, liquid, solute or suspension) is divided up in a number of smaller quantities (fractions) in which the composition changes according to a gradient.

In a study by Timmerman *et al.,* (2003), it was found that extractable P using the stronger extractant, Calcium lactate/lactic acid (CAL method) was found to be 427 mg/L, ranging 196-743 mg/L and total P was found to be 0.35% ranging 0.2 to 0.52% (Timmerman *et al*., 2003). The compost tested was made from fruit, vegetable and food residue combined with SSGW.

2.2 Review of Incubation Trial Publications

Research carried out on SSBW and SSGW composts in Switzerland (Frossard *et al*., 2002) indicated that these composts contained relatively large amounts of rapidly available inorganic phosphate. The slowly or non-exchangeable phosphate was bound to calcium in the form of apatites or octacalcium phosphates. In their review, they found that the amount of P which can be extracted from composts varied from 3% of total P when water is used as an extractant or up to 98% when strong acids are used as extractants.

The studies of Frossard *et al*., (2002) involved 16 composts made mainly from urban organic and woody wastes. The amount of extractable P ranged from 54.6% to 95.1%, but not all of this was readily plant available. Sequential extraction techniques were undertaken on four of these with water and bicarbonate extractable P being rapidly plant available, the sodium hydroxide (NaOH) extractable P is bound to Fe or Al oxides or to organic substances, and the hydrochloric acid (HCl) extractable P is only sparingly soluble. From Table 4, it can be seen that 30 to 50% of the inorganic P was rapidly extracted and available for plants.

Table 4: Percentage of total inorganic P extracted (Frossard *et al*., 2002)

Compost:	Sample 1	Sample 2	Sample 8	Sample 14	Average
Extractant					
Water	19.6	10.4	16.3	3.2	12.4
$NaHCO_3$	26.9	26.1	34.5	26.7	28.6
NaOH	14.5	9.0	7.9	24.8	14.1
HCl	31.3	50.5	36.1	35.6	38.4
Residual	7.6	4.0	5.2	9.7	6.6

Water and $NaHCO_3$=labile P, NaOH=moderately labile P,
HCl=non-labile or moderately recalcitrant, Residual= recalcitrant.

Adler (2005) who studied the phosphorous content and form in various green waste composts, found that the inorganic fraction of total phosphorus was consistently high in composts, about 70 to 95%, the fraction of total inorganic phosphorus, which is water-extractable ranged from a relatively low 1-12% to a high 15-40%.

A leaching test was carried out in Bord na Móna to asses the leaching of P from 3 composts from Ireland, namely a SSGW, SSGW and dairy processing compost and a SSBW over a six-month period (Prasad, 2006 unpublished). The technique used for this leaching test was to use leaching columns which were packed with one litre of compost. At day zero, one litre of water was added and the leachate analysed for nutrients including P. Subsequently, this leaching was carried out at regular intervals over 6 months. This technique to assess the leaching is described in a paper (Prasad, 2004). There was little difference between the amount P leached as a % of total P applied from various composts. The highest amount of leachate of P was from compost containing dairy processing waste but it was still very low at 0.21% of the total P applied. It also had the highest P content of 0.65%. The total P in the leachate as percentage of the total P applied was around 0.1% for SSBW and was 0.19% for SSGW respectively.

Ergrinya-Eneji *et al.*, (2003) found that water-soluble and HCl-soluble-P were the dominant fractions of P in a livestock-manure/straw compost, and ranged between 18% and 39% and 18% and 36%, respectively. However, the former declined progressively with time of composting, while the latter increased, indicating transformation of the more vulnerable water-soluble P to the more recalcitrant HCl extractable P. This is in agreement with the results of Preusch *et al.*, (2002) which suggested that the more stable compost had lower extractable P concentrations in amended soils than unstable compost. Preusch *et al.*, (2002) definition of stability is that the material was composted for a longer period of time e.g. 12 weeks.

A laboratory experiment was conducted by Gagnon and Simard (1999) to determine the impact of compost feedstock and manure management on the P release from 23 on-farm and 6 industrial composts. Composts were mixed with the Ap (ploughed) horizon of an Arago sandy loam (Humo-Ferric Podzol), at 200mg N kg super (-1), and incubated for 13 weeks in glass jars at 35°C. The soil test Mehlich 3[7] P content at the end of the incubation period was higher from the poultry litter than from any other sources, whereas P was strongly immobilised from week 1 to week 13 in the fresh solid, beef and young dairy manure compost amended soils. This means that P availability as shown by Mehlich 3 test was higher in composted poultry manure than composted cattle manure.

A laboratory study was conducted by Xia Yi Ping *et al.*, (2005) to evaluate the effect of compost amendment on mobility and leaching of phosphorus from a peat based commercial container medium containing 700 g kg^{-1} peat, 200 g kg^{-1} perlite and 100 g kg^{-1} vermiculite at varying amendment rates of compost (0, 25:75, 50:50, 75:25 and 100:0 on volume basis). The total P of the medium increased significantly ($P<0.01$) and quadratically with increasing compost amendment. Extractable P increased initially with an increasing compost amendment of up to 50:50 and then decreased with further increasing compost rate. However, with increasing compost rates from 25:75 to 100:0, extractability of P (extractable concentration as a percent of total) was decreased, indicating that compost amendment could lower the leachability of these elements from the medium.

Fractions that are easily extractable e.g. with water or CAT extraction are easily plant available and/or susceptible to leaching depending on soil. Fractions extracted with stronger extraction (e.g. $NAHCO_3$ or dilute acids) become plant available over a period of growing season and unlikely to leach.

2.3 Review of Pot Trials Publications

Trials Using Mostly SSBW and SSGW Composts

The effects of five compost materials on plant growth and nutrient uptake was investigated in a pot experiment (Maher, 2005). The materials were two samples (SSGW1, SSGW2) and SSBW, spent mushroom compost (SMC) and onion waste compost. This experiment was designed to study the effectiveness of these composts as a source of P for plants. In the experiment, the composts were added to soil at rates equivalent to 25 and 50 t/ha and these rates are higher than suggested in the now withdrawn EU second draft of the Technical Working Document on Biological Treatment of Biowaste (2001). A control treatment without P included and a treatment of inorganic fertiliser

[7] The Mehlich-3 test was developed in North Carolina for routine analyses of P, K, Ca, Mg, sodium (Na), and micronutrients. The advantage of this test is that it may offer the possibility of using one test for P and other nutrients across acid, neutral, and high-pH soils.

were also included. In the P experiment, nitrogen and potassium were supplied to all treatments as a base dressing and as a liquid feed throughout the experiment so that only P was limiting growth.

The amended soils were filled into 11cm diameter pots (8 replications of each treatment) and placed on a glasshouse bench. Cabbage seedlings were used as the test crops. Three successive crops were grown over a period of about a year. Dry weights were recorded and plant tissue analysed for nutrient content. Dry matter production was recorded and P uptake was calculated. In this P experiment, all the compost treatments gave a significant increase in dry weight and P uptake over the control. These results showed that absolute uptake (taking superphosphate at 100%), was 62% to 92% for SSGW and SSBW, 133% to 183% for SMC and control was 34%. Because the rate of P application using compost was higher, this explains the higher recovery. The recovery of P in relation to total P from SMC was 109% and from SSBW and SSGW 66% to 88% respectively. In conclusion, these results showed that compost from certain type of feedstocks e.g. SMC which contains chicken manure gave high P availability while SSGW gave lower P availability. However, the rates used were relatively high.

