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Project identification

1. Defra Project code: WR0214
2. Project title: AGRONOMIC BENEFIT OF INDUSTRIAL BIOWASTES
3. Contractor organisation(s): Centre for Environmental Control and Waste Management, Department of Civil and Environmental Engineering, Imperial College London
4. Total Defra project costs (agreed fixed price): £ 42,000
5. Project: start date ..... 01 April 2006
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Executive Summary

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Introduction
Predicting N release in agricultural soils amended with organic residuals is essential to ensure that there are sufficient nutrients for crops, and minimal losses to the environment. Factors such as moisture, temperature, soil type and organic residuals type may affect the amount of mineralised nutrients. Industrial biowastes are increasingly being used as soil amendments as a diversion from landfill disposal; these materials result from a diverse range of processes and vary greatly in physical and chemical characteristics. There is little published or advisory information regarding their agronomic benefit, therefore research is required to quantify their fertiliser value. Information is also required to describe microbial transformations and immobilisation of N in biowastes-amended soil, which may vary between soil types influencing extent and rate of nutrient release.

Objectives
The objectives of this research were to quantify mineralisation of N in biowastes-amended soil, and investigate other agronomic benefits of biowastes, with the aim of developing fertiliser guidelines.

Methods
A programme of field trials was established at Imperial College Silwood Park campus in 2006-2007 to quantify the agronomic value of a range of industrial biowastes. Biowastes from the vegetable, meat and dairy industries and from aerobic and anaerobic digestion plants were investigated. A systematic design was used, which allowed for 4 rates of application plus an unamended control. Biowastes were incorporated into the soil to minimise losses of N by NH_3 volatilsation. Perennial ryegrass was used as an indicator crop as it is effective at capturing available N. Yield response (fresh and dry weights) and N offtake in biowastes-amended soils, in comparison to mineral N fertiliser, were used to calculate the replacement N fertiliser value (N equivalency). In 2006, plant tissue was analysed for other major nutrient elements, and trace elements (including P, K, Mg, S, Na, Ca, B, Fe).

In addition, a laboratory incubation experiment was set up to investigate N transformations, including microbial biomass N dynamics in biowastes-amended soil. Three contrasting soil types were amended with the aerobic and anaerobically digested biowastes from the programme of field experiments. A mineral fertiliser treatment and anaerobically digested biosolids were included as reference materials.

Outcomes

Nitrogen equivalency ratio values for different biowastes have been calculated relative to mineral N, thus a value of 0.5, for example, indicates that the N applied in a particular biowaste is 50 % as available as the same amount of total N applied in the mineral fertiliser source. Significant linear relationships between rate of total N application from biowastes and crop response were found in most cases, with the exception of treatments with a low total N content. These materials require investigation under higher rates of application, to assess potential soil conditioning benefits, or with added mineral N to measure the value of other nutrient resources in the biowaste. The liquid aerobic digestate of food wastes (TAD) had N equivalencies in the range of 0.59-0.76, despite lower mineral N contents than anaerobic digestates, demonstrating a large pool of rapidly mineralisable organic N. Liquid anaerobic co-digestates of food waste and animal slurry (AD) had N equivalencies of 0.68-0.85 depending on length of storage, which tended to reduce the amount of available N. The N equivalency of dewatered anaerobic digestate from mechanically sorted municipal solid waste (ADMSW) was equivalent to dewatered digested biosolids (DMAD) in the 2006 trial, at 0.52, but there was no significant response to ADMSW in 2007. Differences in response to ADMSW and the stored or fresh AD co-digestate, between the two years of the experiment, demonstrated the potential for variation in the properties of the material brought about by differences in length of storage.

The N equivalency for DMAD was approximately 20 % greater than values found in previous trials. This indicated that elements other than N may be affecting the crop response in grass fertilised with this material at top rates of application. Elemental analysis of the crop indicated that S supplied in DMAD may be contributing to the crop response, as the tissue content of this element was 4 times greater than in mineral N fertilised grass. The anaerobic digestate of MSW was also a significant source of S.

The results of the laboratory incubation experiment, to investigate microbial biomass N and mineral N in biowastes amended soil, demonstrated lower recoveries of N in fine-textured soil with low stability waste. Denitrification was suspected as the potential mechanism for this observation.

Biowastes from certain industrial sources (for example, biological treatment sludges) may contain potentially toxic elements and organic contaminants that could limit their value as agricultural fertilisers. However, the use of the majority of biowaste sources in agriculture, and all of those considered here, is not restricted by inorganic or organic contaminants.

Future research

The experimental design utilised in the programme of field trials was appropriate for further investigation into the agronomic benefit of industrial biowastes. Future field investigations could adopt the same systematic design with ryegrass as an indicator crop and include a further range of biowastes (leather and tannery/pharmaceutical/further food industry wastes) and a range of soil types. Nitrogen equivalencies should be determined relative to mineral fertiliser N and anaerobically digested biosolids. Fertiliser controls should be included for P, K and S. This design should provide an absolute value of the availability of N from each biowaste type, because incorporation of the biowastes into the soil minimises gaseous losses of N by NH_3 volatilisation and ryegrass is effective at capture of available N. Further investigation is required at an operational scale, with field monitoring (agricultural crops) to calibrate the findings of the ryegrass trials. Further investigation is also required into the variability introduced by length of storage into fertiliser value as this study indicated that N availability decreased following a period of storage.

Interactions between soil type and biowaste type on N availability, and the implications for

gaseous N losses to the environment from biowastes-amended soils requires further research. Denitrification rates relative to soil moisture and biowaste type could be determined by laboratory investigation.

We recommend that fertiliser guidelines and a decision support tool be developed for industrial biowastes to improve confidence and reliance on land application as a means of recycling these important nutrient resources.

Project Report to Defra

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   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

1. INTRODUCTION

1.1 Background

The term 'biowastes', in this report, is used to refer to organic residuals from industrial and commercial processes, excluding agriculturally derived wastes and wastewater treatment sludges. An estimated 7 million tonnes of these materials are spread on agricultural land annually in the UK (Gendebien *et al*., 2001), and this is regarded as the main potential alternative management route to landfill disposal (Gendebien *et al*., 2001; Defra, 2007). Under the new Environmental Permitting Regulations (SI, 2008), certain industrial biowastes may be applied to land, currently regulated through a notifiable exemption, to be obtained prior to land-spreading. Those wishing to spread industrial biowastes to agricultural land must provide a risk assessment and demonstrate that they provide either benefit to agriculture or ecological improvement. Biowastes represent a diverse range of materials from the food and drinks industry, pharmaceutical, leather and tanneries and textile industries. Hence, they are highly variable in terms of physical and chemical properties, such as organic matter and nutrient element content. The new regulations are currently out for consultation; under the new proposals, it is likely that the application of these wastes to land will be increasingly regulated under environmental permitting.

Total nutrient concentrations in organic fertiliser sources do not reflect their availability for plant uptake. In addition to mineral forms, nutrients will be in organic forms not all of which will be available for crop uptake. To gain maximum economic benefit and prevent environmental damage by losses of nutrients to the environment, it is important to accurately quantify nutrient availability in organic residuals. In addition, under the Nitrates Directive (CEC, 1991), the supply of N to crops from fertilisers and organic sources must not exceed crop requirements. There has been extensive research into the use of livestock manures and slurries in agriculture (Smith *et al*., 1984; Nicholson *et al*., 1996; Jackson and Smith, 1997; Nicholson *et al*., 1999), and biosolids from wastewater treatment (Hall, 1983a;b; Serna and Pomares, 1991a; Serna and Pomares, 1991b; Hérnandez *et al.,* 2002; Cogger *et al*., 1999; Smith and Bellett-Travers, 2001; Smith *et al*., 2002b; Smith *et al*., 2003; Breedon *et al.*, 2003; Morris *et al*., 2003.; Corrêa et al., 2004; Cogger *et al*., 2004; Tarrasón *et al*., 2007), and fertiliser guidelines exist for these materials (MAFF, 2000). However, with the exception of paper wastes (King, 1984; Aitken *et al*., 1998; Douglas *et al.,* 2003; Levy and Taylor., 2003; Gibbs *et al*., 2005; Burgos *et al*., 2006), there has been little quantitative research on the properties or agronomic characteristics of industrial biowastes, and the availability of N from these organic residuals. The complexity and variability of the materials require the development of fertiliser guidelines, to improve confidence in their agronomic value, gain maximum economic benefit from their use in agriculture and to prevent release of excess nutrients to the environment.

A programme of field experiments was set up to investigate the agronomic benefit of industrial biowastes. For the initial experiment, established in Spring 2006, a range of biowastes were selected to include representative materials from the vegetable, meat, and dairy processing industries, fish production and the drinks industry. Digestates of municipal solid waste and of food processing waste were included to investigate the effects of pre-treatment on the fertiliser value. An example of an anaerobic digestate fresh from the digestion plant and after a period of lagoon storage, and a fish farm waste which varied in length of time in a settlement pit were selected to investigate the effects of storage. The digested biowastes applied in the 2006 field trial were included in the 2007 trial to investigate the reproducibility of the crop response, in addition to a selection of different materials from food and drinks processing industries.

In addition, a laboratory experiment investigated N transformations, including microbial biomass N dynamics, in biowastes amended soil. The materials investigated were the aerobic and anaerobic digestates from the field experiment. Dewatered mesophilic anaerobically digested biosolids (DMAD) (digested sewage sludge cake) and inorganic N (NH_4Cl) were included as reference materials.

1.2 Objectives

- To characterise the total and mineral nutrient concentrations in a range of selected industrial biowastes;
- To quantify the nitrogen release properties of chosen industrial biowastes in a programme of detailed, systematic field experiments relative to digested sewage sludge and mineral fertiliser;
- To examine the production of other important plant nutrient elements from the selected industrial biowastes, including: P, K, Mg and S;
- To determine the influence of soil type and environment on nutrient release behaviour and soil microbial activity by laboratory incubation;
- To develop a preliminary set of recommendations on the agronomic and nutrient properties and produce an advisory pamphlet;
- To develop a framework of proposed research priorities on industrial biowastes for consideration by the Defra Waste and Resources Research Programme.

