Composting of pig waste
and its use as a soil conditioner in horticulture.

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Declaration

I declare that all sources are acknowledged and that this thesis is my own composition and the result of my own research.

Patrick Gethin
Summary

Piggeries produce a large volume of waste and concerns over the treatment and disposal of this waste have led pig industry organizations, such as the Australian Pig Research and Development Corporation (PRDC) to seek new options which are environmentally compatible. Composting is one option that could help reduce the volume of waste to be disposed of as well as converting the waste into a product that has value as a soil conditioner.

A prototype composting system was used as the basis for this project. This system had been set up at a piggery in the south west of Western Australia to test the viability of composting. The project focussed on assessing the value of tests for ensuring the efficiency of composting and to select benchmark tests that could be easily used on other composting systems. It was found that pig waste could be readily composted using an ‘in tunnel’ composting system. The most predictive tests for monitoring the composting process were the carbon to nitrogen ratio of the compost and temperature and moisture content of the composting waste during and at the end of composting. Overall, the C:N ratio was the most predictive test of the state of decomposition of the compost. Other studies of composting unique waste types, such as slaughter-house waste, have also shown that these three factors are the most predictive of compost decomposition.

It is essential to produce a mature composted product in which most of the readily degradable compounds have been broken down as application of immature compost to soil often results in immobilisation of soil nutrients. Methods for assessing compost maturity were tested and a new, potentially more predictive, method of using microbial biomass as an indicator of compost maturity was found to be suitable for composted pig waste, although further refinement of the method is required. Simpler tests assessing the inhibition of seed germination by water extracts from compost and C:N ratio of the composted product were also predictive of compost quality.

The second part of this project comprised of a series of experiments assessing the suitability of composted pig waste as a soil conditioner for horticulture in Western Australia on soils with a very high sand content, low nutrient holding capacity, low water holding capacity and low nutrient content. The first experiment evaluated whether there was a high potential for N and P from the compost to be rapidly leached and
contribute to the pollution of the water table. Potential losses were compared to those associated with similar amounts of N and P applied as inorganic fertilisers. This experiment was conducted using leaching columns in which sand was mixed with compost at rates up to 80 t/ha, with or without inorganic fertiliser. Under high leaching conditions, compost applied at 80 t/ha resulted in only 1% of applied P being leached (10 kgP/ha) as opposed to 20% of P applied as superphosphate. Compost applied at 80 t/ha resulted in 13% more P being leached when applied in conjunction with a conventional application of inorganic P fertiliser. Thus, when estimating the potential for P to be leached under horticultural crops it is important to consider the contribution of soil conditioners as well as inorganic fertilisers. From these results it can be inferred that under normal conditions, where leaching rates are much lower, a significant amount of P would be supplied by the compost for plant uptake, therefore having considerable value as a P fertiliser. Losses of N from fertilised, sandy soil were also increased by the application of compost with up to 20% more ammonium and nitrate being leached than the sum of the amount leached when either compost or Ammonium-Nitrate fertiliser were applied alone. This indicates that there is an interaction between the added inorganic N and the compost, increasing the rate of N mineralisation from the compost.

In a field experiment comparing compost and conventional soil conditioners, composted pig waste had beneficial properties as a soil conditioner. Water holding capacity, total soil P, microbial biomass and soil carbon were all increased and soil bulk density was reduced where pig compost was applied and pig compost compared favourably with other common soil conditioners, such as peat and poultry litter. These findings indicated that composted pig waste could be used as an alternative for poultry litter in Western Australian horticulture on sandy soils.

Horticulture in Western Australia currently relies on poultry litter as a soil conditioner for sandy soils, but is expected to be prohibited due to environmental concerns that it is a prime and significant breeding ground for stable flies in suburban areas around Perth. However, it has never been used for conditioning the soil before growing carrots as it has the potential to cause detrimental effects on carrot yield and quality. A field experiment was set up to determine whether composted pig waste could be used as a soil conditioner for carrot production in place of poultry litter. The objective was to provide growers with the opportunity to improve soil fertility during the carrot phase of rotations as well as to improve carrot yields. The experiment was conducted on a
commercial carrot property in which compost was included in the conventional cropping program. The composted pig waste was not suitable for use as a soil conditioner for the production of carrots in this study. The compost had a similar effect to poultry litter in that it increased the quantity of deformed and split carrots and decreased total carrot yield.

The amount of nutrients supplied by a soil conditioner is not normally considered when fertiliser requirements for a crop are determined. However, at conventional application rates of soil conditioners in Western Australia (20 t/ha) significant amounts of nutrients are applied, (eg = 200 kgP/ha from 20 t/ha compost) and a proportion of these will become available to plants. If this is taken into account it could reduce fertiliser requirements. The availability of P from composted pig waste needs to be determined to calculate its replacement value. A field experiment was set up to assess the availability of P from compost for lettuce growth, a crop with a high P demand. The yield response to applied compost was compared to a well defined lettuce yield response curve for superphosphate (McPharlin et al. 1996). A standard test for available P (bicarbonate extractable P) was also used to determine whether it was able to predict lettuce response to P applied in the compost. Compost did not supply sufficient P to achieve the same maximum yield obtained for superphosphate. The maximum P uptake for superphosphate was 18 kg/ha compared with only 12 kg/ha for compost. Bicarbonate extractable P was not a useful predictor of lettuce response to compost P application.