Sinaj *et al*., (2002) assessed the importance of some soil and composts properties on the utilisation of compost P by white clover (*Trifolium repens* L.). This study was carried out with samples collected from four composts made from SSBW and SSGW, and with two soil samples taken from a P rich sandy and of a P limited clayey calcareous soil. Uptake of compost P or KH_2PO_4-P by white clover was measured on the same amended soils during 16 weeks. The total coefficient of utilisation of compost P (CU-P)[8] by white clover reached values in both soils for the four composts ranging between 6.5% and 11.6% of the added P. While in the presence of KH_2PO_4 the CU-P reached values ranging between 14.5% in the clayey calcareous soil and 18.5% in the sandy acidic soil. Results obtained in the sandy acidic soil suggest, that white clover initially used a fraction of the rapidly exchangeable compost P. While at a later stage plant roots enhanced the ineralization of compost organic P and took up a fraction of the mineralised P. Such trends were not observed in the claylike calcareous soil probably because of its high sorbing capacity for P. In the sandy acidic soil, application of compost increased the uptake of soil P by the plant from 31.4mg P kg^{-1} soil in the control without P to values ranging between 37.9 to 42.7mg P kg^{-1} soil in the presence of composts.

Lineres and Morel (2004), evaluated several studies of the relative phosphorus availability i.e. the plant availability of waste P expressed as that water-soluble mineral fertiliser using the same method. This method consists of cultivation of perennial rye grass (*Lolium perenne*) using a pot in a greenhouse over about 4 months. Before mixing the soil organic waste or soluble mineral phosphate, the P ions were labelled with ^{32}P. They found that the relative phosphorus availability as follows; SSBW containing SSGW 54% and pig manure 99% indicating lower P availability from compost vis-à-vis manure.

Zhang *et al*., (2004) evaluated the solubility and fractionation of P in media containing 0, 25, 50, 75, or 100% compost derived from biosolids and SSGW for potential impacts on the environment. As the compost proportion in peat based media increased from 0% to 100%, concentration of total P increased. Incorporation of compost to the peat based media also decreased the proportion of total P which was water-soluble. However, concentrations of bioavailable inorganic phosphorus ($NaHCO_3$−IP), readily mineralisable organic phosphorus (NaHCO3−OP), potentially bioavailable inorganic phosphorus (NaOH−IP), and potentially bioavailable organic phosphorus (NaOH−OP) was still higher in the media

[8] Plant p uptake as a percentage of added P

amended with compost because of higher total P concentration in the compost.

Iglesias-Jiménez *et al*., (1993) conducted a greenhouse pot experiment to evaluate the effectiveness of city refuse compost (CRC) [9] as a P source for soils with high P fixation capacity and compared it to inorganic P. Mature CRC and K_2HPO_4 were applied at rates equivalent to 125, 250, 375, 500 and 625kg P/ha to a ferrallitic soil from the island of Tenerife (Andeptic Paleudult) with a high content in active Al + Fe (4.82%) and a high P fixation capacity (87%). Perennial ryegrass (*Lolium perenne*) was grown in pots and plants were harvested at regular intervals after seedling emergence. CRC increased plant P concentration and soil labile P proportional to the applied rate of inorganic P. The best growth were obtained from a compost application of 30 t/ha equivalent rate. An important residual effect (what is left over from previous years) in the supply capacity of P in relation to the phosphate fertiliser was also observed. The relative agronomic effectiveness (RAE) in relation to this case inorganic P in comparison to K_2HPO_4 was 66% after 6 months, this took into account not only plant P uptake but also labile P. The soil P fixation capacity was significantly reduced from a compost application of 40 t/ha equivalent rate. Competition in adsorption between organic ligands and phosphate, in combination with net □ineralization of organic P in compost, might account for the high RAE value obtained. It was concluded that city refuse compost may be a suitable P amendment for sesquioxic (oxides, oxyhyoxide or hydroxide of iron and aluminium) soils due to its high RAE, and the residual effect on P supply.

Scherer (2004) conducted a greenhouse experiment to investigate the effect of compost made from SSBW within the official classes of stability III and V (Self Heating Test[10]) on growth and P exploitation of ryegrass (*Lolium perenne cv. Turilo*). As compared to control (without P application), the compost application resulted in a significant yield increase. The application of composts of the official class of stability V resulted in higher yields as compared with the application of compost of the official class of stability III. P uptake of ryegrass was higher in the treatments in the class of stability V. Based on CAL extractable compost P exploitation, P ranged between 8.5% and 104% in the first year of compost application and in total (sum of two years) 37.8% and 204.5%. P exploitation on the basis of total compost P ranged between 3.6% and 22.1%. These results showed the more stable compost is, it resulted in higher uptake of P.

Traore *et al*. (1999) investigated in a laboratory study, the effect of composting time on phosphate exchangeability of compost derived from three feedstocks: house refuse compost, sewage sludge compost and SSBW compost, using an isotopic exchange kinetic method. They found that composting of the three feedstocks systematically lead to a decrease in water-extractable inorganic P with time. The house refuse compost containing the highest concentration of organic matter had the lowest concentration of slowly exchangeable inorganic P. The changes during composting were related to the loss of water-soluble inorganic P from composts and the formation of phosphate precipitates with Ca, Mg and/or Fe during composting. Overall this showed that a decrease in water soluble P as a result of composting has implication regarding leaching, i.e. water soluble P would be more susceptible to leaching.

[9] Unknown if this is source separated

[10] Self Heating test classes

Degree Celsius (°C)	Self Heating Stage	Description
>60	I	Raw compost
60 to 50.1	II	Fresh compost
50 to 40.1	III	Fresh compost
40 to 30.1	IV	Mature compost
< or equal to 30	V	Mature compost

Trials using Mostly Animal Manure Compost

Total P, water-soluble and total N concentration in co-composted SSGW and broiler litter were quantified during composting in a study of Felton *et al.*, (2004). P and N concentration of the compost were measured as they varied with compost treatment and time during a 63-day compost process followed by 30 day curing. They found that water- soluble P decreased from 11.5% to 2.2% of total P after active composting was completed. Total P concentration increased slightly during composting. But curing had no effect on water-soluble P. They also found water-soluble P concentration in compost from piles which were not turned or aerated was twice as high compared to compost were turned/aerated. This indicated that optimum conditions for aerobic composting of poultry manure reduces water-soluble P

The objective of a study conducted by Adler and Sikora (2003) was to examine the effect of poultry manure compost on available soil P levels. Compost of different stability was studied to evaluate the effect of biological activity on extractable P levels in two contrasting soils, a loam and clay. Compost samples from a feedstock of turkey litter and orchard grass of different ages of the composting process were added to a loam or clay soil at 0.15 and 0.30–g total P kg soil^{-1} and then incubated for 8 weeks. At day 1 and at 2, 4, and 8 weeks of composting, water-extractable and Mehlich 1[11] soil test extractable P was determined. The effect of compost age was most pronounced in the loam on day 1 with water-extractable P compared to the Mehlich 1 extractable P fraction. These data suggest that water-extractable P may increase when loam soils are amended with biologically active, unstable compost or when the absorption capacity of the soil is not sufficient to offset the effects of the compost addition. Because water-extractable P is implicated in runoff events, caution should be exercised in applying unstable composts to critical source areas within the watershed, which are most vulnerable to P loss in surface runoff and erosion.

Sikora and Enkiri (2005) carried out a growth chamber study using 15cm pots where silt loam soil with less than 10mg kg^{-1} Mehlich 3 extractable P was amended with poultry litter compost (PLC) or triple superphosphate (TSP) at rates of 0, 25, 50, 100, and 150kg P ha^{-1}. Nitrogen was supplied to be uniform across all treatments, taking into account the N mineralisation rate of PLC. Fescue (*Festuca arundinacea Schreb*) was grown and harvested three times over 103 days. Yield of fescue was not linearly related to rate of amendment but yield was not affected by PLC or TSP. Models describing yield changes with rate were different for TSP and PLC. No statistical differences in P uptake were seen, and a single quadratic equation described P uptake with rate. These data indicate that PLC added to soils on a total P basis provided the same amount of fertiliser equivalents as TSP.