2. MATERIALS AND METHODS

2.1 Field Experiments

2.1.1 Location

The field trials were located at Silwood Park, the Imperial College campus in Berkshire, and were established between 3-5 May in 2006 and 25-27 April in 2007. The soil was a light, sandy loam, pH 5.7-6.9 with a low organic matter (OM) content (2.5-3.2 %) and a cation exchange capacity (*CEC*) of 7.3-10.7 meq 100 g^{-1} ds. Phosphorus, K and Mg indices (MAFF, 2000) were 2/3, 2- and 2, respectively. Nitrogen was available at a concentration of 14.3-15.2 mg kg^{-1} dry soil **(**ds).

2.1.2 Biowastes

Descriptions and abbreviations of biosolids and biowastes investigated in the programme of experiments are given in Table 2.1. The dry solids (DS) contents of the solid materials were determined by drying overnight at 105 ^{o}C in a forced air oven, and the solid wastes were applied according to their dry solids (DS) content. The DS, organic matter (OM), pH and nutrient contents are given in Tables 2.2-2.3. The trout wastes had relatively low total N contents of approximately 1 % DS (Table 2.2), this is a result of their mixture with sediment and soil in the settlement lagoon, their mineral N content was also relatively low at approximately 3.5 % total N. Total N content of ADMSW ranged between 1.5–2.32 % DS, which was less than 50 % of the total N content of DMAD, however, mineral N was 15.3–18.4 % of the total N. Total N in TAD was between 3.43–4.04 % DS, comparable to the amounts available in the biosolids, available N was approximately 10 % total N, similar to that of DMAD. This was a liquid biowaste that was considered with the solid materials due to its high DS content; the proportion of mineral N was less than the liquid digested biosolids, indicating that the aerobic digestion method does not degrade the organic material to the same extent as anaerobic digestion. Vegetable waste was a relatively rich source of total N and contained 2.42 % DS, and mineral N was equivalent to 8.3 % of the total N content. The potato sludges, Salt whey, KG and Abattoir had a low total N content, reflecting their low DS content (Table 2.3). However, whereas the mineral N content of Salt whey and KG was less than 10 % of total N, most of the total N in Abattoir was in mineral forms, equivalent to 65 % total N. The anaerobic co-digestates, AD fresh and AD stored, had a high total N content as did Yeast and Ice-cream. However, whereas AD fresh and AD stored had high mineral N contents similar to the liquid digested biosolids, between 40–72 %, in Ice-Cream and Yeast the mineral N content was only 1 % and 1.5 % of total N, respectively.

Table 2.1 Waste description and source

	Waste Description & Source	Abbreviation	2006	2007	Incubation
1	Dewatered mesophilic anaerobic digested biosolids (Southern Water, Ashford)	DMAD	●	●	●
2	Abattoir wash water (A&G Barber, Chelsmford)	Abattoir	●		
3	Trout farm waste (uneaten food/faeces), old (UK trout farm)	Trout old	●		
4	Trout farm waste (uneaten food/faeces), fresh (UK trout farm)	Trout fresh	●		
5	Potato processing sludge (FenMarc, March)	Potato sludge	●		
6	Potato processing wash water (FenMarc, March)	Potato wash	●		
7	Chopped vegetable waste (broccoli/carrots/onions/potatos/parsnips) (FenMarc, Elm)	Vegetable		●	
8	Waste ice-cream mix (Unilever, Gloucester)	Ice-cream	●		
9	Fatty ice-cream waste from dissolved air flotation (Unilever, Gloucester)	Ice-cream DAF	●		
10	Stilton production waste (salty whey) (Tuxford & Tebbutt Ltd., Melton Mowbray)	Salt whey		●	
11	Brewery waste (kieselguhr) (UK brewery)	KG	●		
12	Brewery waste (live yeast and beer) (Fullers, Chiswick)	Yeast		●	
13	Anaerobic co-digestate (food waste/abattoir/farm) pre-storage (Summerleaze, Holworthy)	AD fresh	●	●	●
14	Anaerobic co-digestate (food waste/abattoir/farm) post-storage	AD stored	●	●	●
15	Thermophilic aerobic digestate (vegetable/bread/cooked meat)	TAD	●	●	●
16	Anaerobic digestate (municipal solid waste)	ADMSW	●	●	●

Table 2.2 Physical and chemical characteristics of DMAD and solid biowastes (DS basis)

Biowaste		DS (%)	OM (%)	pH	Total N (% DS)	Mineral N (% Total N)	Total Concentration (mg kg^{-1} ds)			
							P	K	Mg	S
DMAD	2006	30.8	58.2	7.0	4.70	10.3	29.3	0.90	1.7	9.3
	2007	27.8	60.5	6.7	4.67	12.4	30.2	1.58	2.67	10.3
	Lab.	28.9	60.1	7.2	4.64	9.09	28.0	1.94	2.98	11.5
Trout old	2006	40.9	16.2	7.2	1.00	3.73	4.15	1.57	2.16	3.69
Trout fresh	2006	36.9	16.5	7.2	0.92	3.52	5.47	1.15	1.87	3.38
Vegetable	2007	8.32	89.3	5.2	1.71	18.2	3.99	38.3	1.64	5.62
TAD	2006	20.3	95.6	3.6	1.50	18.4	1.74	6.72	0.61	1.65
	2007	26.7	95.1	3.8	2.32	15.3	2.72	3.18	0.69	1.24
	Lab.	17.1	86.0	4.4	3.50	8.01	3.881	5.44	2.38	3.22
ADMSW	2006	37.2	56.6	7.3	4.04	14.1	2.60	2.93	3.99	5.02
	2007	34.0	52.3	7.6	3.43	8.12	4.29	5.36	6.28	7.42
	Lab.	28.9	42.3	8.8	2.32	15.3	4.43	5.06	7.99	7.97

Table 2.3 Physical and chemical characteristics of liquid biowastes (FW basis)

Biowaste		DS (%)	OM (%)	pH	Total N (g m^{-3})	Mineral N (% Total N)	Total Concentration (g m^{-3})			
							P	K	Mg	S
Abattoir	2006	0.13	0.07	7.7	1.24	21.1	<0.01	103	16.3	4.40
Potato sludge	2006	2.14	1.26	3.9	0.15	15.2	<0.01	2031	90.5	54.9
Potato wash	2006	0.60	0.31	5.3	5.35	1.06	<0.01	153	17.5	153
Ice-cream	2006	35.2	3.39	4.4	1.66	1.28	664	1771	150	239
Ice-cream DAF	2006	9.17	8.84	3.5	0.95	6.4	74.9	151	20.1	170
Salt whey	2007	4.64	2.13	4.3	0.75	5.01	1064	2019	221	224
KG	2006	5.46	0.58	3.9	6.85	1.5	<0.01	50.4	9.48	24.2
Yeast	2007	10.2	9.31	6.1	0.73	65.0	182	2087	116	353
AD fresh	2006	5.14	3.45	8.3	7.21	39.3	287	2102	256	274
	2007	5.03	3.63	8.3	6.73	53.1	362	2751	412	246
AD stored	2006	5.70	3.94	8.1	6.19	46.6	343	1765	342	237
	2007	4.95	3.60	8.3	5.46	71.8	178	1536	127	218
	Lab.	5.25	3.79	8.2	5.91	46.6	340	1975	348	334

2.1.3 Design

The field experiment was a systematic design (Cleaver *et al*., 1970; Smith and Hadley, 1988) arranged as three replicate blocks each with 14, 1.2 m x 10.5 m main plots in 2006 and 12 main plots in 2007. The main plots were divided into 5 subplots, each 2.52 m^2. The solid materials were applied at rates of 0 (control), 2.5, 5, 7.5 and 10 t DS ha^{-1} and liquid materials were applied at rates of 0, 20, 50, 75 and 100 m^3 ha^{-1}. In 2007, rates of application for the liquid wastes were reduced to 0, 20, 40, 60 and 80 m^3 ha^{-1} for AD fresh and AD stored and Yeast. Mineral N calibration plots were established with inorganic fertiliser, prilled ammonium nitrate, applied at rates of 0, 60, 120, 180 and 240 kg N ha^{-1}. The rates of mineral N supplied to the calibration plots were also reduced to 0, 50, 100, 150 and 200 kg N ha^{-1}, as the top rate applied in 2006, of 240 kg N ha^{-1} was in excess of the linear section of the crop response curve. Three additional control treatments were included with the same rates of application for mineral N plus a base dressing of P, K or P and K together. Phosphorus was applied as granulated triple-super phosphate at a rate of 22 kg P ha^{-1} and K was applied as KCl a rate of 50 kg K ha^{-1}. In 2006, in the case of biowastes treatments where a low N content was expected, treatments 5 and 6, a base dressing of N was applied at a rate of 120 kg N ha^{-1}. The treatments were applied to the soil surface and incorporated immediately using a pedestrian operated rotary cultivator, set to a cultivation depth of 10 cm. This was to minimise NH_3 volatilisation losses and maximise N recovery. Following N analysis of the waste materials it was considered appropriate to apply a top dressing of ammonium nitrate at a rate of 120 kg N ha^{-1} to further biowastes treatments with a low total N content (treatments 3,4,8 and 9, Table 2.1) this was applied on 7 June 2006. Perennial ryegrass (*Lolium perenne*) cv Guilford was sown at a rate of 100 kg ha^{-1}. Perennial ryegrass was used as an indicator crop as it is effective at capturing available soil N (Addiscott *et al*., 1991; Christian and Richie, 1998).

