MEMORANDUM Job 10416 Y3M2:3A.2

**To**: Biosolids Partner Councils

**From:** Katie Beecroft and Jen Prosser, LEI

**Date**: 8 April 2020

**Subject:** Guidance on Determining Nitrogen Mineralisation Rates

## OVERVIEW

This memo aims to collate current literature on the mineralisation of Nitrogen (N) in biosolids to provide guidance on N mineralisation rates when applied to land. A broad range of resources are already available on the topic that effectively outline relevant research and existing knowledge. This memo summarises these resources highlighting primary influencing factors and providing a full reference list with summaries for further information (Appendix A).

## PROJECT BACKGROUND

Lowe Environmental Impact (LEI), The Centre for Integrated Biowaste Research (led by ESR), and 10 lower North Island Councils are working together to develop a biosolids strategy that includes the potential collective management of sludge, with a focus on beneficial use. The MfE funded project has been running for three years and aims to identify and test options for discharge and beneficial use of biosolids, in particular for smaller councils who may not have been able to achieve such solutions individually. The resulting toolbox of scenarios may reduce the cost of sludge management and increase the certainty and viability of available solutions for Councils.

## WHAT IS A BIOSOLID

Biosolids predominately consist of the solid organic residual from wastewater treatment processes. While such materials can come from a range of industries and treatment facilities, in the context of this summary they are sourced from municipal wastewater treatment plants.

Typically, residual material starts as a sludge or slurry that then goes through a series of processes to reduce moisture content, producing a thickened material resembling organic compost.

In order to be considered a biosolid, and not a slurry or sludge, the material has to have been satisfactorily stabilised (via an approved method/process), so that it will not break down in such a way to cause a nuisance (i.e. odour) or attract vermin, an so that contaminants (microbial and chemical) are reduces to below acceptable levels (NZWWA, 2003).

More details on the characteristics and definition of biosolids is provided in Fact Sheets 1 - 7 of the Regional Biosolids Strategy (2020)

## REGULATORY ENVIRONMENT

All discharge methods for biosolids require consideration of the quality of the material (potential microbial, inorganic and organic contaminants as well as nutrients) and any potential interaction with the discharge environment. The discharge environment may include soil, water, air or a contained environment such as landfill or monofill.

Beneficial use of biosolids by application to land relies on nutrients being available for plant growth. Biosolids are nutrient rich (N, P, trace elements) and can have fertiliser value when used as a soil amendment. Biosolids and biosolids products contain high concentrations of N. Due to this fact, N is typically the design loading parameter for land application i.e. application should be equivalent to (but not greater than) an agronomically beneficial N amount. Ensuring that N is applied at rates equal to plant requirements reduces the risk of leaching or movement of N to the wider environment. However, regional and district plans, consent applications and relevant guidelines (NZWWA, 2003) for biosolids use treat all N as readily available (Fact sheets 7 and 8 or the Regional Biosolids Strategy, 2020).

It is frequently assumed that organic amendments, such as biosolids, behave the same in the environment as inorganic fertilisers, and many nutrient fate models are based on this assumption; which is not the case. This frequently used approach limits the volumes that can go onto land based on values that in some cases are not relevant to potential adverse environmental effects. In New Zealand, a default value of 200 kg total N/ha/year is often adopted for biosolids application. However, application rates should be based on site characteristics, climate, mineralisation rates and the nutrient need of the crop so as to truly reflect any potential adverse effects (NZWWA, 2003).

## MINERALISATION OF N IN BIOSOLIDS

The Regional Biosolids Strategy – Lower North Island identified the availability of nutrients in biosolids as an area of interest to producers and regulators. As mentioned, current regulation to use of biosolids in NZ assumes that all N present is immediately available, however, this is known to be incorrect and can prove prohibitive to beneficial use. Evidence suggests that approximately 30-40 % of the N from biosolids will be available in the first year with some 20 % the subsequent year (NZWWA, 2003). This can make biosolids ideal as a long-term source of nutrients.