In conjunction with the work on P fractionation by Frossard *et al.*, (2002) mentioned earlier, a plant growth trial was conducted on white clover (Sinaj *et al.,* 2002). The total co-efficient of utilisation of compost P ranged from 6.5% to 11.6% over a 16 week period. In a sandy acid soil used, the results suggested that initially the white clover used a fraction of the rapidly exchangeable compost P, while at a latter stage plant roots enhanced the mineralisation of compost organic P, which was then taken up. These results suggest that the highly mobile phosphorus fraction is reduced after composting manure. Their data suggests that the more stable composts had lower extractable phosphorous concentration in amended soil as also found by

[11] The Mehlich-1 extractant (implemented in 1953) was developed by Dr. Adolph Mehlich for the North Carolina Department of Agriculture Soil Testing Division. It is a versatile soil extractant that is used for determining the amounts of phosphorus, potassium, calcium, magnesium, zinc, manganese, copper and boron. It is made up of a dilute solution of hydrochloric and sulfuric acids, thus it is often referred to as the "double acid" extractant. It works well for acidic, low cation exchange capacity (CEC) soils.

Preusch *et al.*, (2002). Even though in their studies the addition of composts does not affect phosphorous uptake, because compost phosphorus was as available as triple superphosphate, soluble phosphate appears to be affected by biological factors such as stability[12] of the composts.

A study by Zvomuya *et al.*, (2000) utilised chemical properties of eight composted and two non-composted beef cattle manures to predict cumulative phosphorus uptake (CPU) during a 363 day controlled environment chamber bioassay. Ten growth cycles of canola (*Brassica napus L.)* were raised in pots containing 2kg of Dark Brown Chernozemic clay loam soil (fine-loamy, mixed Typic Haploboroll) mixed with 0.04kg of the amendments. Inorganic P fertiliser (KH_2PO4) and an unamended control were included for comparison. Apparent phosphorus recovery (APR) from composted manure (24%) was significantly lower than that from non-composted manure (33%), and the fertiliser (27%). Total water-extractable phosphorus (TP H_2O) and total phosphorus (TP) concentration of amendments were adequate to model amendment-derived cumulative phosphorus uptake (ACPU) explaining 81% of the variation in ACPU.

A study to evaluate plant-available P in poultry litter compost (PLC) compared with triple super phosphate (TSP) was conducted in a growth chamber using fescue (*Festuca arundinacea Schreb*) (Sikora and Enkiri 2003). Phosphorus amendments from 0 to 150mg P kg^{-1} soil were added to Sassafras soil (typic Hapludults, fine-loamy, siliceous, and mesic). Nitrogen rates were constant over all P treatments at 150kg N ha^{-1}. Fescue was harvested three times during an 84-day study, and clippings, as well as roots and crowns at the termination, were analyzed for P content. Cumulative dry weight of fescue clippings was the same for both TSP and PLC and did not change with increased P application from 0 to 150kg P ha^{-1} soil. These data suggest that the Sassafras soil was not deficient in P (Mehlich 3 extractable P was approximately 125mg P ha^{-1}) and that the N application rate of 150kg N ha^{-1}, which was constant across all P treatments, determined yields. Cumulative phosphorus uptake was the same for PLC and TSP but, in this case, was linearly related to P application rate. At the 84-day harvest, greater P uptake was recorded for 100 and 150kg PLC-P ha^{-1} rates than for all other treatments, which suggested that organic compounds in the PLC may be blocking adsorption sites and/or releasing soluble P with time. Phosphorous uptake by roots and crowns was approximately equal to cumulative P uptake of clippings. Statistical analysis indicated no effect of P source or rate on P uptake by roots and crowns, but only two of four replicates were harvested. Because PLC was equal to TSP in supplying P to fescue, composting of poultry litter does not seem to affect P availability in the same manner as it affects N. Compost application based on crop N needs and N availability will result in greater plant-available P additions than if uncomposted poultry litter is added.

[12] Sinaj *et al.,* (2002) gave no information on their interpretation of stability.

3. A Review of Field Trials Publications

A number of publications using source-separated green waste (SSGW), source-separated biowaste consisting of green waste, food and non-recyclable paper (SSBW), and other miscellaneous source-separated biodegradable materials (MISC) (food processing residuals, spent grain, *etc.*) manure and sewage sludge based composts are summarised in the following Section.

The papers have been reviewed for the release of phosphorus in field trials (Section 4) and at the end of the Section 4.3, Table 2 gives examples of phosphorus release from various composts from pot, incubation and trials reviewed.

Trials using Mostly SSBW and SSGW Compost

The effect of two composts, spent mushroom compost (SMC) and SSGW, and nitrogen on the performance of autumn harvested cabbage were investigated in a field experiment at Kinsealy (Maher, 2005). The soil was a heavy textured grey-brown podzolic with moderate to good drainage with a history of vegetable crop production. These treatments were combined in a factorial experiment 2 (compost type) x 3 (rate of compost) x 2 (inorganic N. In addition, there was a control treatment where no compost or fertiliser was applied and another treatment which received 150kg N as calcium ammonium nitrate and inorganic P and K as determined by soil analysis, (Control + NPK). This treatment represented normal commercial practice. Although the trial was about nitrogen nutrition, limited information on P uptake is available and this will be presented here.

Both composts were applied at three rates, 25, 50 and 250 t/ha of fresh material. The first two rates were chosen to represent normal agronomic practice, compliant with environmental regulations to avoid nutrient overloading. The highest rate was used because this is the rate appropriate for suppression of soil borne diseases. At each rate, each compost was applied with or without the addition of inorganic N at the rate of 150 kg/ha (as calcium ammonium nitrate). In relation to P, results are given in Table 5.

Table 5: Effect of compost type and rate on P nutrient uptake

Effects of compost type & Rate	Rate (t/ha)	P Uptake (kg/ha)
SMC	25	30.0
SMC	50	33.1
SMC	250	58.1
SSGW	25	24.1
SSGW	50	26.3
SSGW	250	24.3
Control		19.1
NPK	Recommended rate	29.7
Compost type	**Mean P Uptake (kg/ha)**	
SMC	40.4	
SSGW	25.9	

The P uptake was significantly lower from composted greenwaste than from spent mushroom compost which contained poultry manure. The rates of application affected the uptake with higher rates as expected, showing higher P uptake. However at the very high rate of 250 t/ha there was a decrease in yield and therefore P uptake. This reduction of growth was probably due to high salt content (Electrical conductivity –EC) and due to lack of sufficient N. The rates increased P uptake significantly from SMC but did not increase with SSGW.

The effect of two composts (SMC and SSGW) on the performance of onions was investigated in a further field experiment at Kinsealy. The soil was same as in the previous trial. This trial was also oriented towards N nutrition but limited information can be observed regarding P nutrition. Both composts were applied at three rates, 25, 50 and 250 t/ha of fresh material. The first two rates were chosen to represent normal agronomic practice compliant with environmental regulations to avoid nutrient overloading. A treatment without compost was included. At each rate, each compost was applied with or without the addition of inorganic N at the rate of 140 kg/ha (supplied calcium ammonium nitrate). At the zero compost rate where N was given, dressings of inorganic P and K were applied according to soil analysis. This treatment could be taken to be normal commercial practice.