2.1.4 Harvesting and Analysis

Plant material was harvested using a pedestrian operated reciprocating blade mower at a height of 2 cm above the soil surface, a 1.28 m^2 (0.8 x 1.6 m) of each subplot was harvested. Four harvests were taken during 2006 and two harvests were taken in 2007. Fresh weights were measured and sub-samples of fresh material were dried to a constant mass at 80 ^oC in a forced-air oven to determine dry matter yield. The dried material was ground to <1 mm. Dried ground grass was analysed for total N and P content using a standard Kjeldahl digestion method (SCA, 1986). An automated colorimetric technique using a multichannel segmented flow analyser (Skalar SAN^{plus} Segmented Flow analyser, Skalar, Breda, The Netherlands) was used to simultaneously determine total N and P in the digested solution. In addition, subsamples of grass from the first harvest in 2006, from the top rates of application for each plot, and randomly selected control plots were analysed for full elemental

concentration. Plant tissue was analysed by ICP-AES (Fisons-ARL 3580B ICP, Ecublens, Switzerland) following a standard aqua-regia digestion method (MAFF, 1986).

2.1.5 Statistical Analysis

Relationships between cumulative fresh and dry weight yields and N offtake and the total N applied in biowastes were statistically analysed by linear regression techniques and compared to mineral N calibration plots. Linear models had the form: $y = a + bx$ where y is the yield or N removal in harvested crop (t ha^{-1} fresh or dry matter or kg N ha^{-1}) and x is the rate of total N addition in the biowaste or inorganic N fertiliser. Where the linear regression was statistically significant ($P \leq 0.05$), the slopes (ie this is the regression coefficient that represents the rate of change of the variable y as a function of changes in x and is indicated by 'b' in the linear model above) of the regression equations for each biowastes treatment were compared to the slope (which has a different 'b' value) obtained for mineral N to obtain N equivalency values for the biowastes as a proportion of the crop response and availability of mineral N (Kiemnec *et al*., 1987; Smith *et al*., 2001; Smith *et al*., 2002; Morris *et al*., 2003). Where the crop response was curvilinear at top rates of application, quadratic equations ($y = a + bx + cx^2$) were fitted to the data. In general, the regression coefficient for the quadratic term (x^2) in the crop response models was not significant and the yield pattern therefore approximated to a linear function of N application. If the quadratic relationship was significant, however, the data point for the top rate was removed and the quadratic equation was re-fitted to test the statistical significance of the x^2 regression coefficient. In all cases, this was not significant ($P > 0.05$), therefore a linear model was fitted to the remaining data points, and the yield response relative to mineral N was calculated by comparing the linear regression coefficients. Only in a minority of cases was it necessary to follow this procedure. Yield response to manure N is considered to be linear between applications of 0-300 kg N ha^{-1} (Whitehead, 1995), as this is within the range of standard rates of application of fertiliser N, it was appropriate to only consider the linear response. A mean N equivalency value was calculated from each of the indicators of crop response to N (fresh yield; dry yield and N offtake) to each biowastes treatment.

2.2 Laboratory Incubation

Three soil types were used, a sandy silt loam (Brices Field) and a silty clay (North Sidelands) both from Wye, Kent, and a loamy sand from Silwood Park, the site of the field trials. The soils had contrasting OM contents; Brices Field and Silwood Park had OM contents of 1.9 % and 2.1-3.2 % ds and North Sidelands contained approximately twice the amount of OM compared to the other soil types, equivalent to 4.0 %. Physical and chemical characteristics of the soils are given in the main report (Tables 2.1-2.3). These soils were selected to investigate microbial biomass N (MBN) dynamics following biowastes amendment in contrasting soil types and to allow comparisons with field data. Soils were sieved to 5.6 mm to remove stones and plant debris, and stored in loosely tied black polyethylene sacks at 4 ^{o}C for 4 days before use. Samples of each soil (10 g) were dried overnight at 105 ^{o}C in a forced air oven to determine the gravimetric water content by loss in mass of the soil (MAFF, 1986). The water holding capacity was measured using a procedure modified from Harding and Ross (1964). The soils were air-dried for 8 hours to reduce their moisture content until they reached approximately 50 % water holding capacity (WHC), which is within the standard range used for laboratory incubation experiments (Harding and Ross, 1964; Smith *et al*., 1998).

Three processed biowastes were used: a thermophilic anaerobic digestate of food waste (TAD); an anaerobic digestate of municipal solid waste (ADMSW); an anaerobic co-digestate of food/farm and abattoir waste (AD); see Table 2.1 for details of sources. Nitrogen concentrations and physico-chemical characteristics of the wastes are given in Tables 2.2 and 2.3. In addition, dewatered mesophilic anaerobic digested biosolids (DMAD) was included as a reference material. An unamended soil and an mineral N control, receiving NH_4Cl, were included for each soil type. The solid materials, ADMSW and DMAD, and TAD, which was a liquid with a high dry solids content, were applied to the soils at a rate equivalent to 10 t DS ha^{-1}, and the liquid, AD, was applied at a rate of 50 m^3 ha^{-1}. The mineral N treatment, NH_4Cl, was applied at a rate of 200 kg N ha^{-1}. Rates of incorporation were calculated on the assumption that the soils had a bulk density of 1 and the cultivation depth was 10 cm. The solid materials were weighed out and thoroughly mixed into a slurry with 50 ml deionised water, a hand blender was used to homogenise ADMSW, which contained fibrous material. Ammonium chloride was dissolved in 75 ml of deionised water, and the unamended control soil also received 75 ml

of deionised water to maintain equivalent moisture content. The wastes and mineral N were then carefully mixed into 2.1 kg portions of soil using a hand mixer, and then sieved to pass 5.6 mm, to ensure uniform incorporation.

The amended and control soils were weighed out into triplicate, 100 g portions in polythene bags (140 X 140 x 50 cm), for each removal time of the experiment. A gap was left in the seal of each bag to allow gas exchange, and the samples were placed in an incubator at 25 ^{o}C. Samples were removed after 0, 3, 6, 13, 20, 34 and 48 days. This time period was chosen as NO_3-N production from the wastes was expected to reach a maximum by approximately 50 days as observed in previous incubation experiments with biosolids at similar temperatures (Smith *et al*., 1998; Smith and Durham, 2002; Breedon *et al*., 2003). The mass of each bag was recorded and moisture was kept constant throughout the incubation experiment by addition of deionised water. At each removal time soil was weighed out for microbial biomass C and N determination, and gravimetric moisture content and the remaining soil was frozen at -18^{O}C, and later analysed for mineral N.

A chloroform-fumigation, direct extraction protocol based on the methods of Vance *et al*. (1987), Brookes *et al*. (1982, 1985) and Saggar *et al*. (1981) was used for measurement of microbial biomass C and N concentration (Section 5.3.5, main report). The filtered extracts were kept at 4 ^{o}C until analysis for total dissolved organic carbon using a Shimadzu TOC 5000.

Microbial biomass C (MBC) was calculated according to the following equation:

MBC (µg C g^{-1}soil) = E_C / K_{EC};

where E_C is the organic C extracted from fumigated soils minus that extracted from non-fumigated soil and K_{EC} is the extractable part of microbial biomass C after fumigation (Joergensen *et al*., 1995). The K_{EC} value used to transform the difference between the organic carbon into microbial biomass was 0.45 (Vance *et al.,* (1987). The extracts were frozen at -19^{o}C prior to analysis for microbial biomass N content, samples were kept at 4 ^{o}C overnight to defrost. Determination of the microbial biomass N was carried out using a Kjeldahl procedure adapted from Brookes *et al*. (1985). An automated colorimetric technique using a Skalar SAN ^{plus} segmented flow analyser (Skalar SAN^{plus} Segmented Flow Analyser, The Netherlands) was used to simultaneously determine total N and P in the digested solutions. The difference between total N in the fumigated and non-fumigated samples is the chloroform-labile N pool and is proportional to microbial biomass N:

Microbial biomass N = chloroform-labile N/ K_{EN}

The K_{EN} value used to transform the difference between the organic nitrogen into microbial biomass N was 0.54 (Brookes *et al.*, 1985). Concentrations of NH_4-N, NO_3-N and NO_2-N in soils were determined following a standard procedure (MAFF, 1986). The filtrate was analysed using a multichannel automated colorimetric analyzer (Skalar SAN^{plus} Segmented Flow Analyser, The Netherlands).

3 RESULTS AND DISCUSSION

3.1 Characterisation of Physical and Chemical Properties of a Selected Range of Biowastes

An initial aim was to characterise the physical and chemical characteristics of the selected range of biowastes. The DS, OM, pH and nutrient contents are given in Tables 2.5-2.8, and described in the Materials and Methods of the main report (Section 2.4.3). Biowastes from certain industrial sources (for example, biological treatment sludges) may contain potentially toxic elements and organic contaminants that could limit there value as agricultural fertilisers. However, the use of the majority of biowaste sources in agriculture, and all of those considered here, is not restricted by inorganic or organic contaminants.

3.2 Quantification of the N Release Properties of Industrial Biowastes Relative to Anaerobically Digested Biosolids Cake and Mineral N Fertiliser

Linear regression coefficients ('b' values indicating the slope of the regression relationship, see explanation above) and r^2 (this is the coefficient of determination, which is a value from 0.0 – 1.0 that indicates the total amount of experimental variance explained by the model; the larger this value the

stronger the relationship) values, where a significant relationship between rate of N application and crop response was found in 2006 and 2007, are provided in Tables 3.1 and 3.2. Section 2.1.5 explains the importance of the slope (b) values that indicate the increase in yield (t ha^{-1}) or N removal in harvested herbage (kg N ha^{-1}) per kg of N added per ha in the biowaste or inorganic fertiliser. In the majority of cases, the r^2 results were >0.5 and were typically >0.7 indicating a strong or very strong (eg >0.8) relation between the crop yield or N offtake in harvested crop and the total amount of N applied in the different biowastes or mineral fertiliser. Nitrogen equivalency values were calculated for biowastes treatments that demonstrated a significant relationship between rate of total N application and crop response ($P \leq 0.05$), by comparing linear regression coefficients of the crop response with biowaste N to those obtained for mineral fertiliser N, as described above. An N efficiency ratio is calculated for the biowaste relative to the mineral N response by dividing the slope of the relationship for the biowaste ($b_{biowaste\text{-}N}$) with the slope for inorganic fertiliser ($b_{mineral\text{-}N}$). These values, shown in Table 3.3, were determined using three different crop measurements including: fresh yield, dry yield, and N offtake; each provides a key measure of the crop response to N application and collectively they give an overall indication of the N availability in the applied biowaste or fertiliser.