Overall, this study showed that solid waste from piggeries can be readily composted to produce a product suitable for many situations in horticulture as a soil conditioner; it has potential to be used instead of poultry litter, the most widely used soil conditioner in horticulture in regions surrounding Perth, Western Australia.
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Chapter 1. Introduction

Large volumes of organic waste are continuously produced around the world from a wide range of sources such as municipalities (Table 1.1), animal production, timber industries, sewage and food industries. In Western Australia, 1.2 million tonnes of organic waste material are produced each year within the Perth metropolitan region (Tingay and Associates 1997). The consequences of not developing suitable treatment and disposal methods for wastes include the accumulation of large volumes of odorous, putrescent wastes, the contamination of ground water and soil and the loss of a useful source of nutrients and organic matter.

Pressure is being placed on waste producers, via legislation and public concerns, to improve waste treatment methods. Older techniques, such as dumping and burning wastes have become less acceptable due to their negative effects on the environment. Composting is now being explored as a desirable option for treating organic wastes. It has the benefit of rapidly stabilising wastes, reducing odour production and growth of pathogenic organisms as well as reducing the volume and water content of the waste. A composted organic waste can often be more readily utilised and is likely to have less negative impact on the environment than uncomposted material (Mathur 1991, Hansen et al. 1993, Harada 1994, McPhail and Van Oostrom 1993).

Solids in the effluent stream from intensive piggeries are an example of a waste for which alternative treatment systems are being sought throughout the world (Collins and Parsons 1993, Lau et al. 1993). The production of pigs in intensive housing generates large amounts of effluent solids. In the past, these wastes have been treated and stored in anaerobic ponds. A 2000 sow piggery may produce 10 t/day dry matter as effluent, ie 5 kg/day/sow (Roberts 1994). This system results in high levels of nutrients, especially N and P, accumulating in treatment ponds posing a potential environmental threat to surrounding water bodies. This project was initiated to examine the potential for producing compost suitable for horticultural use to reduce the amount of waste and nutrients in treatment ponds.
Table 1.1 World production of municipal waste and the percentage that is composted (USEPA 1997).

<table>
<thead>
<tr>
<th>Country</th>
<th>Municipal solid waste produced (million t/yr)</th>
<th>Percent of waste composted (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>25</td>
<td>3.2</td>
</tr>
<tr>
<td>Japan</td>
<td>60</td>
<td>4.2</td>
</tr>
<tr>
<td>United States</td>
<td>210</td>
<td>3.7</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Netherlands</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Italy</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>France</td>
<td>20</td>
<td>11.5</td>
</tr>
<tr>
<td>Spain</td>
<td>20</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Several studies have examined methods for composting pig waste (Collins and Parson 1993, Lau et al. 1993, Pandey et al. 1993.). None have included an assessment of effects of the compost on soil fertility. Clearly, this is an oversight as soil application is the primary end use of compost. Hence, there is a need to define a composting system specific to pig waste and then to assess its beneficial and detrimental effects on soil fertility. By investigating these two issues, there is potential to increase the acceptance of compost as a sustainable waste treatment option for piggeries to reduce their detrimental effect on the environment and to improve productivity by adding value to their waste.
Chapter 2. Literature Review

2.1 Introduction
Composting involves the decomposition of organic matter, which may include noxious wastes, by aerobic microorganisms, resulting in the production of a stabilised, humus-like product. The main benefits from composting wastes are: rapid breakdown of odour causing compounds, a reduction in moisture content, the elimination of most pathogens and the production of a soil conditioner.

Composting has been used to treat organic wastes for several thousand years. However, it was not until the 1940’s that industrial composting techniques were developed and research into the process was instigated (Mathur 1991). Since then, techniques for composting have greatly progressed. Improvements in technology and design have resulted in composting systems being developed for a wide variety of wastes, that would otherwise be burnt or buried, causing air, water or land pollution. Wastes that have been successfully composted include manure, food residues, slaughter house waste, sewage and paper sludge (Lau et al. 1993, Van Oostrom et al. 1988, Sikora and Sowers 1985).

Although all composting processes are based on similar principles, variability in composition of waste types requires the establishment of guidelines specific to each waste. Thus, to set up a composting process for a new waste type, two major factors that need to be taken into account are (i) the development of a method which is specific to the type of waste and circumstances and (ii) the usefulness of the compost as a soil conditioner and fertiliser.