Both SMC and SSGW increased levels of P in the soil. The increase of 0.28mg for SMC and of the order of 0.04mg for SSGW per tonne of compost. SMC had a higher content of P. P uptake from plants growing in the composted SSGW treatment in compared to SMC treatment was approximately 80% at 25 t/ha, and 79% at 50 t/ha, and 59% at 250 t/ha, and was 84% in relation to superphosphate. These results showed that the availability of P from SSGW is less than SMC.

A five-year field trial using compost derived from SSGW was carried out in south-east England on different soil types on a range of sites (Wallace 2006b). A range of crops included potatoes, sugar beet and winter wheat. There were 8 treatments which included compost at 50 and 100 t/ha without and with two rates of N, two controls, one untreated and one with a standard rate of fertiliser. The first part of the trial was carried out for 3 years. In phase 2 of the trial, the trial was conducted on a fewer number of sites for another 2 years. In years 4 and 5, the compost rates were reduced to 30 and 60 t/ha. In this trial, which was focussed on contribution of compost to nitrogen nutrition, the following was observed in relation to phosphorus. In soil samples taken at the end of cropping, 2 sites of the 7 sites had an increase by one unit of P in soil test (Olsen[13]). Even then, the increase in soil test index was not consistent in all the compost treatments. In fact, the increase in P index was present in only one treatment out of six after 3 years of application. The trend was similar to the fourth/fifth year. There was little or no increase in the P index and where it was the case, it happened in only one out of six compost treatments. These results indicate that no significant increase in soil test P is likely even at the rate of 60 tonnes/ha of compost. However, soil type could be a factor.

In a long-term compost trial (1995 to 2002) Timmerman *et al.*, (2003) investigated the benefits of compost (vegetable, fruit and SSGW compost) including effects on plant nutrition. This trial was carried out on six sites in south-west Germany. Application of compost increased soil test P (CAL extract). In the control, the average extractable P was around 18mg P/g of soil at the start of the trial and dropped to 16mg P/g of soil at the end of the trial. The increase in extractable P was at the rate of 5 t/ha, 10 t/ha and 20 t/ha was 1, 4 and 8 mg/g respectively over the trial period. For every application of 100kg P/ha as a compost, the increase in extractable P was 0.7mg P_2O_5/g. The average utilisation of phosphate (P efficiency) was around 35% to 60% over 7 years. The fertiliser efficiency[14] of the compost was found to be between 35% to 45%. With inorganic fertiliser the fertiliser efficiency is 20% in the first year and 40% to 45% in the following years (total 60% to 65% as against 35%

[13] The Olsen test is reliable for extracting P from neutral and high-pH (calcareous) soils.

to 45% for compost). Timmerman *et al.*, (2004) concluded that an application of 7 to 10t dry matter of compost per hectare, will keep the soil test P value the same. It can thus replace inorganic fertilisation as it has similar fertiliser efficiency. Timmerman *et al.*, (2003) concluded that the limitation of rate of compost application should be based on P nutrition.

Mkhabela and Warman (2005) carried out a study to evaluate the effects of municipal solid waste (MSW) compost on soil P availability and uptake by potato (*Solanum tuberosum*) and sweet corn (*Zea mays*) crops grown in a Pugwash sandy loam soil in Nova Scotia, Canada. Three rates of compost, one rate of chemical fertiliser (NPK) and one mixture of 1/2 MSW compost and 1/2 NPK fertiliser (mixture) were used on both crops taking into account soil P test results. During the second year, another treatment with the recommended levels of NK treatment was added. The MSW compost and the mixture treatments resulted in statistically equivalent concentrations of tissue P as the NPK treatment in both crops and both years. Tissue P concentration in potatoes ranged from 1.92 to 2.25 and 2.60 to 3.17 g kg^{-1}, while in corn it ranged from 3.08 to 3.46 and 2.32 to 3.16 g kg^{-1} in 1996 and 1997, respectively. The MSW compost and MIXTURE treatments generally resulted in equivalent concentration of Mehlich 3 extractable soil P compared to the inorganic fertiliser. In addition, the application of both inorganic fertiliser and MSW compost decreased P adsorption by the soil by up to 30%. Municipal solid waste compost may be a good source of P for both potatoes and sweet corn. They concluded that due to the low availability of compost N, supplementary N in the form of inorganic fertiliser may have to be added together with compost in order to enhance N availability to crops.

In a literature study carried out by Amlinger *et al.*, (2006) on the benefits of compost, it was reported that according to Kluge (2003) the absolute supply of P at an application rate of biocompost compost of 6-10 t ha^{-1} $year^{-1}$ is around 13-17kg of which the efficiency is 30 - 50%. The efficiency of compost P is 15-20% in the application year and is 40-50% over 10 to 20 years. Therefore, there is a good correlation between nutrient supply through compost and plant available P pool in the soil. They concluded that plant availability of P in the first years is less than mineral P fertiliser compared to that available from compost.

Trials using Mostly Animal Manures compost

A study was conducted by Eghball & Power (1999) in Nebraska, USA, from 1992 to 1996 to evaluate effects of P and N based manure and compost application on maize yield, N and P uptake, soil P level, and weed biomass. Composted and non-composted beef cattle feedlot[15] manures were applied to supply N or P needs of maize for either a 1 or 2 year period. Phosphorus based manure or compost treatments also received additional fertiliser N as needed. Fertilised and unfertilised checks were also included. Manure or compost application increased maize grain yield in all 4 years as compared with the unfertilised control. Annual or biennial manure or compost application resulted in maize grain yields similar to those of the fertiliser treatment. Phosphorus based manure or compost application resulted in similar grain yields to those for N based treatments but had significantly less soil available P level after 4 years of application. Biennial manure or compost application resulted in maize yields similar to that for annual application but increased available P in the soil. Annual P based beef cattle feedlot manure or compost application is the most effective method of using these resources when soil P build-up is a concern. There was no difference between composted manure or uncomposted manure in this case.

[14] Uptake in relation to total P

[15] Feedlot is a type of confined animal feeding operation

A trial by Eghball (2003) was based on the principle that phosphorus (P) leaching in manure amended soil can be influenced by the P fractions added when manure or composted manure is applied. This study was conducted to determine leaching of different P fractions following beef cattle feedlot manure or compost application. Manure and composted manure were applied to meet the nitrogen (N) or P needs of corn (*Zea mays* L.) for either a one or two year period. Fertilised plots and unfertilised control plots were also used. The P based treatments also received additional N fertiliser. Soil P fractions were determined for various soil depth increments. After 4 years of manure and compost applications, leaching of plant available P was observed to a soil depth of 30cm. The differences among treatments for total and inorganic P were significant only at the 0 to 15cm soil depth increment. Greater concentrations of total, available, and inorganic P fractions were observed for the N based manure and compost treatments as these management strategies received more P than P based compost treatment. More than 70% of beef cattle manure or composted feedlot manure P was inorganic. Water soluble P was a small fraction of total P in beef cattle feedlot manure or composted manure (<13%). They concluded that leaching of plant available P, following manure and compost applications, can pollute the ground water if P comes in contact with ground water, especially in areas with shallow and/or fluctuating ground water and in areas with till drainage.