Table 3.1 Summary table of linear regression coefficients and r^2 values for mineral fertilisers, biosolids and biowastes in the 2006 experiment. NS=not significant (P>0.05); † Low TN wastes: regression relative to rate of application

	Fresh yield		Dry yield		N offtake	
	Slope	**r^2**	**Slope**	**r^2**	**Slope**	**r^2**
Mineral N	0.077	0.78	0.011	0.70	0.46	0.92
DMAD	0.037	0.94	0.0072	0.93	0.21	0.90
Abattoir	0.12	0.72	0.022	0.73	0.58	0.55
Trout old†	0.44	0.33	0.13	0.38	3.46	0.36
Ice-Cream DAF†	NS	NS	NS	NS	0.30	0.50
KG†	0.039	0.65	NS	NS	NS	NS
AD fresh	0.057	0.95	0.012	0.95	0.36	0.93
AD stored	0.051	0.85	0.0076	0.85	0.33	0.91
TAD	0.056	0.89	0.01	0.86	0.29	0.90
ADMSW	0.043	0.30	0.0072	0.37	0.17	0.52

Table 3.2 Summary table of linear regression coefficients and r^2 values for mineral fertilisers, biosolids and biowastes in 2007 field experiment. NS=not significant (P>0.05)

	Fresh yield		Dry yield		N offtake	
	Slope	r^2	Slope	r^2	Slope	r^2
Mineral N	0.04	0.57	8.19	0.41	0.25	0.71
Mineral N+K	0.049	0.84	10.8	0.85	0.26	0.88
Mineral N+P	0.039	0.68	7.48	0.51	0.21	0.79
Mineral N+P+K	0.064	0.53	11.49	0.57	0.31	0.65
DMAD	0.032	0.76	5.81	0.74	0.15	0.81
Vegetable	0.024	0.77	6.64	0.78	0.12	0.72
Salt whey	0.026	0.26	NS	NS	NS	NS
Yeast	0.051	0.94	11.4	0.88	0.23	0.89
AD fresh	0.052	0.94	9.15	0.83	0.19	0.85
AD stored	0.041	0.77	8.76	0.88	0.23	0.94
TAD	0.037	0.76	6.71	0.74	0.19	0.81
ADMSW	NS	NS	NS	NS	NS	NS

An example of the cumulative response of perennial ryegrass to application of biowastes and mineral N fertiliser application, measured as dry yield is shown in Figure 3.1 (2006 data) (See also Sections 3.3 and 4.3, of the main report). The majority of the biowastes were a significant source of N, and an increase in crop yield and N offtake was observed with increasing rates of application of total N. The N equivalency ratio values are relative to mineral N, thus a value of 0.5, for example, indicates that the N applied in a particular biowaste is 50 % as available as the same amount of total N applied in the mineral fertiliser source. Therefore, the performances of the biowastes as N sources for crop growth can be compared directly to mineral N and relative to each other. For example, in 2006, the N

equivalency value for DMAD was 0.52, thus suggesting that the N contained in the biosolids was apparently 50 % as available as the mineral N fertiliser (Table 3.3). This value is somewhat larger than we have previously measured for DMAD at this site – previous field trials indicate an equivalency value of 0.30 for this sludge type (Smith *et al*., 2001; Smith *et al*., 2002; Morris *et al*., 2003). This suggested that factors in addition to the N supplied in DMAD were also contributing to the apparent crop response, therefore leading to an overestimate of the N equivalency value in this case. Indeed, elemental analysis of DMAD (Table 2.2) and plant tissue from the field experiment demonstrated this material to be a significant source of S, and that this probably contributed to the crop response, increasing the apparent relative response in comparison to mineral N fertiliser. Thus, DMAD treated grass contained 5.02 mg S g^{-1} DM, which was more than three times the S concentration (1.34 mg g^{-1} DM) in grass leaf tissue from plots receiving the mineral N source (Table 3.4). Sulphur contents in ryegrass are typically in the range 2-5 mg g^{-1} DM (Whitehead, 1995).

Table 3.3 N equivalency values of biosolids and biowastes for each measure of crop response (fresh yield; dry yield and N offtake) compared to linear regression coefficients with mineral N controls.

	2006				2007			
	Fresh yield	**Dry yield**	**N offtake**	**Mean**	**Fresh yield**	**Dry yield**	**N offtake**	**Mean**
DMAD	0.48	0.64	0.45	0.52	0.50	0.51	0.48	0.50
Abattoir	1.51	1.92	1.24	1.60	-	-	-	-
Vegetable	-	-	-	-	0.38	0.58	0.39	0.45
Salt whey	-	-	-	-	0.41	NS	NS	0.41
Yeast	-	-	-	-	0.80	0.99	0.89	0.85
AD fresh	0.74	1.03	0.78	0.85	0.81	0.80	0.61	0.74
AD stored	0.66	0.68	0.70	0.68	0.64	0.76	0.74	0.71
ADMSW	0.56	0.64	0.37	0.52	-	-	-	-
TAD	0.73	0.93	0.63	0.76	0.58	0.58	0.61	0.59

Anaerobically digested municipal solid waste (ADMSW) was also a significant source of S. However, the plant tissue S contents from the other biowastes treatments were comparable to the mineral N fertiliser control and S was therefore assumed not to be contributing to crop response in these treatments. Previously, a base dressing of K_2SO_4 had been applied across the site at Silwood Park (Smith *et al*., 2001; Smith *et al*., 2002; Morris *et al*., 2003), but this was not done for the biowastes experiments as an additional aim was to assess transfer of other plant nutrient elements to the crop, in addition to quantification of N availability. In addition to these observations relating to S availability, the plant tissue analysis (Table 3.4) showed that potato wastes, AD and TAD were a significant source of K (this is discussed further in Section 3.3). In 2007, a further selection of mineral N controls was established, which included a mineral N gradient, plus base dressings of P and K, and a combination of P and K. In 2007, the N equivalency value of DMAD relative to mineral N fertiliser was extremely high, at 0.70 (see Table 4.2, main report). The N equivalency value of DMAD relative to mineral N fertiliser, with a base dressing of P and K was 0.50, similar to the value of 0.52 obtained in 2006 (Table 3.3). **This value is still somewhat higher than may be expected for digested biosolids cake, probably due to the S input in DMAD, however, the results indicated that the crop response to the compound (ie N+P+K) fertiliser dressing was the most appropriate for comparing the biowaste sources and this is discussed further below.**

It is rare to have significant NO_3^- leaching losses below grassland during the summer period (Whitehead, 1995). Leaching losses at Silwood Park, previously measured following biosolids-amendment, were found to be minimal from ryegrass amended with biosolids (Morris, 2006). However, there was exceptionally high rainfall recorded in the growing season in 2007 (total rainfall received from May – August 2007 was 370 mm compared to 231 mm for the same period in 2006), and it is highly probable that leaching of fertiliser mineral N took place from the inorganic reference treatment, which may explain the high N equivalencies relative to mineral N fertiliser. Thus, the soluble mineral N treatment would be potentially more susceptible to losses by N leaching compared to the biowastes due to the slower release on organic N by mineralisation processes. Losses of mineral N from the inorganic fertiliser control plots may also have been reduced indirectly by the base dressing of P and K in 2007, which would have stimulated root growth improving the efficiency of crop uptake of applied

mineral N. The N equivalencies relative to the mineral N gradient with applied P+K were therefore considered to be an appropriate comparison of N availabilities in the biowastes between years.