First, this review considers the critical conditions required for composting and how monitoring these conditions can be used to assess the performance of the composting system. This includes the assessment of waste suitability for composting, the establishment and maintenance of a suitable environment for composting to occur and the development of completion criteria for the composting process. Basic principles for the development of composting processes have been described in several reviews (for example Mathur 1991, Gotaas 1956). Many studies consider variations upon these basic principles which may need to be considered for optimising a composting process. The few studies published on composting pig waste have used different mixes of pig waste and other organic amendments as well as different composting conditions (Collins and
Parson 1993, Lau et al. 1993, Pandey et al. 1993). An optimum technique for composting pig waste has not been developed. This review seeks to examine both the general principles for composting and the observed variations from these rules, providing a broad background of knowledge from which composting processes, for any waste type, such as pig waste mixed with other organic amendments, can be developed and their suitability assessed.

Second, the effects of compost application on soil are evaluated. The way in which compost is used is largely governed by its benefits as a soil conditioner or fertiliser and its cost effectiveness. It is important to clearly identify and quantify benefits of a specific compost so that users receive information on its performance. Unlike the composting process, very little is known about the effects of compost application on soil fertility and even less is known for composted pig waste. Therefore, the effects that compost application have on soil will be summarised and principles relating to its application will be developed and used to predict the effects of applying composted pig waste to soil.

This project is of particular interest to the pig industry as it has been funded by the Pig Research and Development Corporation. Thus, guidelines for composting and use of pig waste will be considered in detail.
2.2 Considerations for the development of a composting system

Composting involves the breakdown of organic wastes by mesophilic and thermophilic microbes under aerobic conditions. The products are stabilised organic matter (compost), carbon dioxide, heat, water and nutrients (Zucconi and Bertoldi 1986, Gotaas 1956). Composting differs from natural breakdown of organic matter in soil in that an environment within the waste is artificially created and controlled to allow microbes to degrade organic matter to produce a desirable composted product.

\[
\text{organic waste} + O_2 \xrightarrow{\text{degradation}} \text{compost} + CO_2 + H_2O + \text{heat} + \text{nutrients}
\]

The microbial activity responsible for composting can be divided into several stages. Once a compost pile is created, by heaping organic matter up or placing in a vessel, the first stage of microbial activity begins. During this stage, mesophilic microbes begin to breakdown readily available compounds in the waste such as sugars, starch, amino acids, proteins, pectins and inorganic N (Stratton et al. 1995). Heat, a by-product of this process, is trapped inside the composting material raising its temperature. Once the internal temperature of the composting material exceeds 40°C, 1-3 days after pile formation, thermophilic microbes replace mesophilic microbes increasing the rate of degradation due to their higher rates of metabolism.

During the second stage of composting, thermophilic microbes, especially *Bacillus spp.* and actinomycetes continue to rapidly degrade organic compounds such as proteins, fats, sugars and starches (Chen and Inbar 1993). The temperature of the composting material continues to increase up to 70°C. Water content is reduced through evaporation and organisms pathogenic to humans and plants are killed. Many odour causing compounds are also broken down during this period. Unlike the first stage, the length of this stage is highly variable depending on waste type and may last from weeks to months (Gotaas 1956).

Once the readily degradable compounds have been broken down, the rate of composting decreases and the temperature of the compost pile decreases creating a third stage where mesophilic microbes re-colonise the compost. Fungi are especially important at this stage as they degrade some of the more recalcitrant compounds such as cellulose,
lignocellulose and lignin (Stratton et al. 1995). This stage is known as the maturing stage after which the compost is ready for use as a soil conditioner. This stage may last from weeks to months (Chen and Inbar 1993).

**Figure 2.1** Theoretical temperature profile during the three stages of composting (adapted from Gotaas 1956).

For the three composting stages to occur successfully and for the material to be completely composted, it is essential that particular conditions are created and maintained during the composting process to allow microbes to degrade at optimal rates to produce compost. The major factors that affect the rate of composting are carbon to nitrogen ratio (C:N), moisture, pH, aeration and temperature (Gotaas 1956).

### 2.2.1 C:N ratio

Microbes responsible for composting use carbon from organic matter as an energy source to synthesise cell compounds. Nitrogen from the waste is required for the production of amino acids and other nitrogen containing compounds essential for cell maintenance and growth (Stratton et al. 1995). The C and N content, and subsequently the carbon to nitrogen ratio (C:N) of a waste, are the first assessments that need to be made before deciding if a waste can be successfully composted.

The theoretical optimum C and N requirements for microorganisms is 30 units of C for every unit of N that they use, with 66% of C respired as CO₂ and 33% used with N for synthesis of cell components (Gotaas 1956). However, the availability of C and N for microbial utilisation differs between waste types. If C is contained in compounds which are difficult to degrade (such as lignin), it will be less available for microbial utilisation.
and optimal rates of composting will occur at higher C:N ratios. Similarly, if N is contained in a less available form, a greater quantity of this N will be required for the composting process to operate. Differences in C and N availability thus result in a range of optimal C:N ratios from 16:1 and 40:1 for differing waste types (Collins & Parson 1993, Mathur 1991, Gotaas 1956, Stratton et al. 1995). It has been suggested that an ideal ratio for composting pig waste is 16:1. This is quite low and it is likely that as there is an excess N in comparison to C odorous compounds could be lost via volatilisation. Indeed this ratio is more than half that used in another pig waste composting study (48:1) in which vertical reactors were assessed for composting pig waste (Lau et al 1993).