Gilley and Risse (2000) used low phosphorus (0.20-0.36% P) and high P (0.36-0.46% P) composted feedlot manures and applied them annually at 6 different treatments for three years, before the 2001 crop season. Treatments effect on soil test phosphorus was detected more often with soil tests (Bray P1 and Mehlich 3 and Olsen-P[16]) than with water-soluble P. Considerable risk of phosphorous loss exists even when the soil test phosphorus is moderate, as it has much potential for P transport. Soil test phosphorus is closely related to phosphorus concentration in runoff, and common agronomic soil test is useful in assessment of phosphorous runoff risk. Risk assessment tools such as the phosphorus index needs to allow the risk value of phosphorous loss to increase indefinitely as the soil test phosphorus increases. Risk may be less with excessive build-up of soil phosphorus through manure application on fields. Gilley and Risse (2000) state that repeated manure application can lead to an excessive soil test phosphorus level and an increased phosphorus concentration in run-off. Gilley and Risse (2000) also concluded that land application typically decreases water runoff and sediment loss presumably due to increase water infiltration and this effect can persist for several years following manure/compost) application.

Wortmann and Walters (2006) conducted research to evaluate soil test phosphorus in prediction of phosphorous concentration in run-of loss and to determine the residual effects of composted manure on runoff P loss and leaching in a field trial. Research was conducted from 2000 to 2004 under natural runoff events. Composts with low phosphorus and high phosphorus had been applied during the previous three years resulting in broad application of 750 and 1,150kg phosphorus hectare^{-1}. Runoff in sediment losses were 120% and 69% greater with no composts and residual composts treatments (previous years application). The residual effect of compost application in reducing sediment and runoff loss was evident more than three years after application and should be considered in phosphorus indices. Wortmann and Walters (2006) concluded that soil tests are useful in predicting long-term runoff concentration.

The overall objective of a study by Bar Tal *et al.,* (2004) was to determine the loading limits of

[16] The Bray, Mehich and Olsen are three different chemical extractants of P from soils.

composts which should be applied annually to wheat under specific conditions. Bar Tal *et al.,* (2004) conducted a container experiment in greenhouse during four years. It included eight treatments: sewage sludge compost and cattle manure compost, each applied annually to sandy soil, at rates equivalent to 30, 60 and 120 t/ha m^2 with two controls, one fertilised and one unfertilised. The total amount of phosphorus taken up by plants in all the compost-rate treatments was less then 10% of the amount applied throughout the three years: whereas 30 to 50% of the phosphorus applied by the mineral fertiliser was taken up.

A previous study by Sikora and Enkiri (2003) compared triple superphosphate (TSP) to poultry litter compost (PLC) as a source of P for fescue indicated that overall they were equal. But, when N became limited during the final harvest, PLC supplied more P to fescue than TSP at comparable rates. A subsequent study was initiated to determine if P from PLC was more available to fescue than TSP when N was not limited (Sikora and Enikiri 2004). Sassafras soil was amended with PLC and TSP at rates of 0, 50, 100 and 150kg ha^{-1}. Nitrogen was supplied to be uniform across all treatments taking into account the N ineralization rate of PLC. Two harvests of fescue were taken and analysed for yields and P uptake. Nitrogen was added to all treatments at the original application rate of 120kg ha^{-1} and two more harvests plus roots were collected. Yields were affected by harvest date but not by P rate or source of P. P uptake was affected by date and rate but not by source of P i.e. from poultry compost or superphosphate. The P uptake response to PLC and TSP was curvilinear and linear respectively, but within the range of P application rates used, the source of P was not a significant factor in P uptake by fescue. Based on the current study testing the effect of unlimited N, addition of supplemental N did not affect P supply from either source. Poultry litter compost is considered equal to TSP in supplying P to fescue and N availability did not affect these conclusions (Sikora and Enkiri, 2003).

Trials using Mostly Sewage Sludge compost

In a trial conducted by Wen-Guang *et al.*, (1997) digested, dewatered sewage sludge (DSS); irradiated sewage sludge (DISS); irradiated and composted sewage sludge (DICSS); and composted livestock manure (CLM) were applied for two years at five rates (0, 10, 20, 30, and 40 t/ha per year) in a field experiment in Ontario, Canada. Uptake of P was measured in lettuce, bean (*Phaseolus vulgaris*) and petunia in 1990. Uptake of P was also measured in consecutive harvests of lettuce in 1991. Percentage of total P that was extractable by 0.5M Na HCO_3 was much higher than in CLM (30–70%) in DSS, DISS, and DICSS (0.8–5.6%). Phosphorus uptake by crops harvested in an early stage of growth, lettuce in 1990 and first cut lettuce in 1991, and the extractable soil P linearly increased with total P applied. The lack of response in P uptake with bean pod and petunia in 1990, and the second cut lettuce in 1991, was possibly due to their advanced stage of crop maturity. Much larger amounts of P were applied with DSS, DISS, and DICSS than with CLM, while P uptake and extractable soil P did not increase compared to that in the treatment which received no P. The low availability of P in sludge was probably caused by Fe and Al which precipitated P. Sludge irradiation and/or composting had no significant effect on P availability.

A three-year compost field trial based on intensive continuous vegetable crop production was carried out on coarse sand in Western Australia and medium loamy soil in Victoria by O'Reilly *et al.,* (2003). The crops grown were lettuce and carrots in rotation. The compost used was green waste and poultry manure and composted in open windrows over 12 to 14 weeks. The rate of compost application was at 30 and $60m^3$ plus a 0 control. These trials showed on average, that the compost phosphorus was

40% as effective as the application of inorganic phosphate (superphosphate).

Korboulewsky *et al.,* (2002) evaluated the environmental hazard of sewage sludge compost applied in March 1999 at 10, 30, and 90 t ha^{-1} fresh weight in a vineyard in south-eastern France. At the recommended rate, a risk of N leaching was very low, but phosphorus (P) appeared to be the limiting factor. Phosphorus significantly increased only in plots amended with the highest rate in the topsoil and subsoil. At lower rates, although no significant differences were observed, P added was greater than the quantities absorbed by vines. Korboulewsky *et al.,* (2002) concluded that P will accumulate in the soil and may reach concentrations which will pose a risk to surface waters and ground water. Therefore, although the current recommended rate (10 t $ha/^{-1}$) increased soil organic matter without the risk of N leaching, total sewage sludge loading rates on vineyards should be based on P concentrations.

Warman and Termeer (2005) present the data from two years of experiments of the application of aerobically digested sewage sludge, anaerobic lagoon septic sludge, sewage sludge compost or fertiliser to soils for grass forage and feed corn (*Zea mays*) production at two different sites in Nova Scotia. Crop yields, plant tissue and Mehlich 1 extractable soil nutrients were evaluated; 15 elements were analysed in the plant tissue and nine elements in the soil extracts. Their paper describes the results of crop yields, plant N, P and K content and Mehlich 1 extractable P and K. The research demonstrated the fertiliser produced higher yields of grass forage than the sludge and the compost but equivalent to the sludge in corn yields. Forage and corn N, P and K contents, however, varied with treatment, crop and year, while the compost amended soils were highest in extractable nutrients. They conclude that both sludges and the compost, therefore, could be effective sources of N, P and K for crop production. Compared to the conventional fertiliser, the nutrient availability from the organic amendments (especially N and P) was considerably lower than the 50% assumed at the start of the experiment. The sludges however, provided higher nutrient availability than the compost.

Pagel *et al.,* (1987) carried out a field and pot studies over several years at Berlin Malchow. Wet sewage sludge, dry sewage sludge and refuse compost were applied to a sandy soil for 2, 3 or 4 years. In some cases mineral P fertiliser was also applied. Data on P sorption (on the surface of particle) and desorption , P equilibrium concentration and P buffering revealed that the organic materials did not improve the P status of the soil but caused stronger fixation and sorption of phosphate and a lowering of P in the soil solution. An increase in soluble phosphate reaching the groundwater is therefore unlikely (Pagel *et al.,* 1987).