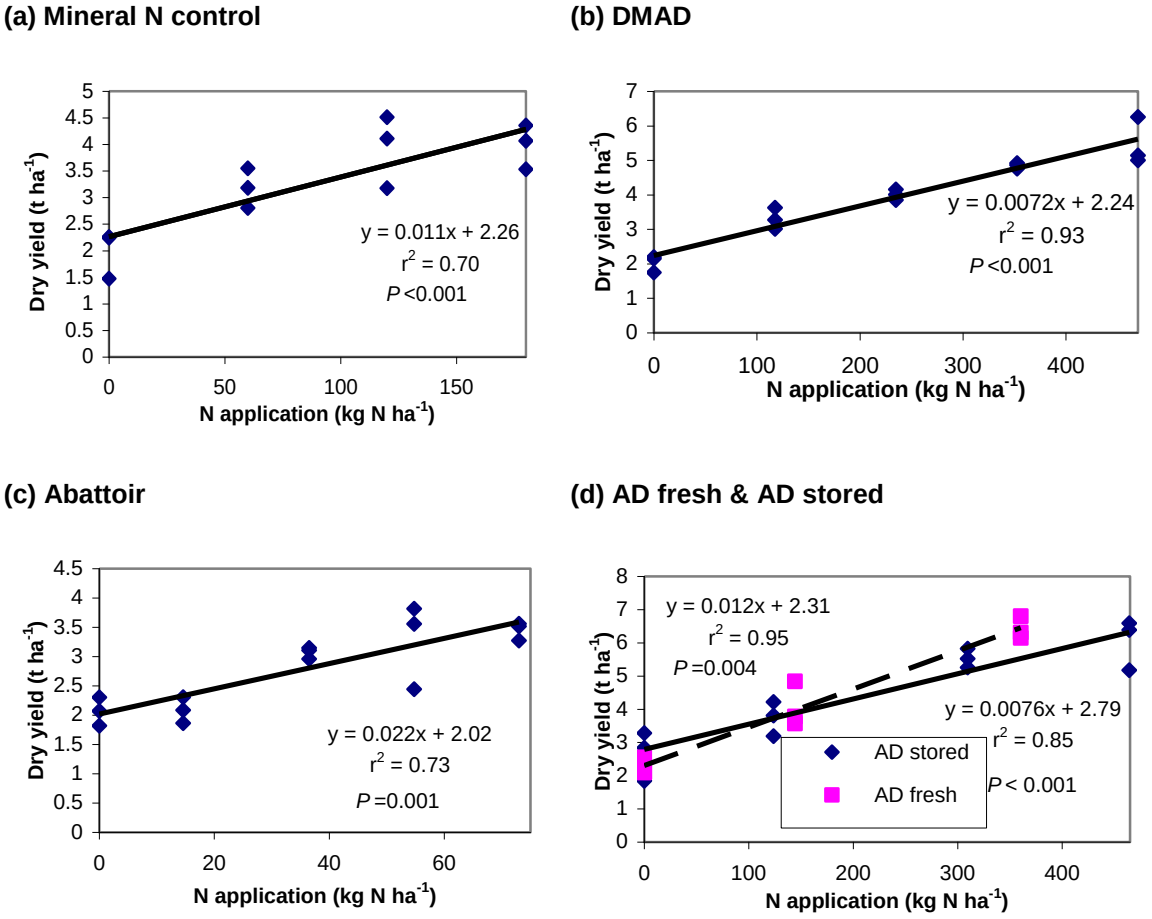


Figure 3.1 Cumulative ryegrass yield (4 harvests, dry Yield) relative to N application from mineral N fertiliser and biowastes treatments. Regression equations, r^2 values and *P* values from ANOVA test of significance are shown on each graph.

Table 3.4 Total element concentrations in plant tissue (first harvest 2006) from amended soil (top rate of application) and unamended control

	Element concentration (mg g^{-1} DM)					Element concentration (µg g^{-1} DM)		
Treatment	**P**	**K**	**Mg**	**Ca**	**S**	**Na**	**Fe**	**Mn**
Unamended Control	3.06	30.5	1.93	11.8	1.88	77.1	683.5	111.5
Mineral N	3.44	33.6	2.06	14.3	1.34	<0.001	150.9	140.0
DMAD	2.88	36.8	1.65	12.1	5.04	<0.001	153.4	103.6
Abattoir	3.60	34.2	1.66	11.9	1.68	<0.001	254.6	89.8
Trout old	1.85	22.4	2.09	11.3	2.30	<0.001	<0.001	89.3
Trout new	1.87	20.6	1.98	11.6	1.98	<0.001	<0.001	80.9
Potato sludge	3.61	38.3	2.05	10.4	2.02	<0.001	551.4	51.9
Potato wash	3.04	33.7	1.85	11.9	2.48	<0.001	351.1	69.3
KG	2.07	21.6	1.73	10.6	1.92	<0.001	<0.001	114.6
Ice-cream	2.38	22.4	1.61	8.55	1.73	<0.001	<0.001	149.7
DAF	1.82	26.2	1.96	10.2	2.12	606.1	153.9	170.3
AD fresh	3.09	36.8	2.02	12.5	2.11	313.8	397.5	98.4
AD Stored	3.22	42.1	1.57	8.83	2.58	<0.001	658.0	138.6
TAD	2.72	41.0	1.09	6.26	2.10	429.6	259.0	57.8
ADMSW	3.29	34.2	1.74	12.6	3.86	148.7	455.7	43.0

Despite the lower total N content, the N equivalency obtained for ADMSW in 2006 was equivalent to DMAD, at 0.52 (Table 3.3), which may reflect its greater mineral N content of 18 % compared to 10 %

TN in DMAD (Table 2.2). Materials containing a larger fraction of their total N content in mineral forms would be expected to have an associated larger N availability since inorganic N is potentially immediately available for crop uptake upon application to the soil. ADMSW was also a source of plant available S for crop growth, which may have also contributed to the apparent crop response to this material relative to the mineral N fertiliser controls (Table 3.3). Nevertheless, the findings demonstrated similarities between biosolids from wastewater treatment and mechanically separated MSW that has undergone a similar biological stabilisation process. By contrast, in 2007, there was no significant crop response to ADMSW application, despite the addition of N to the soil in the biowaste. This may have been due to the longer period of stockpiling and storage of the material in 2007, reducing the component of mineralisable N, compared to 2006 so that the stability of the applied product was different at both application times. The total N content of ADMSW was also smaller in 2007 compared with 2006, which would be consistent with an extended storage period and the loss of N through NH_3 volatilisation.

The N equivalencies for AD fresh and stored were 0.85 and 0.68 respectively, in 2006 (Table 3.3); similar values of 0.74 and 0.71 were also obtained in 2007 (Table 3.3). These values are in the same range as would be expected for digested animal slurries (Shröeder *et al*., 2007). The fresh and stored AD had relatively similar N equivalencies in 2007, whereas there was a difference of 0.17 obtained in 2006. The mineral N content of AD stored in 2007 was greater than AD fresh, 71.8 % TN in comparison to 53.1 %, whereas in 2006 mineral N contents were similar, 39.3 % TN for AD fresh and 46.6 % for AD stored (Table 2.3). This suggested that, in 2007, there had been continued mineralisation of N in AD during storage. Storage also increased stabilisation of the organic matter; the N equivalency for AD stored in 2007 was equal to its mineral N content, which indicated that there was little further mineralisation of organic N. Despite a low mineral N content in comparison to the liquid anaerobic digestates, N equivalencies for TAD were similar to the other digested liquids, and were 0.76 in 2006 and 0.59 in 2007 (Table 3.3). This indicated that TAD contained a larger pool of rapidly mineralisable N than anaerobically digested biosolids as has previously been reported for aerobically digested sludge (Hérnandez *et al.,* 2002). Some deviation would be expected due to seasonal differences in the performance of biowastes as fertiliser materials, however, the results showed that N equivalency values measured between years were relatively consistent overall.

Abattoir wash water, investigated in the 2006 crop response trial, had an N equivalency of 1.6 (Table 3.3). This indicated that the abattoir wash water was a significant source of available N, as expected from its high mineral N content. The N equivalency was greater than 1, however, the concentrations of nutrient elements in the plant tissue were similar to those for the mineral N fertiliser control (Table 7). The high N equivalency may be explained as an artefact, however, as the TN application from this source was low and the yield response was at the lower end of the range of response for the mineral fertiliser control. Vegetable waste mix investigated in 2007 had an N equivalency of 0.45 (Table 3.3), similar to DMAD, indicating that it was an effective source of available N. Despite its low mineral N content of 1.5 %, yeast waste from brewing was also a significant source of readily mineralisable N, with an N equivalency of 0.85 (Table 3.3). This is consistent with the findings of Douglas *et al.* (2003), who found that brewing wastes applied at equivalent rates of TN to mineral N fertiliser produced equivalent or greater yields. A significant response in fresh yield relative to N addition was found for Salt whey, but there was no significant relationship for dry yield or N offtake (Table 3.3). This may have been due to its low TN content of 0.95 kg m^{-3}, compared to 6.85 kg m^{-3} in Yeast, for example (Table 2.3) .

In summary, the research has shown that N fertiliser equivalency values can be developed for different generic types of biowaste materials and that this information can form the basis of appropriate fertiliser recommendations and guidance to maximise the agronomic benefit from these nutrient sources.

3.3 Nutrient Transfer and Other Agronomic Benefits

A further aim of the investigation was to quantify other agronomic benefits and to examine nutrient transfers from biowastes to crops. Total nutrient element concentrations in plant tissue fertilised with biowastes (top rates of application and unamended controls) are shown in Table 3.4.

A significant crop response to rate of application (Table 3.2) was measured for the combination of trout farm waste and mineral N fertiliser. Effects of biowastes on soil physical properties were not measured

here, nevertheless, these observations suggested that application of fish farm waste potentially increased crop yields by improving the soil structure and water holding capacity. This is emphasised given that the sandy soil type was vulnerable to moisture stress and poor structure.

Some of the biowastes examined contained relatively little total N (Table 2.2 and 2.3) and would therefore not be expected to have significant value as N fertiliser replacements. These treatments were therefore applied with a dressing of inorganic N fertiliser to remove this limitation to crop growth (Section 2.1.3) so as to observe other potential agronomic benefits. Under non-limiting N conditions (when N fertiliser was supplied to the plots in combination with the biowaste) a significant response was measured between rate of application of Ice-cream DAF and N offtake, and KG and fresh yield; however, plant tissue analysis did not detect any element effects in these treatments. Nevertheless, it is possible that the supply of trace elements in these biowastes was important in stimulating root growth, although root development was not measured in this investigation.

There was no significant yield response following application of either of the potato processing wastes, however, plant tissue analysis demonstrated that these waste types were an effective source of K and increased the plant tissue K content to 41.0 mg g^{-1} DM compared to 33.6 mg g^{-1} for the mineral N control (Table 3.4). The mineral N treatment was not supplied with K, other than the residual amount present in the soil, therefore, although no overall yield response was observed for the potato waste treatments, the increased K uptake by the crop compared to the control indicated that these biowastes were a significant source of K for crop production. Full elemental analysis of plant tissue was not conducted in 2007, however, the vegetable waste also had a significant K content; 38.3 g kg^{-1} compared to less than 10 g kg^{-1} in the other solid biowastes, and therefore would also be expected to supply more K for crop growth. Plant tissue analysis indicated that the biowastes, and DMAD and ADMSW in particular, were a significant source of S (Table 3.4).