Microbial availability of C and N could perhaps be considered an ideal measurement for determining whether a waste had a suitable C:N ratio for composting. Microbial availability of both C and N are difficult to define as well as time consuming to measure, so as a substitute total C and N contents are widely used even though they are less suitable for predicting the correct C:N ratio for optimal composting.

In practice, C and N contents are only adjusted in extreme cases where composting is likely to be severely limited or where secondary problems arise from excess amounts of C or N. Wastes with excess N relative to C (low C:N ratio), such as poultry litter (15:1), may lose N through volatilisation of ammonia compounds, reducing the nutrient value of the compost and polluting the air (Hansen et al. 1993). This problem can be reduced by increasing the C content of the compost material. For example straw can be added to pig manure to increase the C:N ratio (Collins and Parson 1993). In contrast, excess C in relation to N, (a high C:N ratio), results in a reduced rate of composting unless N is added. For example, (NH₄)₂SO₄ can be added to straw to make the C:N ratio more suitable for composting (Horwath and Elliot 1996).
2.2.2 Moisture

The microorganisms responsible for composting live in thin films of water surrounding particles of organic matter within the composting material. Water is essential for the survival of these organisms, preventing them from dehydrating as well as providing a medium from which they can absorb $O_2$ and nutrients. Excess water slows the rate of oxygen diffusion and leads to anoxic conditions.

The optimal level of moisture for composting depends greatly on the water holding capacity of a waste, the higher the water holding capacity the greater the optimal water content (Mathur 1991). The range in optimal water content for composting is reflected in broad recommendations of 40-60% moisture (Gotaas 1956) and 45-90% moisture (Mathur 1991). Moisture contents between 50 and 70% are adequate for composting pig waste (Collins & Parson 1993). In practice, composting is often carried out at water contents outside optimal ranges, as indicated in Table 2.1, where moisture contents ranged from 23% (straw) to 76% (sewage sludge). Despite this variability, it should be possible to quantify moisture contents required for composting specific waste types. From Table 2.1, it is apparent that approximately 70% moisture content is suitable for composting sewage sludge. It has been suggested that 75-85% and 70-80% moisture content is suitable for solid manure (Gotaas 1956, Mathur 1991).

2.2.3 pH

The pH of waste changes throughout the composting process. During the initial mesophilic stage, waste pH generally falls due to the production of organic acids (e.g. acetic acid, citric acid) as microbes begin to degrade the waste. The waste pH then increases to become alkaline during the thermophilic stage, as ammonia is produced from the degradation of proteins. The pH of the finished product is normally neutral to slightly alkaline (Chen and Inbar 1993).

The optimal starting pH for composting is considered to be between pH 5.5 and pH 8 (Mathur 1991, Inbar et al. 1993) but composting can be practised up to pH 11 (sewage sludge) and down to pH 4.2 (bark) (Table 2.1). There is little need to adjust pH for composting to occur. Problems may occur if a particular waste is composted at an extreme pH level, in which case pH adjustments may be necessary. Volatilisation of
ammonium ions (NH$_4^+$) and trace element immobilisation occurs in some high pH wastes. Heavy metals become more readily available for plant uptake and are more likely to affect surrounding organisms if a waste of low pH is composted (Mathur 1991).