Environmental risk, and nutrient benefit, due to N in biosolids and sludge is dependent on the form of N present. Mineralisation is the decomposition of organic matter in soil releasing nutrients into a soluble inorganic form that may be available to plants. In brief, the N cycle (Figure 1) shows that organic N from organisms and vegetation (excreta and degrading matter) is mineralised to ammoniacal ($NH_4^+$) forms of N through microbial processes. $NH_4^+$ is then able to be nitrified to the oxidised forms such as nitrite ($NO_2^-$) and nitrate ($NO_3^-$), and then denitrified to N gases ($N_2$, $N_2O$) which are lost to the atmosphere. These latter forms of N ($NO_3^-$, $NO_2^-$ $NH_4^+$, $N_2$, $N_2O$) are referred to as inorganic N. There are many excellent soil science and agronomy texts which describe the process of N mineralisation and the N cycle in general (McLaren and Cameron, 1996; Henry *et al.*, 1999) and provide further detail on these complex processes.

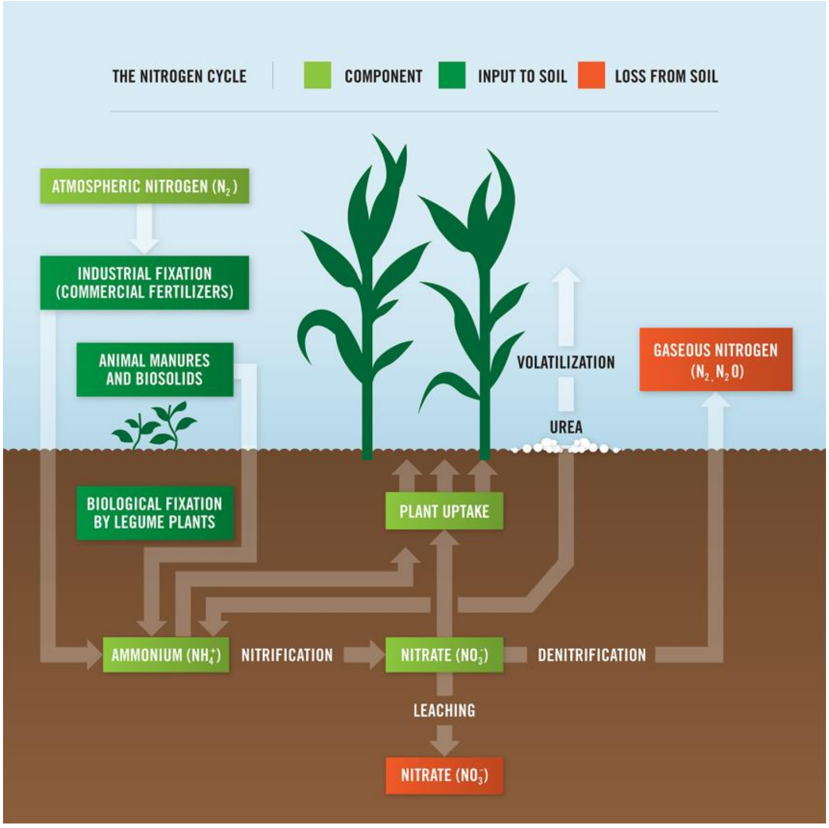


**Figure 1: The Nitrogen Cycle (after Koch Agronomic Services, 2020)**

N becomes available for plant and organism uptake, and for transmission through the environment, in its inorganic (or mineralised) forms ($NO_3^-$, $NO_2^-$ $NH_4^+$, $N_2$, $N_2O$). The initial amount of N available for use is dependent on the amount of inorganic N present in the original material.

Typically, biosolids contain between 1 – 6 % total nitrogen (TN) depending on the sludge source and treatment (NZWWA, 2003). N in biosolids is predominantly in the organic form, and mainly from microbes that are involved in the wastewater treatment process. Some inorganic N is also present as mineralised N.

As noted above, N in organic material is converted to inorganic N by mineralisation. The conditions under which mineralisation occurs and the rate at which N is released from biosolids or sludge depends on the soil environment and temperature, and on the N containing compounds present. The compounds are, in turn, dependent on the source of the sludge, treatment process that they underwent and the stabilisation process that they are subjected to.

## FACTORS INFLUENCING MINERALISATION

### Processing and Age of Biosolids

Biosolids may be thermally dried, amended with chemicals or other biological matter (e.g. lime amendment, enzymes, chemical fertiliser, composting with green waste). Biosolids can also be aged or 'fresh' and straight from a wastewater treatment process. All of which are factors that affect the N content and potential mineralisation of the product.