3.4 The Interactions between Organic Residual Type and Soil Type on N Dynamics, Including Microbial Biomass N, under Laboratory Conditions

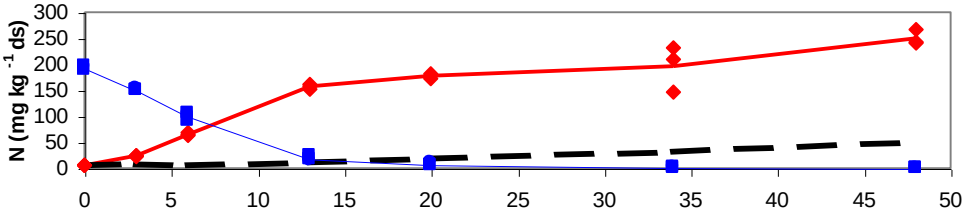
Nitrogen transformations, including microbial biomass N, in biowastes-amended soil were investigated in a laboratory incubation experiment under controlled temperature and moisture conditions (Section 5, main report), in three different soil types. The experiment included an unamended control and mineral N (NH_4Cl) and dewatered digested biosolids (DMAD) were also included as reference treatments.

Mineral N dynamics are presented in Figures 3.2-3.6, and final recoveries of mineral N in each of the amended soils are shown in Tables 3.5-3.7. The mineral N control demonstrated that there were greater rates of nitrification in the higher fertility silty clay soil (North Sidelands) followed by the lower fertility sandy loam (Silwood) and then the sandy silt loam (Brices) (Figure 3.2). This is consistent with their MBC concentrations (Figures 5.6-5.10, main report), and therefore nitrification is related to the size of the microbial population in each soil type. Silwood and Brices soils had similar OM contents (Table 2.1, main report), therefore the differences in fertility between these two soil types may be related to the sand contents of the soils. Silwood soil contained 75-80 % sand compared to 35-41 % sand in Brices soil. Hence, Silwood soil was lighter and coarser-textured, and therefore better aerated; Hernandez *et al*. (2002) reported increased microbial activity in a sandy soil due to improved aeration properties.

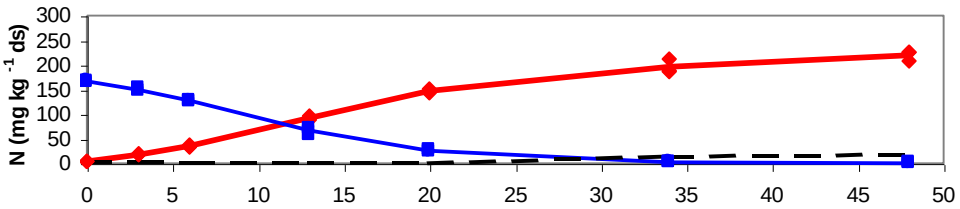
Mineral N recoveries indicated that there were losses of N from the soils, in particular from the silty clay soil amended with TAD and ADMSW. Furthermore, recoveries of mineral N in the silty clay amended with TAD and ADMSW were lower than the unamended control (Table 3.5). The unrecovered N was not immobilised in the microbial biomass (Figures 5.11-5.15, main report), however, there was an increase in MBN concentration in TAD-amended soil between days 0-20 in all three soil types.

Added N recovered in the microbial biomass was significantly greater in TAD amended soil than for the anaerobically digested biosolids (DMAD) and anaerobically digested biowastes (ADMSW and AD). Microbial biomass C in DMAD and ADMSW amended soil was generally equivalent to unamended soil in all three soil types. This indicated that there was greater microbial activity resulting from addition of a low stability organic matter source. This was consistent with previous findings that greater microbial immobilisation of N occurs with less stable sources of organic matter (Recous and Mary, 1990; Jedidi *et al*., 2004; Calbrix *et al*., 2007).

(a) Silwood (loamy sand)



(b) Brices (sandy silt loam)



(c) North Sidelands (silty clay)

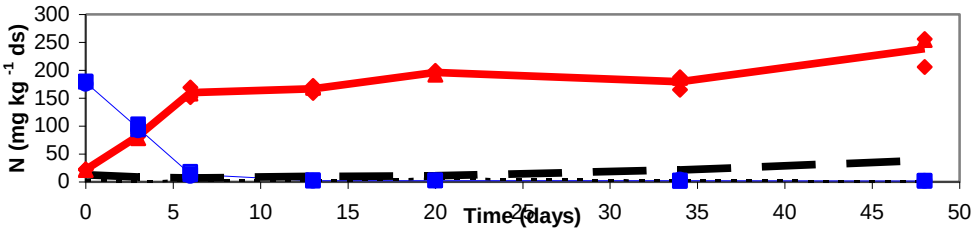
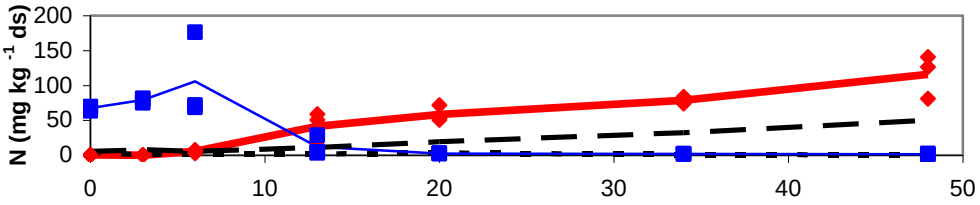
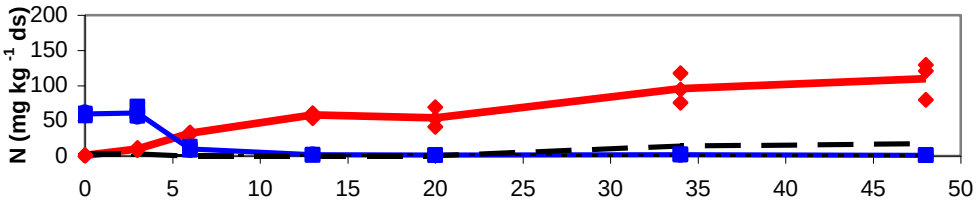


Figure 3.2 Concentration of NH_4-N and TON in relation to time, in three contrasting soils, amended with NH_4Cl (NH_4-N, ■ ; TON, ♦——♦; replicates,) and in unamended control soils (NH_4-N, ------- ; TON, — — —).

(a) Silwood (loamy sand)



(b) Brices (sandy silt loam)



(c) North Sidelands (silty clay)

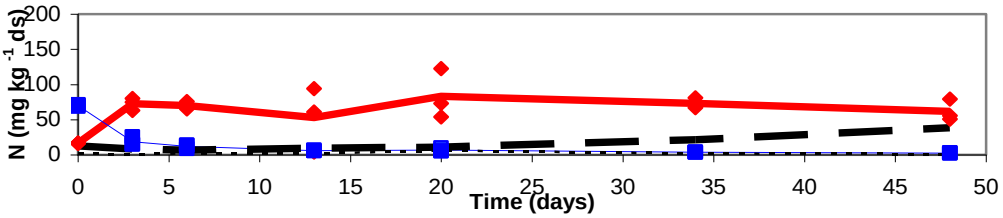
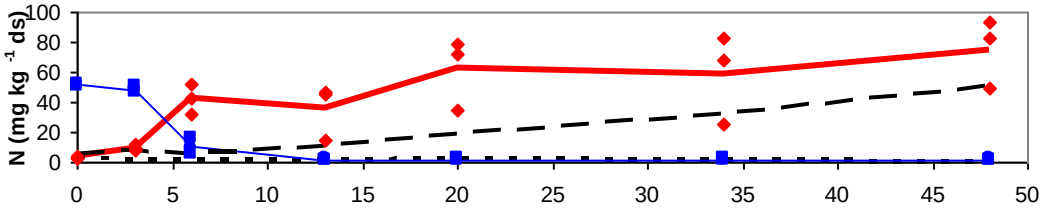
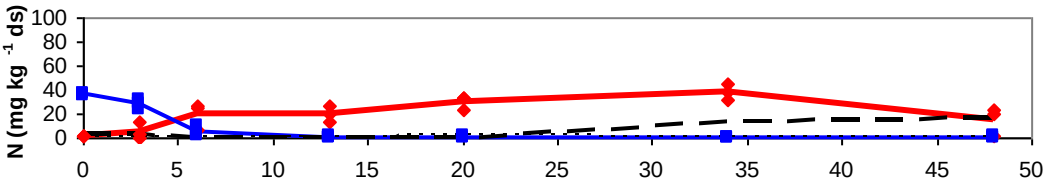


Figure 3.3 Concentration of NH_4-N and TON in relation to time, in three contrasting soils, amended with DMAD (NH_4-N, ■ ; TON, ♦——♦) and in unamended control soils (NH_4-N, ------- ; TON, — — —).
(a) Silwood (loamy sand)



(b) Brices (sandy silt loam)



(c) North Sidelands (silty clay)

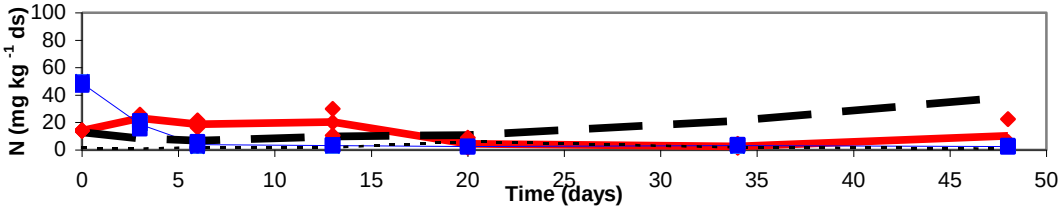
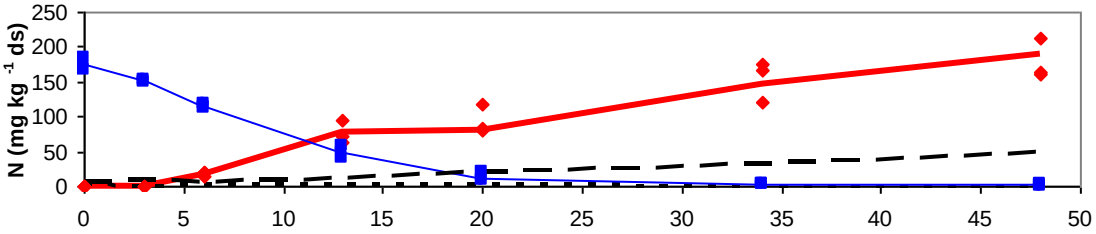
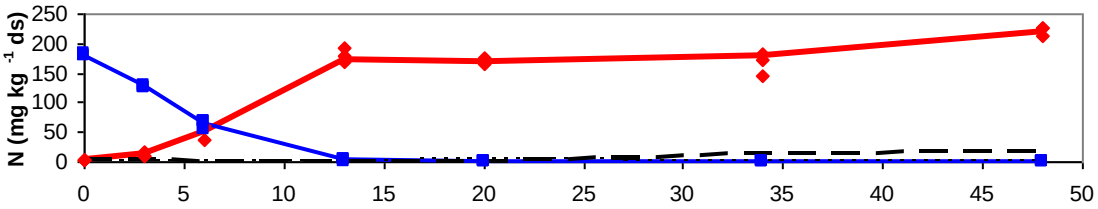


Figure 3.4 Concentration of NH_4-N and TON in relation to time, in three contrasting soils, amended with ADMSW (NH_4-N, ■ ; TON, ♦——♦) and in unamended control soils (NH_4-N, ------- ; TON, — — —).