Inman *et al.,* (1982) conducted a field study to study the effect of composted sewage sludge on $P0_4$ in soil water at three depths. Composted sewage sludge was applied at rates of 0, 150, and 300 dry t/ha. Compost was manufactured from approximately 65% sewage sludge and 35% woodchips. Testing of data was not possible due to missing data. However, the values indicate that water samples from the compost treated plots were equal to or lower in the phosphate and samples taken from controlled plants. The relatively low phosphate values in water samples from compost treated soil may be due to phosphate precipitation by Ca present in the composts. In addition, microbial immobilisation of phosphate in compost treated soil may be may have decreased water-soluble phosphate.

Table 6 on the following page shows some examples of the p release from different types of compost under field and pot trial conditions.

Table 6: Examples of P release from composts in pot and field trial

Authors	Type/Source compost	Availability of phosphate as% of Total P	Availability of phosphate as % related to super phosphate	Type of trial	Crop Grown	Duration of trial and comments
Maher, 2005	SSGW, SSBW SMC	N/A	66-88%, SMC =109%	Pot	Cabbage	Up to 1 year
Bar Tal *et al*., 2004	Cattle manure compost sewage sludge compost	10%	20% -30%	Pot	wheat	Up to 3 years
Sinaj *et al.,* 2002	Solid kitchen and Ggarden waste	6.5% – 11.6%	44% – 63%	Pot	White Clover	Up to 4 months
Scherer, 2004	SSBW	3.6% – 22.1%	N/A	Pot	Ryegrass	Up to 2 years
Sikora & Enkeri, 2003	Poultry litter compost	N/A	100%	Pot	Fescue Grass	
Zvomuya *et al.,* 2006	Composted beef cattle manure	N/A	88% Non-composted manure 122%	Pot	Canola (*Brassica napus*)	Trial duration 363 days
Maher, 2005	SSGW and SMC	N/A	Availability of P from SSGW 61% of SMC	Field Trial	Cabbage	A nitrogen trial but some data available on P from this trial
Timmerman *et al*., 2003	SSGW				Various	7 years
Warmer & Termer, 2005	Sewage sludge compost	N/a	50%	Field	Forage Grass and Feed corn	
Igelesias- Jiménez *et al.,*1993	City refuse compost	N/A	66%	Pot	Perennial Rye grass	Up to 6 weeks

NA= information not available

4. Discussion

Much of the emphasis on nutrient release from compost has been on release of nitrogen N particularly nitrate nitrogen (Amlinger *et al.,* 2003). There is lack of information on mineralisation or release of P when compost is added to soil. The availability of phosphates from compost is difficult to determine. Even water-soluble, inorganic phosphate applied to soil is often quickly fixed and rendered unavailable. To be used in nutrient management plans, based on fertiliser recommendation systems, a compost equivalent P value compared with triple superphosphate could be estimated. This might allow for lock-up effects in the soil. Any P uptake results or soil test value as a result of compost application is affected by the properties of the soil unlike nitrate nitrogen which barely reacts with soil. Any discussion on P mineralisation from composts should be cognisant of the above limitations. This literature review indicates that the mineralisation of P from composts is affected by the following factors.

First and foremost, an important factor is the feedstock of the compost. For example, P mineralisation of compost based on poultry manure (or spent mushroom compost which contains poultry manure) as evidenced by P uptake or by effect on soil test value is similar to inorganic fertiliser (superphosphate) (see for instance Sikora & Enkiri 2004, Sikora & Enkiri, 2005; Gagnon & Simard, 1999; Maher 2005). On the other hand, compost based on greenwaste gave an efficiency equivalent of 60% to 80% *vis-à-vis* Triple Superphosphate. A relative agronomic effectiveness of 66% from City Refuse Compost was found by Iglesias-Jiménez *et al.,* (1993). In a trial, Warman and Termeer (2005) report nutrient availability of less than 50% of 'conventional fertiliser'. Another factor, which has to be taken into account, is the effect of composting on release of P from manure and sewage sludge. Generally' it has been found that composting reduces availability of P from manure and sewage sludge in relation to non-composted material (e.g. Warman & Termeer, 2005).

The addition of composts results in initial immobilisation or initial mineralisation of soil phosphorus had been shown to depend on the C:P ratio (it can influence mineralisation of stable organic matter) of the organic material added. Immobilisation is likely to occur with a C:P ratio of >200 (Hannapel *et al.,*1964).

However for mineralisation to occur in soil, the organic amendment must contain at least 0.2% of total phosphorus, otherwise net immobilisation will occur (Iyamuremye and Dick, 1996). Findings show that figures greater than 0.2% is required for release to occur. Among the Irish compost quality database, it would indicate that maximum release would be in the order-Miscellaneous (source-separated biodegradable materials e.g food processing residuals, spent grain, *etc)* >SSBW (source-separated biowaste) consisting of green waste, food and non-recyclable paper >SSGW (source-separated green waste) on basis of the mean total P value. However, on the basis of numbers of samples which were greater than 0.2%, it was greatest in miscellaneous (100% of the sample), SSGW (75% and then SSBW (8%). Almost none of the compost samples on basis of C:P ratio would immobilise P but rather release P. However, there is inconsistency in the use of C:P ratio as an index of immobilisation or mineralisation and this is possibly due to the quality of organic carbon (Dalal, 1977) or due to inorganic phosphorus in organic material.

The biological stability of compost can affect P availability as shown by a decrease in water-extractable P or decrease in chemically extractable P (Adler and Sikora, 2003; Traore *et al.,* 1999; Egrinya – Eneji *et al.,* 2003; Inman *et al.,* 1982). Some water soluble P is consumed by microbial activity and some P bound to complex forms is freed as microbes die and decompose. The decrease suggests that composted products will release P more slowly and releasing less easily water (and easily extractable P) soluble P to the environment (Felton et al., 2004). The amount of water extract able P is very low in compost as shown by Frossard *et al.,* (2002) and Eghball (2003). Using a very weak extractant ($CaCl_2$+DTPA), the amount of P extracted was very low and followed the order greenwaste<biowaste (green waste + food) <spent mushroom compost (Maher 2005). In another study it was found the lowest figures for CAT extractant were for SSGW with SSBW< Miscellenous (Prasad and Foster, 2009). According to Sharpey & Moyer (2000), water-extractable P and presumably CAT extractable P (a very weak extractant) may be used to estimate the leaching potential of P for land applied compost. Most of the P is bound to soil particles and organic matter but soluble P can move with flowing water. It is the soluble component which has pollution potential (Felton *et al.,* 2004).

Some authors have related P mineralisation or P uptake as percentage of total P in the compost. The figures are 3.2-22.1% (Scherer (2004), 0.5 to 1.7% for MSW (Warman & Termeer, 2005; Maher, 2005). There is usually an increase in soil test P determined by various methods (CAL, Olsen's, Morgans) as a result of compost application. For instance Timmerman *et al.,* (2003) found that for every 100kg P/ha applied as a biowaste compost there was an increase of about 0.3 mg. Studies in the U.K using Olsen's method found increases in one Olsen unit[17] when compost was applied at a rate of 100 tonnes/ha. However, information under controlled conditions, laboratory or greenhouse of this type is almost non-existant. This type of information would be valuable for nutrient management planning and for assessment of leaching potential of compost P as it has been shown that soil test P is related to P concentration in runoff (Wortmann & Walters, 2004; Gilley and Risse, 2000).

It appears from this study, that leaching of P from compost applied P is less likely to be a problem than from inorganic P fertiliser or untreated manure or biosolids even if the bioavailibity of compost P is similar to superphosphate P. This is because;

- Composting process reduces water-soluble P as well extractable P (for instance a weak extract such as CAT).
- The phosphate in compost is in slow release form and availability can extend over a long period, up to 20 years (Amlinger *et al.,* 2006).