The % of total N in a sludge is influenced by both the source and processing, Table 1 below provides a summary of data obtained from 18 differing municipal sludges tested throughout the

Regional Biosolids Strategy (Reports 1-14 of the Regional Biosolids Strategy). The data indicates that the more aged a product (i.e. oxidation pond sludge or geobags) the lower the % total N.

**Table 1: Average nitrogen and phosphorus (%) as found in 18 sludges sampled throughout NZ over three years (2017-2019).**

| Sludge | N (%) | P (%) |
|---|---|---|
| **Oxidation pond sludge** | 2.0 | 0.4 |
| **Geobagged pond sludge** | 0.8 | 0.2 |
| **Fresh WWTP sludge** | 4.8 | 1.7 |
| **Composted biosolids** | *1.9 | *1.3 |

*value is not an average and represents a sample pool of only one location.

The type of N present is also heavily influenced by processing. In general, an aged biosolid such as pond sludge from geobags will contain less readily available N such as $NH_4^+$, and therefore pose less risk to the environment. Whereas, a sludge direct from a wastewater treatment plant will likely contain elevated $NH_4^+$, which when converted to the more mobile forms of $NO_2^-$ and/or $NO_3^-$ poses a risk to leaching if conversion exceeds plant requirement. In general, mineralisable N will decline with the extent of biological stabilization during sewage sludge treatment (Rigby *et al*., 2015).

Rigby *et al*. (2015) determined that the overall mean values of mineralizable N, as a proportion of the organic N content, were 47% for aerobic digestion (AeD) biosolids, 40% for thermally dried (TD) biosolids, 34% for LT biosolids, 30% for mesophilic anaerobic digestion (MAD) biosolids, and 7% for composted (Com) biosolids. In addition, they noted that biosolids air-dried or stored for extended periods had lower total and mineralizable N values compared to mechanically dewatered types (Rigby *et al*., 2015)

## C:N Ratio

The C:N ratio of the biosolid is known to heavily influencing the eventual availability of N when applied to soil. As mentioned, mineralisation is the process whereby organic N is transformed into inorganic or mineral N (available to microbes and plants) by microbes. Microbes immobilise some of the released N in their biomass, however when the release of N from organic sources is greater than their requirements mineral N builds up in soil and is thus available to plants. It has been shown that in order for this process to occur the C:N ratio of an organic amendment needs to be below 25:1 (as microbes utilise C and N relative to each other - McLaren and Cameron, 1996). In other words, when there is low carbon in the biosolids relative to N, there will in turn be more N available for plants as mineralisation occurs.

## Soil

Soil type has an impact on the rate at which biosolids mineralise. Factors such as the soil microbial health (abundance and variety in soil bacteria) and soil pH play a role in enhancing or retarding mineralisation. With mineralisation found to be slower in more acidic soils (Curtin *et al*., 1998) and increased in soils with higher pH (Wang *et al*., 2003). However, the main control on the rate of mineralisation is the soil moisture status whereby mineralisation is more rapid in moist conditions (Henry *et al*., 1999). Soil type influences the ability of the soil to retain or drain moisture (i.e. sandy soils are porous and drain moisture where clay soils retain it) whilst climatic conditions influence replenishment and evapotranspiration.

## Temperature

N mineralisation increases with increasing temperature (Pu *et al.*, 2012; Rigby *et al.*, 2015; Wang *et al.*, 2003), primarily due to reduced microbial activity at lower temperatures. Henry *et al.* (1999) notes that for a 10˚C decrease in temperature, microbial activity decreases by half, and at 4˚C minimal activity occurs, whilst Wang *et al.*, (2003) reported over double the percentage of N mineralisation under 20°C (average 22.8%) compared to 10°C (average 9.7%). Meaning the application of biosolids in warmer summer months is likely to exhibit a greater/more rapid release of N than if it occurs during cooler winter months.

## Time

Mineralisation rate influences the length of time that the biosolids can gradually release and supply N. This in turn impacts on the return period for biosolids applications. Of particular importance with time is that the rate of mineralisation changes as it progresses. In the first-year mineralisation is highest with rates in the order of 30 to 40 % of the initial N becoming available (NZWWA, 2003). As the ratio of readily degradable organic compounds to more recalcitrant forms decreases, mineralisation slows down. It is unlikely all N in biosolids will be mineralised and available to plants as some will be tightly retained in soil organic matter.