(a) Silwood (loamy sand)



(b) Brices (sandy silt loam)



(c) AD: North Sidelands (silty clay)

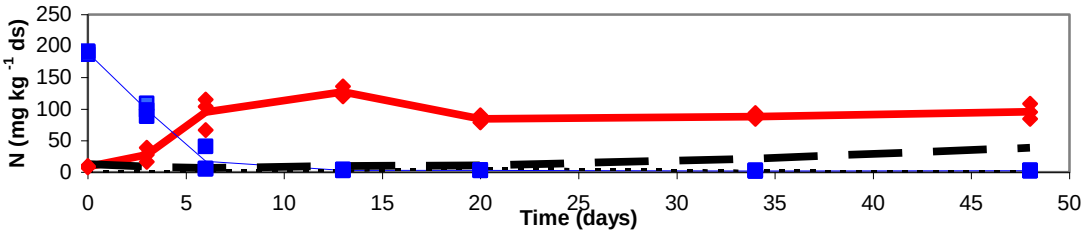
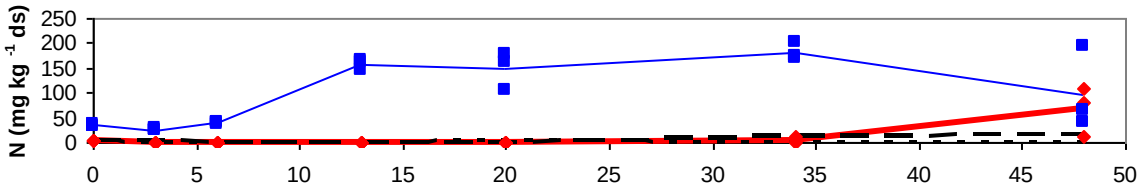
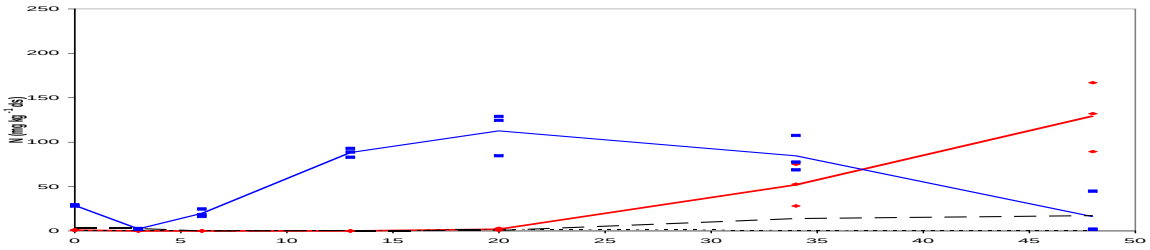


Figure 3.5 Concentration of NH_4-N and TON in relation to time, in three contrasting soils, amended with of AD (NH_4-N, ■ ; TON, ♦——♦) and in unamended control soils (NH_4-N, ------- ; TON, — — —).

(a) Silwood (loamy sand)



(b) Brices (sandy silt loam)



(c) North Sidelands (silty clay)

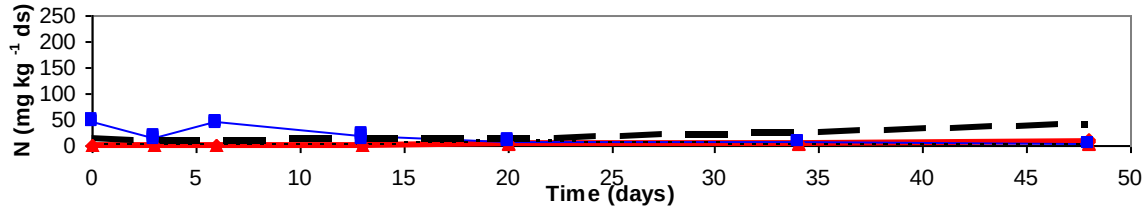


Figure 3.6 Changes in concentration of NH_4-N and TON in relation to time, in three contrasting soils, amended with TAD (NH_4-N, ■ ; TON, ♦——♦) and in unamended control soils (NH_4-N, ------- ; TON, — — —).

Table 3.5 Nitrogen Recoveries, Incubation Study, Silwood Soil

Soil Treatment	Day 0, Min-N recoveries (mg kg $^{-1}$ ds)	Day 0, % Total N available	Mineral N Recovery (mg kg^{-1} ds)	Available N (% Total N)	Mineralised N (% Organic N)
NH_4Cl	188.7	94.4	200.3	100.1	
DMAD	57.5	12.4	67.0	14.4	5.87
ADMSW	44.9	19.3	26.5	11.4	-4.58
TAD	27.6	7.89	115.1	32.9	26.6
AD	164.2	55.5	139.3	47.0	0.16

Table 3.6 Nitrogen Recoveries, Incubation Study, Brices Soil

Soil Treatment	Day 0, Min-N recoveries (mg kg $^{-1}$ ds)	Day 0, % Total N available	Mineral N Recovery (mg kg^{-1} ds)	Available N (% Total N)	Mineralised N (% Organic N)
NH_4Cl	167.1	83.5	202.7	101.4	
DMAD	57.7	12.4	93.3	20.1	12.1
ADMSW	35.1	15.1	24.3	10.5	-5.72
TAD	26.9	7.69	127.8	36.5	30.6
AD	179.4	60.6	202.3	68.3	40.3

† Final TON and NH_4-N concentrations for ADMSW amended soil taken from day 34, where there was a peak in TON concentration, including adjustment for control values (not shown)

Ammonium fixation is a potential mechanism for unrecovered N, and it occurs to a greater extent in soils with a high clay content (Tester *et al.*, 1977). However, this was not thought to be a significant factor here as the majority of the added N was recovered in the mineral N controls. Loss of NH_3 by volatilisation is also a possibility. Here the amendments were thoroughly mixed with the soils, this would act to reduce NH_3 volatilisation, which is reduced by incorporation of organic amendments into the soil (Donovan and Logan, 1983).

Table 3.7 Nitrogen Recoveries, Incubation Study, North Sidelands

Soil Treatment	Day 0, Min-N recoveries (mg kg $^{-1}$ ds)	Day 0, % Total N available	Mineral N Recovery (mg kg^{-1} ds)	Available N (% TN)	Mineralised N (% Organic N)
NH_4Cl	185.4	92.7	200.7	100.4	
DMAD	72.5	15.6	73.4	15.8	7.40
ADMSW	48.3	20.8	-26.7	-11.5	-31.6
TAD	33.0	9.44	-28.0	-7.99	-18.1
AD	184.1	62.2	58.8	19.9	-51.1

† Final TON and NH_4-N concentrations for DMAD amended soil taken from day 20, where there was a peak in TON concentration, including adjustment for control values (not shown)

Denitrification, potentially leading to generation of nitrous oxide, occurs under anaerobic conditions, which may arise due to the high biological oxygen demand associated with the microbial decay of organic amendments, and/or high moisture conditions. It is generally thought that denitrification may occur in anaerobic microsites within an otherwise aerobic soil, and such conditions tend to occur more frequently in clay soils with higher organic matter (Smith 1980; Fillery 1983). This would be an explanation for the greater losses of N observed in the silty clay soil in comparison to the coarser textured soils. The losses of N observed in the silty clay were a function of the added organic matter, as there was full recovery of N in the NH_4Cl control (without additional organic matter) (Figure 3.2). The greater apparent losses observed in TAD and ADMSW suggested that these biowastes were less stabilised than AD and DMAD, and therefore supported greater microbial growth and activity and consequently oxygen depletion. These observations are supported by the findings of the programme of field experiments, in which TAD was demonstrated to have a large pool of mineralisable N. Previous research has also shown that aerobically digested organic wastes contain a higher proportion of mineralisable C than anaerobically digested wastes (Hall, 1983b; Serna and Pomares, 1991a; Serna and Pomares, 1991b; Hérnandez *et al.,* 2002). In addition, MBC and MBN analysis of TAD-amended soil, indicated that there was greater microbial activity following soil-amendment with this waste type (Figures 5.9 and 5.14, main report) in comparison to the other amendments. This would have led to the potential depletion of oxygen and development of anaerobic microsites, leaving the silty clay soil more prone to denitrification losses. Anaerobically digested MSW may contain less stable organic C than DMAD due to greater variation in the input material, for example there may be a high proportion of green waste containing complex organic matter with varying degrees of resistance to microbial degradation under anaerobic digestion conditions, which may be degraded in aerobic soil environments. Therefore, whilst the stimulation of soil microbial activity is considered to be a beneficial effect of organic matter application to soil, unstabilised or partially stabilised biowastes may increase the potential risk of denitrifying the inorganic N added directly or mineralised in the soil from applied biowastes.