**Table 2.1** Conditions for composting different waste types from a range of studies.

<table>
<thead>
<tr>
<th>Waste type</th>
<th>C:N start</th>
<th>C:N end</th>
<th>Moisture (%) start</th>
<th>Moisture (%) end</th>
<th>PH start</th>
<th>PH end</th>
<th>Temp (C)</th>
<th>Time (days)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>cattle manure</td>
<td>27</td>
<td>8</td>
<td></td>
<td></td>
<td>8.0</td>
<td>6.7</td>
<td>50</td>
<td>55</td>
<td>Inbar et al. (1993)</td>
</tr>
<tr>
<td>poultry litter</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>55</td>
<td></td>
<td>Hansen et al. (1993)</td>
</tr>
<tr>
<td>poultry litter</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>55</td>
<td></td>
<td>Hansen et al. (1993)</td>
</tr>
<tr>
<td>poultry litter/straw</td>
<td>27-45</td>
<td>14-20</td>
<td>76</td>
<td>66</td>
<td>7.0</td>
<td>7.4</td>
<td>60</td>
<td></td>
<td>Harper et al. (1992)</td>
</tr>
<tr>
<td>sewage sludge</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td></td>
<td></td>
<td>60</td>
<td>21</td>
<td>Van Oostrom et al. (1989)</td>
</tr>
<tr>
<td>sewage sludge/sawdust</td>
<td>11-15</td>
<td></td>
<td>69</td>
<td>45</td>
<td>5.4</td>
<td></td>
<td>60</td>
<td>21</td>
<td>Van Oostrom &amp; Cooper (1989)</td>
</tr>
<tr>
<td>sewage sludge/woodchips</td>
<td></td>
<td></td>
<td>76</td>
<td>22</td>
<td>6.3</td>
<td>8.2</td>
<td>15</td>
<td></td>
<td>MacGregor et al. (1981)</td>
</tr>
<tr>
<td>sewage sludge/woodchips</td>
<td></td>
<td></td>
<td>71</td>
<td>41</td>
<td>11</td>
<td></td>
<td>55</td>
<td>13</td>
<td>Sikora and Sowers (1985)</td>
</tr>
<tr>
<td>cotton &amp; sewage</td>
<td>21</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mondini et al. (1997)</td>
</tr>
<tr>
<td>straw</td>
<td>65</td>
<td>30</td>
<td>23</td>
<td>72</td>
<td>6.3</td>
<td>6.9</td>
<td>28</td>
<td></td>
<td>Forster et al. (1993)</td>
</tr>
<tr>
<td>general</td>
<td>30-35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50-70</td>
<td></td>
<td>Gotaas (1956)</td>
</tr>
<tr>
<td>ryegrass</td>
<td>50</td>
<td>10-15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50</td>
<td>45</td>
<td>Howarth &amp; Elliott (1996)</td>
</tr>
<tr>
<td>slaughter house waste</td>
<td>37</td>
<td>20</td>
<td>71</td>
<td>45</td>
<td>8.3</td>
<td>7.3</td>
<td>40-60</td>
<td>28</td>
<td>Van Oostrom et al. (1988)</td>
</tr>
<tr>
<td>bark</td>
<td>204</td>
<td>50</td>
<td>66</td>
<td>67</td>
<td>4.2</td>
<td>6.8</td>
<td>28</td>
<td></td>
<td>Forster et al. (1993)</td>
</tr>
<tr>
<td>household waste</td>
<td>16</td>
<td>12</td>
<td>73</td>
<td>65</td>
<td>5.7</td>
<td>6.9</td>
<td>280</td>
<td></td>
<td>Forster et al. (1993)</td>
</tr>
<tr>
<td>MSW and sorghum bagasse</td>
<td>18</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mondini et al. (1997)</td>
</tr>
<tr>
<td>sorghum bagasse, pine bark</td>
<td>18</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mondini et al. (1997)</td>
</tr>
</tbody>
</table>

(MSW = municipal solid waste, figures in **bold** indicate they are optimal levels)

2.2.4 *Aeration and oxygenation*

Adequate oxygen concentrations in the compost airspace are essential for the survival of aerobic microbes. It is thus necessary to remove excess carbon dioxide from the compost pile. The commonest forms of aeration are (i) mechanically disturbing and turning the compost pile, (ii) fan-forcing air through pipes at the base of the compost
and up into the pile and (iii) a combination of both methods. The amount of aeration required depends on the type of waste being composted and the design of the composting system. The general aim of aeration is to maintain oxygen concentrations inside the compost pile between 5% and 18% (Mathur 1991).

Few studies have quantified the aeration required for composting. Where aeration has been quantified (eg. as 10 m³ air/hr/ m³ of sewage sludge (Van Oostrom and Cooper 1989)) it is highly specific for the waste type, the composting system and the way that air is delivered. Adequate aeration can be indirectly assessed by measuring compost temperature, which is intrinsically linked to aeration and oxygenation. Temperatures above ambient are associated with aerobic, thermophilic, microbial activity which implies that sufficient oxygen is available (Stratton et al. 1995). Most field composting systems are developed to provide ‘adequate’ aeration instead of using precise aeration rates and use temperature as a surrogate for this.

2.2.5 Temperature

As stated above the temperature of the composting pile readily reflects the performance of the composting process and is used as the main indicator of the state of composting. A temperature greater than ambient is indicative of aerobic microbial degradation because heat is a by-product of the degradation. The higher the temperature the higher the rate of composting up to 70°C. Above 70 °C, composting rate rapidly decreases as higher temperatures kill most of the microbes and de-activate many of the enzymes involved in the degradation process (Mathur 1991). The ideal temperature for a given waste type depends on its chemical characteristics, environmental conditions and the composting method.

Many studies have quantified the ideal temperature for composting specific waste types. Different composting systems have been used, resulting in a range of recommendations (Sikora and Sowers 1985, Van Oostrom et al. 1989, Harper et al. 1992). Despite variations in optimal temperatures, it can generally be concluded that maintenance of temperatures between 50-70 °C for the duration of the process will result in successful composting (Table 2.1).
2.2.6 Determination of compost maturity

Once a composting process has been successfully established, it is necessary to select a point at which the compost is considered to be mature. A compost can be considered mature when most of the readily degradable microbial substrates, which are often associated with odours and having detrimental effects on plants, have been broken down and the composted material is suitable for application to soil. It is difficult to identify an endpoint because microbial degradation of organic matter may continue indefinitely after initial rapid degradation, albeit at a reduced rate. The stage at which organic matter is deemed composted and mature varies among composts, and is often a qualitative rather than quantitative assessment. Nevertheless, it is necessary to use some form of quantitative assessment to produce a high quality compost of known characteristics.