## SLUDGE PRODUCTS COMPARITIVE TO INORGANIC FERTILISER

Inorganic fertilisers vary in their nutrient composition and availability of N release, and the use of each is dependant on the specific purpose required. On comparison to fertilisers, biosolids typically contains less N (%), however the N present is available over a long period of time and in addition biosolids contains high levels of P and numerous trace metals and nutrients that are valuable to plant growth.

**Table 2: Nitrogen % of commonly used inorganic fertilisers compared to biosolids.**

| Product | N Form | Period of Mineralisation | N (%) | P (%) | K (%) | S (%) | Comments |
|---|---|---|---|---|---|---|---|
| Urea | $NH_2$ | Soluble - 14 days (2 weeks) | 46 | - | - | - | Rapidly undergoes ammonification/ hydrolysis and becomes 100% immediately plant available |
| Diammonium Phosphate (DAP) (Cropmaster) | $NH_4^+$ | Soluble - 14 days (2 weeks) | 17.6 | 20 | - | 1 | 100% immediately plant available |
| Ammonium Sulphate | $NH_4^+$ | Soluble- 14 days (2 weeks) | 20 | - | - | 23 | Typically used in low application rates due to high S concentration. |
| Calcium Ammonium Nitrate (CAN) | $NO_3^-$ and $NH_4^+$ | Soluble- 14 days (2 weeks) | 27 | - | - | - | Ammonium nitrate combined with lime at a 2:1 ratio produces CAN |
| Potassium Nitrate | $NO_3^-$ | Soluble- 14 days (2 weeks) | 13 | - | 44 | - | Typically used for higher value crops. |
| Blood & Bone | $NH_2$ | Slow release of N (Months – Years) | 6 | 4 | - | - | Requires the breakdown of material by soil microbes so will take longer to become plant available. |
| Biosolids/sludge | Varied | Slow release of N (months-years) | 1-6 | 0.1-3 | <1 | - | Contains an array of trace metals and nutrients in addition to N, P, K, S. Approximately 30-40% N is available in the first year followed by 20% in the second. Mineralisation slows over time. |

## RELEVENT INFORMATION SOURCES

There is limited guidance available to NZ biosolids producers to determine the release of biosolids derived N into the receiving environment. This is important both, for assessing effects in a consenting process and, for estimating the beneficial use of the nutrients from biosolids and sludge. This memorandum seeks to direct producers to relevant information on N mineralisation from biosolids.

This workstream has reviewed existing research into the mineralisation of N from sludge or biosolids from a range of wastewater treatment and sludge stabilisation processes. The focus is on $NH_4^+$ and $NO_3^-$ production for land applications. Research from New Zealand sites is available but not extensive. Recommended reading includes Wang *et al.* (2003) which considers the rate of mineralisation as influenced by temperature, soil type and biosolids origin. The following table and graph are reproduced from Wang *et al.* (2003) and describe the first year after biosolids application.

**Table 2: The rate of N mineralisation in biosolids as influenced by temperature, soil type and biosolids origin (after Wang et al., 2003)**

**Table 4. Means of cumulative mineralized nitrogen.**

| Biosolids type† | Soil type | N mineralized 10°C | N mineralized 20°C |
|---|---|---|---|
| | | % | % |
| AnM | brown | 8.7 | 29.0 |
| | volcanic | 5.9 | 17.1 |
| AeM | brown | 22.4 | 50.4 |
| | volcanic | 19.6 | 36.0 |
| PP1 | brown | −3.3 | −1.9 |
| | volcanic | −0.3 | 4.0 |
| PP2 | brown | 10.7 | 12.6 |
| | volcanic | 13.8 | 35.1 |
| LSD‡ | | 6.4 | 6.4 |

† AnM, anaerobically digested municipal biosolids; AeM, aerobically digested municipal biosolids; PP1 and PP2, two pulp and paper industrial biosolids from two aerated wastewater stabilization lagoons.

‡ Differences between means greater than the least significant difference are statistically significant ($p < 0.05$).