Final N recoveries in mineral N controls were approximately 100 % of total N additions in all three soil types, indicating that there were no N loss mechanisms operating in soil in the absence of organic matter addition (Tables 3.5-3.8). Final recoveries of N in DMAD-amended soil ranged between 14-20 % total N, which was at the lower end of previously reported N availabilities for this biosolids type (Smith *et al*. 1998b; Breedon *et al*., 2003). Estimating the mineralisable N fraction in biosolids and biowastes by incubation requires sufficient time to allow the microbial N conversions to proceed to completion and the incubation period chosen here was based on findings from previous incubation experiments at 25 ^{o}C (Smith *et al*., 1998b). However, the lower recoveries obtained for DMAD-amended soil compared to previous work may be due to incomplete mineralisation of DMAD, potentially due to a less active microbial population, as the soils were collected during the winter period. This implied mineralisation of the other biowaste types was also not complete by the end of the incubation period. Final recoveries of N were greatest in soil amended with liquid anaerobic co-digestates of food waste and animal slurry, between 20–68 % total N. In two of the soil types investigated, N availabilites for AD were within the range that would be expected for liquid digested biosolids (Coker *et al*., 1966; Ryan *et al*., 1973; Hall *et al*., 1983a.; Kiemnec *et al*., 1987; Smith *et al*., 1998b). This supported the findings of the biowastes field investigation and indicated that anaerobic co-digestates of animal slurries and food wastes have similar N release characteristics to anaerobically digested biosolids.

The mineral N recovered in AD-amended soil was significantly greater than in the other biowastes and biosolids treatments (P<0.05). This is to be expected from the high proportion of mineral N in this biowaste type (47 % of total N). Final recoveries of N in TAD-amended soil in the laboratory incubation ranged between -8-36.0 % total added N. These values were lower than expected from the field investigation, in which biowaste N was 59-76 % as available as mineral N fertiliser in TAD-amended soil (Tables 3.3); in the silt clay soil type tested, less mineral N was recovered than the amount initially added to the soil. In ADMSW-amended soil, final N availability was -11.5-11.5 % of the total added N. Again, this is much lower than expected, as in ADMSW-amended soil, added N was found to be 52 % as available as mineral N fertiliser in the 2006 field experiment (Table 3.3). The recoveries of mineral N were lower than expected, especially in TAD and ADMSW amended soil in the silty clay soil. The implication of these results for biowaste management is that application of unstabilised or partially stabilised biowastes to fine-textured soils should be undertaken with caution when there is a risk of partial soil saturation, to minimise the risk of N losses by denitrification and the emission of nitrous oxide, a potent greenhouse gas.

3.5 Advisory Leaflet

An advisory leaflet was produced, based on the findings of this programme of experiments, and is available in Appendix 2 of the main project report.

4. CONCLUSIONS

4.1 Total and Mineral Nutrient Concentrations in Industrial Biowastes

The nutrient composition and other chemical properties were measured for a range of industrial biowaste types. As would be expected the nutrient composition depended on the source and the origin of the biowaste and the degree of dewatering, which increased the overall nutrient content. Most of the wastes examined contained amounts of one or more important plant nutrients that would be agronomically significant. Not all the wastes provided a source of N (eg potato sludge and wash water), but did supply other nutrients (eg K in the case of potato wastes).

- Industrial biowastes typically contain amounts of one or more nutrients that can provide agronomic benefit as fertiliser replacements to increase crop yields.

4.2 Nitrogen Release from Industrial Biowastes Relative to Digested Sludge Cake and Mineral Fertiliser

Significant linear relationships between rate of N application from biowastes and crop response were found in most cases, with the exception of treatments with a low total N content. These materials require investigation under higher rates of application, to assess potential soil conditioning benefits, or with added mineral N to measure the value of other nutrient resources in the biowaste. Liquid aerobic co-digestates of food wastes have N equivalencies in the range of 0.63-0.73, despite lower mineral N contents than anaerobic digestates, demonstrating a large pool of rapidly mineralisable organic N. Liquid anaerobic digestates of food waste and animal slurry have N equivalencies of 0.67-0.84 depending on length of storage, which tends to reduce the amount of available N. Dewatered anaerobic digestate of MSW had an N equivalency equivalent to DMAD in 2006 trial, but there was no significant response in 2007. Differences in response to ADMSW and AD stored and fresh between the two years of the experiment demonstrate the potential for variation in the properties of the material brought about by variation in length of storage. Abattoir waste had an N equivalency of 1.54, which indicated that, although it is a good source of mineral N, factors other than N availability are contributing to crop response. However, this could also be explained due to an artefact of the small total N concentration in the biowaste, and the low rate of application of N supplied relative to the range of mineral N treatment rates. Solid mixed vegetable waste had an N equivalency of 0.47, just less than that of DMAD, indicating that it is an effective source of available N. Despite its low mineral N content Yeast had a high N equivalency of 0.9, it is therefore a good source simple organic N compounds which are rapidly mineralised in soil. Application of Trout old and a base dressing of mineral N, resulted in a relative fertiliser value of 0.8, indicating that there are benefits of addition of organic matter in the waste.

- Industrial biowastes are potentially effective replacements to inorganic N fertiliser sources and give predictable crop responses to N application. The N response depends on the total amount of N contained in the material and the relative proportions of mineral and organic N, which can be determined by chemical analysis. The availability of the organic N fraction for mineralisation and release into crop available forms can be readily determined by field or laboratory incubation experimentation and this information, coupled with chemical analysis data, can provide the basis to fertiliser recommendations for different biowaste types.

4.3 Release of Other Important Plant Nutrients (P, K, Mg and S) from Biowastes

Crop yield responses to certain biowaste types and DMAD depended to a large extent on N availability, but there was also evidence that there was a contribution of other nutrient elements to the agronomic value. For instance, chemical analysis of grass leaf tissue showed that vegetable waste, potato sludge and animal slurries were effective fertiliser sources for K and increased the K contents of grass. DMAD application increased the P concentration in the grass crop, confirming that biosolids are an effective source of fertiliser P for crop uptake. Crop analysis also indicated that DMAD supplied a significant amount of S to the crop, which contained four times the amount of S with biosolids application compared to the mineral fertilised grass and therefore potentially contributed to the crop response to this material. However, there was no evidence based on crop analysis that other nutrients supplied by abattoir waste were important in contributing to the yield response to this biowaste type.

- Biowastes can be an important source of other essential plant nutrients (P, K, S and Mg), in addition to N, that contribute significantly to their fertiliser replacement and agronomic value. The fertiliser value of these nutrients can be determined primarily from the chemical analysis of the biowaste.

4.4 Influence of Soil Type and Environmental Factors on Nutrient Release and Microbial Activity

Findings from the laboratory incubation study indicated that losses of N occurred from biowastes amended soil; these were most significant in the silty clay, which had a slightly greater moisture content and WHC. Denitrification was therefore implicated as the mechanism of N loss. This has significant management implications for the use of biowastes on different soil types, and application timing. It also indicated the potential influence of stabilisation treatment on denitrification activity in amended soil. In soil amended with DMAD for all 3 soil types, and TAD and AD for the sandy silt loam and loamy sand, final available N was greater than initial available N indicating net mineralisation from the organic waste sources. Net mineralisation was greatest in the sandy silt loam. The greatest losses of N occurred in ADMSW and TAD amended soil, which suggested that these materials were less stable than AD and DMAD. Biomass C and N concentrations differed between soil types, but there was no indication of differences in immobilisation of N from the biowastes between soil types. Biomass C and N concentrations were greater in soil amended with aerobically digested food waste in comparison to unamended soil in all three soil types. This suggested that addition of less stable waste types may potentially stimulate dentrification activity in soil. By contrast, biomass C and N in DMAD and ADMSW amended soil was generally equivalent to unamended control soil in all 3 soil types. The biomass C and N concentrations decreased below control values in AD amended soil. This may be explained by a short-term transient effect of the high NH_4-N concentration in the microbial biomass in incubated soil amended with this digested product.

- The interaction between soil and biowaste type had important implications for the rate of mineral N production and the potential loss of N from amended soil by denitriification mechanisms. Increased losses were observed for unstabilised biowaste types in clay soil conditions, whereas stabilisation treatment, by anaerobic digestion, lead to an accumulation of mineral N in soil.

5. FUTURE RESEARCH PRIORITIES

- Statistical survey of waste properties held by the Environment Agency relating to current notifiable exemptions and Environmental Permitting for land application and agronomic benefit
- Develop decision support tool to help management and classification of Environmental Permitting

- A Field experimental programme, which should include:
  - A range of selected biowastes
  - A range of selected soil types
  - Intensive systematically arranged trials (ryegrass); ryegrass is an effective indicator crop to determine N availability of biowastes under field conditions and systematically arranged trials allow detailed crop responses to biowastes applications to be determined.
  - Operational scale applications and field monitoring (agricultural crops); more extensive field experiments with a range of agricultural crops and conditions are necessary to validate the fertiliser response and use of biowastes under operational field conditions
  - N effectiveness at increasing crop production and replacing mineral sources, mobility and leaching
- Laboratory experimental programme, which should include:
  - Investigation of interaction between soil type and waste type/carbon availability on N transformations, denitrification processes and N losses
  - A controlled sand-culture bioassay protocol for P availability (+other nutrients) for rapid screening large numbers of biowastes and nutrients
- Development of fertiliser guidance – future revision RB209
- A cost/benefit analysis of the value of applying biowastes with low agronomic benefit versus potential damage to soil caused by increased traffic of tankers and spreading equipment.

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

Rigby, H. and Smith, S.R. (2006) Field experiments to quantify the agronomic benefit of industrial biowastes. *Proceedings of the Joint CIWEM and Aqua Enviro Technology Transfer 11th European Biosolids and Organic Residuals Conference.* Aqua Enviro, Wakefield.

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