Application of compost *per se* reduces runoff and water movement down to the ground water as it increases the water holding capacity of the soil. There is also less movement of sediment and therefore reduction in runoff P and other nutrients (Gilley & Risse 2000, Wortman and Walters 2006). Short-term leaching trials carried out in Bord na Móna (Prasad unpublished, 2007) showed very little leaching (<1%) of P from compost and if superphosphate had been applied as a treatment one would have got over 90% leaching based on the knowledge about water solubility of P in superphosphate.

4.1 Interdependency of Nitrogen and Phosphorus

To explain how the recommendation for compost applied to soil can be used and to highlight the interdependency of P and N inputs the following scenario is examined for example a grower wants to grow a crop of lettuce. We need to look at SI 378 of 2006 – Nitrate Regulations in Ireland which gives the rate recommended for phosphorus and nitrogen in Table 7 and Table 8 respectively (These are Table 18 and 19 of SI 378 of 2006, respectively).

[17] There are different Olsen unit based on the P ranges. See glossary of terms for unit and P ranges

Table 7: Phosphorus rates for lettuce based on soil phosphorus index (Table 18 in SI 378 of 2006)

Crop	Phosphorus Index			
	1	2	3	4
	Available Phosphorus kg/ha as superphosphate			
Lettuce	60	45	35	20

Table 8: Nitrogen rates for lettuce based on soil N index (Table 19 in SI 378 of 2006)

Crop	Nitrogen Index			
	1	2	3	4
	Available Nitrogen kg/ha as mineral fertiliser			
Lettuce	100	90	80	70

As one can see the P rates vary from 20 kg/ha to 60kg/ha and N rates can vary from 70 to 100kg/ha (Table 7 and 8) To get P application rates of 20 kg/ha to 60 kg/ha using compost, compost rates would need to be from 13 t/ha to 40t/ha oven dry weight (26 t/ha 80t/ha fresh weight assuming 50% moisture). This is based on the assumption that the compost has a P content of 0.2% and availability of 75% of the Total P (first year). If the compost has a C:N ratio of 15 and total N of 3%, and availability 10% of total N (first year). The compost rates would only give sufficient nitrogen in only few cases, compare N requirement (Table 8) with Table 9 below which gives the N supplied by compost of various C:N ratios.

Table 9: Effect of applying compost as a P source for lettuce on N availability from compost on various C:N ratio (See Table 20 in SI 378 of 2006 for P index and superphosphate rates

	Phosphorus Index			
	1	2	3	4
	Available Phosphorus kg/ha as Super phosphate			
	60	45	35	20
	Rate of Compost (t/ha) having P of 0.2% and P availability of 75% to give Super phosphate equivalent			
	40	30	23	13
N availability %*	These compost rates will give following N availability of Nitrogen in kg/ha			
12.5	150	113	86	49
8	96	72	55	31
5	60	45	35	20
2	24	18	14	8
0	Immobilisation			

*Depends on C:N ratio.

It is obvious that when the P requirements are to be met with compost, then in most cases the N requirements will not be met even though the % N of compost in the assumption is high.

The interdependency of phosphorus and nitrogen can also be shown from the following example. The N/P ratio of compost is around 5.2 for SSGW, 4.70 for SSBW and 3.66 from Miscellaneous (these are mean values taken from data of Prasad and Foster, 2009). The ratio is somewhat similar for plants such as wheat and corn (Gilbertson et al., 1979). However the release of N from compost is in the order of a negative value to 20% (Prasad, 2009) of total N while P release is 60 to 100% of total P. Thus if N based rate of compost is used the amount of P applied will be in excess of the plant P requirement and potential environmental problem. Vice versa if P based rates of compost used the amount of available N will be well below the plant N requirement and additional inorganic or organic N would need to be applied to get optimum growth.

The amount of CAT extractable P (assuming it is similar to water-soluble P) will need to be considered in certain circumstances. This is because for crops grown in spring, when the soil temperature is low, often P efficiency is manifested even at a reasonable soil test value. In such a situation water-soluble P has to be added if CAT extractable P is approximately less than 250mg P/L (approximately 500mg/Kg).

It should borne in mind that there are certain weaknesses in some of the publications particularly in relation to the objective of this review. This should be kept in mind when considering the conclusion and the above discussion. The weaknesses are lack of clear information on feedstock and stability and as it has been shown in the discussion it can have an affect on P availability. Many authors have different interpretation on what stability means and what is stable and unstable.

In addition the rates of composts are generally in tonnes/ha while P is applied in kg/ha and in most cases when looking at the efficiency of the two sources, the rates have not been applied at equivalent P rates. There is also some confusion regarding the terminology e.g. MSW is widely used in the USA but this is probably similar to biowaste as it is used in Europe.

5. Conclusions

- There are limited publications available on the P availability from composts, as it has not been studied in great depth in comparison to the large number of publication available on the availability of N.
- In conclusion, the availability of phosphorus from compost was determined after reviewing publications on pot trials, incubation trials, field trials and leaching trials. Based on the information from the publications the author made a judgement on the approximate availability of phosphorus from different types of compost (See Table 10).

Table 10: Proposed phosphorus availability from various composts made from different feedstock relative to superphosphate

Compost Type	Relative availability when superphosphate is 100%
Spent Mushroom Compost	100
Manures	90
Sewage Sludge	85
SSBW	75
SSGW	60

- The figures In Table 10 are fairly conservative and are in agreement with some UK findings which states that if 100kg P_2O_5 is applied from compost at 20 t/ha, the availability will be 60% in year 1 and 20% in year 2 (Wallace, 2006a). They make the proviso that availability may vary from the above figure depending on feedstock and the characteristic (stability) of the compost. In addition according to Vogtmann *et al.,* (1993b), the availability of P in compost ranges from 20% to 40%. Similarly, Kluge (Amlinger *et al.,* 2006) stated that in the first year only up to 10% of the P from compost is available.
- Phosphorus availability from compost is much higher than nitrogen availability from compost (Prasad, 2009) and is in the range of 60 to +100% as superphosphate equivalent.
- The amount of P released as a percentage of total P can vary from 3% to 22% over two years.
- Release of compost P can be affected by feedstock. For example, the release of P from composted green waste is 60% of that of superphosphate, whilst composted poultry manure has the same availability as superphosphate.
- Phosphorus content of compost can vary considerably and can also be dependent on feedstock.
- Information on the effect of compost application on soil test P (plant available P) is limited. The quantity of P that is extractable by different soil test extractants is also generally lacking.
- Biological stability is important as it often has a reducing effect on soluble P of compost. Water soluble P is the main pathway of P leaching in the environment.
- The release of P from compost is in a slow release form.

6. Recommendations

This study recommends the following:

- There is a need to emphasise the interdependency of P and N in compost in relation to the SI 376. It is not nitrate leaching from compost that could be a potential problem from compost application; rather it is P that could be potential problem.
- Better characterisation of compost P is needed including the identification of organic P, inorganic P into different fractions which are inorganic P and organic P, water-soluble P and labile P.
- Routine laboratory tests need to be developed to predict compost P availability from different types of compost.
- The effect of the P content from compost on the soil test P (Morgan's and Olsen's extract methods) needs to be determined.
- There is a need to study the effect of composting on P availability from composts made from different feedstocks and the effect of stability on P availability.
- Long-term field trials (>5 years) on different soils using compost would be helpful in establishing the P availability from compost.
- In view of lack of data on P availability from composts and to stay on the side of caution it is strongly recommend that when compost is applied to land soil test P levels should be measured every year. If the soil test value goes up by one unit, application of compost should be terminated on that part of land.
- Beside compost as a source of nutrients, it also has other properties which other organic fertilisers do not have as a source of stabilised organic matter, disease suppression properties, improved water retention. As such, compost should be given as separate classification as a 'soil conditioner' as opposed to being just a fertiliser source.
- Up to 1 January 2011, there is a temporary rule in which more phosphorus can be applied on land than crops require, as long as it comes from manure produced by pigs, poultry or from spent mushroom compost and that the 170kg nitrogen is not exceeded. This rule should be extended to include all types of source-separated compost.
- This report must be read in conjunction with *"A Literature Review on the Availability of Nitrogen from Compost in Relation to the Nitrate Regulations SI 378 of 2006"* (Prasad, 2009), as the available of nitrogen and phosphorus are required for compliance with SI 378 of 2006.