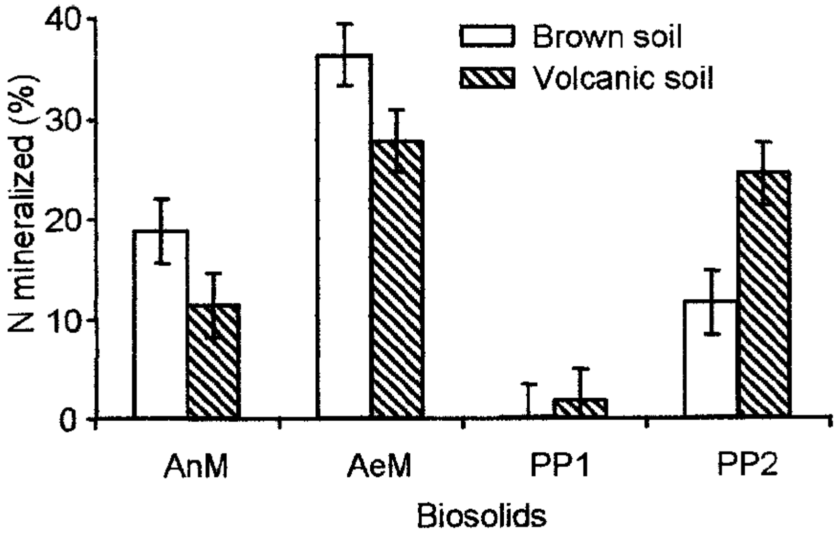


**Fig. 3. The influence of soil on mineralization of different types of biosolids (the means across both 10 and 20°C, % of initial organic N). Error bars are 95% confidence intervals. AnM, anaerobically digested municipal biosolids; AeM, aerobically digested municipal biosolids; PP1 and PP2, two pulp and paper industrial biosolids from two aerated wastewater stabilization lagoons.**

**Figure 2: The rate of N mineralisation in biosolids as influenced by temperature, soil type and biosolids origin (after Wang et al., 2003)**

Other types of biosolids are considered in international research. A comprehensive review is given by Henry *et al.* (1999). The following tables reproduced from that paper outline estimated and measured year one mineralisation from a range of biosolids.

**Table 3: Estimates of N mineralisation rates for various biosolids/sludge products. (After Henry *et al.*, 1999)**

**Table 4.1. Estimates of N mineralization rate ranges for biosolids treatment methods (percent of initial organic N).**

| Biosolids Treatment Method | Mineralization Rate (% of initial organic N) |
|---|---|
| Anaerobically digested | |
| Liquid | 20-40 |
| Dewatered | 25-45 |
| Heat-dried | 25-45 |
| Aerobically digested | 30-50 |
| Lagooned | 10-30 |
| Lime-stabilized | 30-60 |
| Composted | 0-30 |
| Drying bed | 15-40 |
| Oxidation ditch | 30-50 |

**Table 4.2. Results of field studies of N mineralization rates in Northwest biosolids (percent of initial organic N).**

| Biosolids Treatment Method | Mineralization Rate (% of initial organic N) |
|---|---|
| Anaerobically digested | |
| Liquid (2) | 26-27 |
| Dewatered (3) | 32-44 |
| Aerobically digested | 49 |
| Lagooned | 19 |
| Lime stabilized | 55 |
| Composted (4) | 1-27 |
| Drying bed | 37 |
| Oxidation ditch | 45 |
| Biosolids-soil mix | 2 |

Note: Numbers in "( )" indicate more than one wastewater treatment plant tested.
Source: Cowley and Henry, 1997 (Appendix D).

## Appendix A

A summary of relevant mineralisation rate information given in publicly available research data and literature is given here followed by a further list of references.

## Thermal Drying and Alkaline Treatment of Biosolids: Effects on Nitrogen Mineralization

**Authors:** J. Silva-Leal, P. Torres-Lozada, Y.J. Cardoza.
**Published**: 2012
**Journal:** Clean – Soil, Air and Water; Volume 43, issue 1

Multiple methods are used to reduce pathogens within biosolids in order to assess the impact on N mineralization. The authors assess thermally dried biosolids (TDB) and alkalinized biosolid (AB), with untreated, dehydrated biosolid (DB) used as the control. Argonomic rates of biosolid application to sugarcane crops were estimated. Results showed mineralisation rate decreased with increasing biosolid dose of application.

**Direct excerpts from the article around N mineralization:**
*"Mineralization rate decreased with increasing biosolid dose of application. This phenomenon may be due to oversaturation of the mineralization capacity of microorganisms in soil. Indeed, Vieira et al. found that biosolid applications of 4 and 8 times above the recommended for the crop exceeded the maximum rate at which microorganisms can mineralize organic nitrogen. These authors also found high nitrogen losses due to denitrification."* (Silva-Leal *et al.*, 2012).