There are several reviews available which discuss methods of assessing compost maturity (Mathur et al. 1993, Mathur 1991, Finstein et al. 1986, Gotaas 1956, Harada 1994, Chen and Inbar 1993). The criteria for assessment of maturity include temperature, C:N ratio, moisture content, microbial activity and biomass, lack of reheating potential and absence of plant inhibitors. Each of these are considered below.

Under optimal composting conditions, specific changes in compost temperature are the most useful indicators of the state of the composting process and hence progress towards maturity. The ideal temperature profile that should be observed during composting is an initial rapid rise followed by a plateau at 50-70°C and finally a decline towards ambient (Gotaas 1956, Figure 2.1). Under ideal conditions, the final decline in temperature indicates that microbial activity has decreased as a result of the depletion of readily available microbial substrates. Premature declines in temperature can occur if environmental conditions in the composting pile do not favour microbial activity. Too much or too little moisture, too little oxygen and even excessive temperatures can all cause premature temperature declines (Finstein et al. 1986). Other criteria are also required to ensure that temperature decline is directly related to maturity (eg C:N ratio, moisture concentration, microbial activity, phytotoxic tests).

The C:N ratio of compost usually declines over time and can also be used as an indicator of maturity (Table 2.2). Commonly, a decrease in C:N ratio to between 10:1
and 15:1 is considered to correspond with compost maturity (Mathur et al. 1993). At these C:N ratios, neither C or N portions are in excess of microbial requirements and problems of N volatilisation or N immobilisation are not likely to occur. Several of the examples presented in Table 2.1 show mature compost with C:N ratios within this range. However, a decline in C:N to this level cannot always be used as an indicator of completion. For example, the composting of bark resulted in an incompletely composted material being produced with a high C:N ratio of 50:1. This final high C:N ratio reflected the initial high C:N ratio of 200:1 (Forster et al. 1993). Therefore, it is important to take into account the starting C:N ratio before using a final C:N ratio as an indicator.

![Figure 2.2 Ideal C:N ratio trend during composting.](image)

The moisture content of composting waste is another factor used as an indicator of compost maturity (Table 2.2). Moisture content, like the C:N ratio, declines throughout the composting process due to evaporation (Finstein et al. 1986). Loss of moisture can only be considered a secondary indicator of the state of the composting process as it is not directly related to maturity varying with rate of aeration as well as between types of composts and rate of aeration. A drying effect during composting is usually observed (Table 2.1). The extent of drying is not consistent and needs to be calibrated for specific composting materials and methods. If the moisture content drops below a critical level, microbial activity will dramatically decline and the composting process will cease prematurely. Subsequently, a decline in compost temperature occurs which is unrelated to that of a mature compost. This reduces the usefulness of temperature as an indicator of the maturity of a compost and highlights the importance of using several characteristics to determine compost maturity.
Table 2.2 Examples of characteristics and criteria for compost maturity.

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Criteria of compost maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>C:N ratio of waste</td>
<td>decrease, to 15-10:1</td>
</tr>
<tr>
<td>temperature in compost pile</td>
<td>decline in temp at end of composting</td>
</tr>
<tr>
<td>moisture concentration</td>
<td>varies between types, decrease from initial</td>
</tr>
<tr>
<td>microbial biomass</td>
<td>substantial decrease from original</td>
</tr>
<tr>
<td>microbial activity</td>
<td>decrease in CO₂ to a base level</td>
</tr>
<tr>
<td>reheating potential</td>
<td>low level of re-heating at end</td>
</tr>
<tr>
<td>seed germination test</td>
<td>high level of seed germination in compost extract</td>
</tr>
</tbody>
</table>

Compost maturity can be determined by measuring the activity and size of the total microbial population (microbial biomass) in the compost (Table 2.2). The reduction in activity and population size to a base level indicates that most of the readily available microbial substrates have been utilised and that the compost has matured (Mondini et al. 1997, Howarth & Elliot 1996). However, the use of microbial biomass measurements as an indicator is not widely practised although methods have been developed based on techniques widely used for measuring microbial biomass and activity in soil. Due to the different nature of compost and soil (e.g. much higher organic matter content, higher potential microbial population) these methods will require testing and calibration on a wide range of compost types to prove the suitability of the method (Mondini et al. 1997).

Re-heating potential of compost is a characteristic that is not widely used as an indicator of compost maturity. It can be used as a simplistic test that can be conducted readily in the field without expensive measuring devices (Brinton et al. 1995). This method involves taking a sample of compost, believed to be mature, placing it in an insulated container, imposing optimal moisture and aeration conditions and monitoring sample temperature. If there is no increase in temperature, the compost is considered to be mature. An increase in temperature indicates that the compost is still capable of supporting a high level of microbial activity and is therefore not mature and requires further composting.