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8. Glossary of Terms

APR
Apparent Phosphate Recovery

Analysis of Coverience
Similar to Analysis of varience except both factors vary

Ap horizon
This is the top part of the soil horizon which can be ploughed.

APR
Apparent P recovery by plant.

Available inorganic phosphate
Phosphate available to the plant.

Biowaste (Biodegradable Material)
Source-segregated biodegradable waste of an organic or putrescible character.

Compost
Compost means the stable, sanitised and humus-like material rich in organic matter and free from offensive odours, resulting from the composting process of separately collected biowaste.

CAT extractable
Calcium chloride + DTPA extraction.

C:P ratio
The carbon/phosphorus ratio.

Compost stability
Compost stability is associated with the microbial activity. Maturity is sometimes confused with stability but maturity is related to the absence of phytotoxic substances for the growth of plants. More details on stability levels of compost are given in Prasad and Foster (2009). Maturity is determined basically by biotests with plants (phytotoxicity tests), in which the germinating power of seeds in compost is determined. The author has changed the word maturity to stability in this report when stability should have been used.

CUP/ efficiency of plant P uptake
Plant P uptake as a % of added P.

CU-P
Coefficient of utilisation in relation to inorganic P.

CPU
Cumulative phosphorus uptake by plant.

Green Waste (Garden and Landscape Material)
Vegetation waste from gardens and parks including tree cuttings, branches, grass, leaves, prunings, old plants and flowers.

Highly mobile phosphorous fraction
Susceptibility to leaching.

Incubation trial
Compost on its own or mixed with soil is incubated at certain temperature and moisture for a period of time and samples are taken for analysis

Isotopic Exchange Kinetic
This method involves adding ^{33}P to a solution and change of the radioactive over time is recorded as a result of change of exchangeable phosphate over time.

Isotopic exchange kinetic
A technique to determine net mineralisation of P compounds in soil using isotopes.

Ligand from taken L
Bind a molecule which is able to bind to and form a complex with a biomolecule.

Labile P
Labile P are orthophosphate ions adsorbed to the surface and represents easily desorbable P immediately available for plant uptake.

Plant P uptake
P taken up by plant.

Quadratic Regression
Not linear but curvelinear with two values of x.

Relative agronomic effectiveness (RAE)
The RAE of a material compared to an inorganic fertiliser.

Residual effect
What is left over from previous years.

Superphosphate
Superphosphate is made by reacting finely ground phosphate rock with sulphuric acid to convert the insoluble mineral to a plant available form. Superphosphate contains phosphorus and sulphur in a ratio of 1 to 1.16. When applied at a rate to meet P requirements, the sulphur requirements will also be met in the majority of situations.

Soil test Mehlich I
The Mehlich-1 extractant (implemented in 1953) was developed by Dr. Adolph Mehlich for the North Carolina Department of Agriculture Soil Testing Division. It is a versatile soil extractant that is used for determining the amounts of phosphorus, potassium, calcium, magnesium, zinc, manganese, copper and boron. It is made up of a dilute solution of hydrochloric and sulphuric acids, thus it is often referred to as the "double acid" extractant. It works well for acidic, low cation exchange capacity (CEC) soils. The extractant is made of 0.05 M hydrochloric acid + 0.0125M sulphuric acid.

Soil test Mehlich III
The Mehlich-3 test was developed in North Carolina for routine analyses of P, K, Ca, Mg, sodium (Na), and micronutrients. The advantage of this test is that it may offer the possibility of using one test for P and other nutrients across acid, neutral, and high-pH soils. The extractant is made of 0.015M ammonium fluoride + 0.2M acetic acid + 0.25M ammonium nitrate + 0.13M nitric acid.

Soil test Morgan
This extractant is made of 0.54M acetic acid + 0.7M sodium acetate pH 4.8.

Soil test Olsen
This extractant is made of 0.5M sodium bicarbonate pH 8.5. This table below shows the Olsen units based on the different levels of P.

Olsen ppm P	Index Unit
0 – 9	0
10 -15	1
16 -25	2
26 -45	3
46 – 70	4
>71	5

Sesquioxide
Sesquioxide is an oxide containing 3 atoms of oxygen and two atoms of another element. Sesquioxide of iron or aluminium are found in soil.

Sesquioxic
Oxides, oxyhyoxide or hydroxide of iron and aluminium.

Sequential extraction techniques
Extraction of the same sample in sequence, e.g. from weak to a stronger extraction.

Triple superphosphate
Triple Superphosphate is a fertiliser produced by the action of concentrated phosphoric acid on ground phosphate rock. The active ingredient of the product, monocalcium phosphate, is identical to that of superphosphate, but without the presence of calcium sulphate that is formed if sulphuric acid is used instead of phosphoric acid. The phosphorus content of triple superphosphate is therefore greater than that of superphosphate. Triple superphosphate is a common phosphate (P) fertiliser.

Total P
The sum of all forms of phosphorus.

P equilibrium concentration
The concentration at which the system is in equilibrium.

P buffering
This is the change in quantity of sorbed soil required for unit change in solution P concentration.

Water soluble P
Phosphorus soluble in water.

9. Acronyms and Notation

[referring to Ireland, except where otherwise specified]

Al	Aluminium
APR	Apparent Phosphorus Recovery
ACPU	Amendment-Derived Cumulative Phosphorus Uptake
C	Carbon
Ca	Calcium
CABI	Commonwealth Agricultural Bureaux International (United Kingdom)
CAL	Calcium Lactate
CAN	Calcium Ammonium Nitrate
CAT	Calcium Chloride + DTPA Extraction
Cl	Chlorine
CPU	Cumulative Phosphorus Uptake
CRC	City Refuse Compost
CU	Coefficient of Utilisation
cv	cultivar
DSS	Dewatered Sewage Sludge
DISS	Dewatered Irradiated Sewage Sludge
DICSS	Dewatered Irradiated and Composted Sewage Sludge
EC	Electrical conductivity
EPA	Environmental Protection Agency
ERTDI	Environmental Research Technological Development & Innovation
Fe	*Ferrum* (L) - iron
K	*Kalium* (L) – potassium
Mg	Magnesium
MSW	Municipal Solid Waste
N	Nitrogen
Na	*Natrium* (L), sodium
NA	Not Available / Not Applicable
NFEV	Nitrogen Fertiliser Equivalent Values
NPK	Nitrogen, Phosphorus, *Kalium* (potassium)
ORBIT	Organic Recovery and Biological Treatment
P	Phosphorus
PLC	Poultry Litter Compost
pp	*paginae* (L), pages
RAE	Relative Agronomic Effectiveness
RTDI	Research Technological Development and Innovation
SI	Statutory Instrument
SMC	Spent Mushroom Compost
SSBW	Source-separated Biowaste
SSGW	Source-separated Green Waste
STRIVE	Science, Technology, Research, and Innovation for the Environment
t/ha	tonne(s) per hectare
TP	Total Phosphorus
TSP	Triple Superphosphate