**Table 3.** Doses of organic nitrogen applied, nitrogen mineralized in each treatment (DB, AB, and TDB) and percentage of nitrogen lost

| Treatment | Dose of organic N applied (mg/kg) | Total mineralized nitrogen (mg/kg) | Mineralized nitrogen (mg/kg) | Mineralized nitrogen (kg/ha[a)]) | % Nitrogen lost |
|---|---|---|---|---|---|
| D0 | 0.0 | 58.2 | | | |
| D1 DB | 319.4 | 169.3 | 111.1 | 288.8 | 65.2 |
| D2 DB | 638.8 | 275.4 | 217.2 | 564.7 | 66.0 |
| D3 DB | 958.2 | 348.6 | 290.4 | 755.1 | 69.7 |
| D1 TDB | 343.8 | 246.8 | 188.6 | 490.5 | 45.1 |
| D2 TDB | 687.6 | 413.0 | 354.8 | 922.5 | 48.4 |
| D3 TDB | 1031.4 | 498.0 | 439.8 | 1143.5 | 57.4 |
| D1 AB | 374.0 | 152.0 | 93.8 | 243.8 | 74.9 |
| D2 AB | 748.1 | 239.1 | 180.9 | 470.2 | 75.8 |
| D3 AB | 1122.1 | 309.9 | 251.7 | 654.5 | 77.6 |

D0, control treatment; D1, dose 1; D2, dose 2; D3, dose 3; DB, dehydrated biosolid; AB, alkaline biosolid and TDB, thermally dried biosolid. Total mineralized nitrogen includes nitrogen mineralized from soil evaluated.
[a)] kg/ha assuming a soil density of 1.30 g/cm$^3$ and 0.2 m depth.

**Above:** Table demonstrating treatment type (see key below table), dose of organic N applied (mg/kg), total mineralized N (mg/kg), mineralized N (mg/kg) and (kg/ha), as well as percentage of N lost (Silva-Leal *et al.*, 2012).

## Restoration of Abandoned, Degraded Agricultural Soil Using Composted Biosolid: Influence on Selected Soil Properties

**Authors**: A.P. Fernández-Getino, J. Pérez, M.D.M. Albarrán, D.M. Lammerding & I. Walter
**Published**: 2012
**Journal:** Arid Land Research and Management; Volume 26, issue 3.

Authors of this literature undertake a short term (three years) field experiment to study the effects of biosolid application on soil properties, with its motive being to improve physical, chemical and biological properties of soil to enhance fertility in a semiarid climate, in an abandoned agricultural setting. Organic waste – biosolids, were surface applied at an experimental farm at one of three rates: 30, 60 and 90Mg/ha$^{-1}$. Three years following application, chemical properties of the soil including organic C (SOC), humified C fractions (THS-C), water soluble C (DOC), total nitrogen (Nk) basal respiration ($CO_2$-E) and potential nitrogen mineralization increased in the 60Mg/ha$^{-1}$, and 90Mg/ha$^{-1}$ biosolid application rates. Physical soil properties did not change with biosolid treatments in this experiment, however available heavy metals showed a slight increase which was below those considered phytotoxic.

**Estimating mineralisation of organic nitrogen from biosolids and other organic wastes applied to solid in subtropical Australia**

**Authors:** G. Pu, M. Bell, G. Barry, P. Want
**Published:** 2012
**Journal:** Soil Research, volume 50

This article outlines field studies undertaken to investigate mineralisation processes of three biosolid products – aerobic, anaerobic and thermally dried biosolids, when applied to four different soils at a rate of 7-90 wet t/ha. Organic N in all biosolids products was mineralised rapidly under ambient conditions in subtropical Queensland, with rates much faster than from other common organic amendments. Biosolid mineralisation rates ranged from 30 to 80% of applied N during periods ranging from 3.5 to 18 months after application; these rates were much higher than those anticipated. There was no consistently significant difference in mineralisation rate between aerobic and anaerobic biosolids observed. A significant proportion of the applied biosolids total N (up to 60%) was unaccounted for at the end of the observation period. High rates of N addition in calculated Nitrogen Limited Biosolids Application Rates resulted in excessive accumulation of mineral N in the soil profile, which increases the environmental risks due to leaching, runoff, or gaseous N losses. Further, the article states that the rapid mineralisation of the biosolids organic N in these subtropical environments suggests that biosolids should be applied at lower rates than in temperate areas, and that care must be taken with the timing to maximise plant uptake and minimise possible leaching, runoff, or denitrification losses of mineralised N.