In summary, there are several characteristics which can be used to estimate compost maturity but none of them provide a definitive measure. Therefore, it is currently
necessary to rely on the composting operator's prior experience and preference for assessment criteria to make the final decision on the maturity of the compost.

2.3 Effect of Compost Application on Soil Properties

Organic matter contributes to the chemical fertility of soil by supplying essential nutrients, stabilising pH and enhancing cation exchange capacity. Organic matter contributes to some major components of soil physical fertility including soil structure, bulk density, aggregation, infiltration and water holding capacity. Organic matter also contributes to the biological health of the soil, helping to sustain biological productivity (Pankhurst et al. 1997). The effects that organic matter have on soil chemical, physical and biological properties have the potential to be improved significantly by addition of compost. There is also potential for the productivity of soil to be enhanced. The second part of this review considers the influence which compost may have on various aspects of soil fertility.

2.3.1 General responses of plants to compost application.

The application of compost to soil may improve the growth and yield of plants, especially when growth is limited due to nutrient or physical limitations (Table 2.3). However, it is difficult to predict the effect of compost on plant growth and soil fertility as the chemical composition and physical characteristics of composts is highly variable (Table 2.4). It is necessary to examine compost composition in relation to effects on soil properties so that the amount of compost required to improve various components of soil fertility can be identified.

2.3.2 Effects of compost on chemical properties of soils

The main effects that compost application has been observed to have on soil chemical fertility are increased nutrient concentration (N, P, S and K), increased nutrient availability for plant growth and changes in soil pH.
Table 2.3 Effect of various types of compost on plant growth and components of soil fertility.

<table>
<thead>
<tr>
<th>Compost type</th>
<th>Rate (t/ha)</th>
<th>Crop</th>
<th>Plant and soil response to compost application</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW &amp; fertiliser</td>
<td>125</td>
<td>tomato</td>
<td>38% increase in tomato yield over inorganic fertiliser only.</td>
<td>Maynard (1995)</td>
</tr>
<tr>
<td>MSW</td>
<td>470</td>
<td>corn</td>
<td>increased corn yield.</td>
<td>Paino et al. (1996)</td>
</tr>
<tr>
<td>leaf</td>
<td>125</td>
<td>pepper</td>
<td>increased pepper yield over un-composted leaves and inorganic fertiliser control.</td>
<td>Maynard (1996)</td>
</tr>
<tr>
<td>vegetables and paunch contents,</td>
<td>1700</td>
<td>sunflower</td>
<td>yield of sunflowers doubled over a control treatment.</td>
<td>Marchesini et al. (1988)</td>
</tr>
<tr>
<td>urban compost</td>
<td>20</td>
<td>soybean</td>
<td>increased total and available soil P</td>
<td>AVRDC (1990)</td>
</tr>
<tr>
<td>sugar cane</td>
<td>120</td>
<td>soybean</td>
<td>increased total P, K and Ca in soil</td>
<td>AVRDC (1990)</td>
</tr>
<tr>
<td>city refuse</td>
<td>30</td>
<td>rye grass</td>
<td>increased soil labile P and plant P uptake, reduced P fixation in soil.</td>
<td>Iglesias-Jimenez et al. (1992)</td>
</tr>
<tr>
<td>MSW</td>
<td>20,30, 40, 50</td>
<td>rye grass</td>
<td>increased soil N and plant N uptake, proportional to rate, increased DM production.</td>
<td>Iglesias-Jimenez &amp; Alvarez (1993)</td>
</tr>
<tr>
<td>sewage sludge</td>
<td>60, 120, 240</td>
<td>tall fescue</td>
<td>increased yield linear to compost rate, N mineralisation rate slow.</td>
<td>Tester (1989)</td>
</tr>
<tr>
<td>sewage sludge</td>
<td>60, 120, 240</td>
<td>wheat</td>
<td>reduced bulk density and penetration resistance, inc. soil water and pH</td>
<td>Tester (1990)</td>
</tr>
<tr>
<td>sewage sludge and wood chips</td>
<td>22</td>
<td>wheat</td>
<td>immobilisation of soil N occurred, no effect on other elements. 32% inc in DM.</td>
<td>Sims (1990)</td>
</tr>
<tr>
<td>garbage</td>
<td>10, 20, 40</td>
<td>oats</td>
<td>increased soil C, total soil N, mineralisation rates of N and DM production (60 t/ha, 0 t/ha to 92 t/ha, 40 t/ha compost).</td>
<td>Werner et al. (1988)</td>
</tr>
</tbody>
</table>

(MSW = municipal solid waste)
Table 2.4 Nutrient concentrations and pH of various composts (expressed on a dry weight basis).