**Predicting Nitrogen and Carbon Mineralization of Composted Manure and Sewage Sludge in Soil**

**Authors**: R.S. Antil, A. Bar-Tal, P. Fine & A. Hadas
**Published**: 2013
Journal: Compost Science & Utilization; Volume 19, No. 1

Predictions of mineralization rates of different materials to evaluate the influence of soil type and application rate of organic materials, on N and C transformations in soil taken. Four organic biosolids including sewage sludge, sewage sludge compost, cattle manure compost and hen and cattle manure compost were applied to two soils. These were applied at a rate of 2% and/or 4%, with soils incubated aerobically for 168 days at 30 degrees Celsius, with $CO_2$ rates and mineral N concentrations measured throughout this period. A correlation was determined with hot water extractable C and N of all organic amendments, however hen and cattle manure compost immobilized N, despite its soluble N content being high. A computer model, NCSOIL, was used to simulate C and N cycling in soil with organic amendments, and was successful in predicting the mineralization of these elements in sewage sludge, sewage sludge compost and cattle manure compost. NCSOIL software was further used to simulate other mineralization rates and methods.

**Potential benefits and risks of land application of sewage sludge**

**Authors:** R.P. Singh, M. Agrawal
**Published:** 2007
Journal: Waste Management; Volume 28

A good starting point summary document for the reader to become familiar with foundational knowledge of biosolids, their uses and chemical processes involved in application of biosolids to land.

The purpose of this paper is to review the available information on various aspects of sewage sludge application on soil fertility and consequent effects on plant production to explore the possibility of exploiting this by-product for agronomy and horticulture.

**A critical review of nitrogen mineralization in biosolids-amended soil, the associated fertilizer value for crop production and potential for emission to the environment**
**Authors:** H. Rigby, B.O. Clarke, D.L. Pritchard, B. Meehan, F. Beshah, S.R. Smith, N.A. Porter.
**Published:** 2015
**Journal:** Science of the Total Environment; issue 514

A review of findings and data gathered from across the research field of biosolids thighlighting trends including mineralisation.

International controls for biosolids application to agricultural land ensure the protection of human health and the environment, that it is performed in accordance with good agricultural practice and that nitrogen (N) inputs do not exceed crop requirements. Data from the scientific literature on the total, mineral and mineralizable N contents of biosolids applied to agricultural land under a wide range of climatic and experimental conditions were collated.

The mean concentrations of total N (TN) in the dry solids (DS) of different biosolids types ranged from 1.5% (air-dried lime-treated (LT) biosolids) to 7.5% (liquid mesophilic anaerobic digestion (LMAD) bio- solids). The overall mean values of mineralizable N, as a proportion of the organic N content, were 47% for aerobic digestion (AeD) biosolids, 40% for thermally dried (TD) biosolids, 34% for LT biosolids, 30% for mesophilic anaerobic digestion (MAD) biosolids, and 7% for composted (Com) biosolids. Biosolids air-dried or stored for extended periods had less total and mineralisable N compared to mechanically dewatered types. For example, for biosolids treated by MAD, the mean TN (% DS) and mineralisable N (% organic N) contents of air-dried materials were 3% and 20%, respectively, compared to 5% and 30% with mechanical dewatering. Thus, mineralizable N declined with the extent of biological stabilization during sewage sludge treatment; nevertheless, overall plant available N (PAN = readily available inorganic N plus mineralizable N) was broadly consistent across several major biosolids categories within climatic regions. However, mineralisable N often varied significantly between climatic regions for similar biosolids types, influencing the overall PAN. This may be partly attributed to the increased rate, and also the greater extent of soil microbial mineralisation of more stable, residual organic N fractions in biosolids applied to soil in warmer climatic zones, which also raised the overall PAN, compared to cooler temperate areas.

The review suggests a requirement for better characterization of N release and mineralisation in biosolids and that some international fertiliser recommendations may underestimate mineralisable N in biosolids, and the N fertilizer value. Consequently, greater in- puts of supplementary mineral fertiliser N may be supplied than are required for crop production, potentially increasing the risk of fertiliser N discharges to the environment. Thus greater economic and environmental savings in mineral N fertilizer application are potentially possible than are currently realised from biosolids recycling programmes.

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