<table>
<thead>
<tr>
<th>Compost type</th>
<th>N</th>
<th>NO3</th>
<th>NH4</th>
<th>P</th>
<th>K</th>
<th>S</th>
<th>pH</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>broiler litter, wood shavings, peanut hulls</td>
<td>27</td>
<td>2060</td>
<td>40</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>Flynn et al. (1995)</td>
</tr>
<tr>
<td>broiler litter, pine bark, wood shavings</td>
<td>16</td>
<td>880</td>
<td>280</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>Flynn et al. (1995)</td>
</tr>
<tr>
<td>paunch contents, vegetable waste</td>
<td>15</td>
<td>366</td>
<td>18</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>Marchesini et al. (1988)</td>
</tr>
<tr>
<td>urban waste</td>
<td>16</td>
<td></td>
<td>4</td>
<td>11</td>
<td></td>
<td></td>
<td>7.8</td>
<td>Giusquiani et al. (1988)</td>
</tr>
<tr>
<td>city refuse</td>
<td>31</td>
<td>12</td>
<td>38</td>
<td>5</td>
<td></td>
<td></td>
<td>8.4</td>
<td>Iglesiasas Jimenez et al. (1992)</td>
</tr>
<tr>
<td>sewage sludge and municipal refuse</td>
<td>14</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td></td>
<td></td>
<td>6.7</td>
<td>Sims (1990)</td>
</tr>
<tr>
<td>cattle manure</td>
<td>6</td>
<td>0.2</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td>8.4</td>
<td>Paul and Beauchamp (1994)</td>
</tr>
<tr>
<td>garbage</td>
<td>9.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Werner et al. (1988)</td>
</tr>
<tr>
<td>sewage sludge</td>
<td>11</td>
<td>15</td>
<td></td>
<td></td>
<td>4</td>
<td></td>
<td>7.0</td>
<td>Tester (1989)</td>
</tr>
<tr>
<td>mushroom straw</td>
<td>11</td>
<td>4</td>
<td>85</td>
<td>4</td>
<td>6</td>
<td></td>
<td>7.05</td>
<td>Forster et al. (1993)</td>
</tr>
<tr>
<td>household</td>
<td>20</td>
<td>1330</td>
<td>198</td>
<td>3</td>
<td>6</td>
<td></td>
<td>7.0</td>
<td>Forster et al. (1993)</td>
</tr>
<tr>
<td>slaughter house</td>
<td>17</td>
<td>40</td>
<td>2900</td>
<td></td>
<td></td>
<td></td>
<td>7.3</td>
<td>Van Oostrom et al. (1988)</td>
</tr>
<tr>
<td>cattle manure</td>
<td>34</td>
<td>6</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>6.69</td>
<td>Inbar et al. (1995)</td>
</tr>
</tbody>
</table>

2.3.3 Nitrogen

The total N contained in a compost depends on the waste type and composting process. N concentration ranged from 6 g/kg to 34 g/kg across a wide variety of compost types (Table 2.4). The amount of available N for plant utilisation is not directly related to total N (Jarvis et al. 1997) as it depends upon form of N and the rate of release from poorly available forms (Giusquiani et al. 1988, Werner et al. 1988, Paul and Beauchamp 1994, Sims 1990, Iglesias-Jimenez and Alvarez 1993). Few studies have sought to identify the rate at which N becomes available from compost to plants over time although the amount of N taken up by plants has been used to indicate the minimum amount of available N for plant uptake from a specific compost.

As composts are made from a wide range of substrates with differing initial concentrations of N, generalisations about the plant availability of N from compost are not possible. Nitrogen uptake by plants from composted municipal waste was found to
be between 16% and 21% of the total N content of the compost over 6 months (Iglesias-Jimenez and Alvarez 1993). This is similar to the rate of uptake by corn from composted cattle manure, where 8% of total N was utilised by plants over 8 weeks (Paul and Beauchamp 1994). Higher uptake of N from composted biosolids and cow manure of up to 30% of applied N over 12 weeks has also been observed (Chen et al. 1996). In contrast, composted sewage sludge applied to 3 fine-loamy soils did not supply any plant available N over 20 weeks (Sims 1990). Generally, the availability of N from compost for plant uptake is difficult to predict as is the availability of N from non-composted organic wastes or indeed from soil in general. For example availability of N from non-composted sewage sludge to plants has been estimated to be up to 55% of total N per year (Clapp et al. 1986) and 40% per year of total N in farm yard manure is available for plant uptake (Hue 1995, Eck and Stewart 1995).

The immobilisation of plant available N is a potential problem associated with compost use. Net immobilisation is a direct result of compost having an excessively high C:N ratio (>40:1) with soil microbes using plant available N to break down carbon added as compost, temporarily reducing the total amount of plant available N (Stratton et al. 1995). Immobilisation of N in compost is only likely to be a problem for plant growth when immature composts with high C:N ratios are applied to soil and can be easily overcome by applying N fertiliser such as urea.

There is little information about the availability of N from compost to plants. Overall, compost has the potential to supply N to plants but the amount that a compost will supply needs to be determined according to individual compost, soil, plant and management regime using soil and plant analysis to hopefully establish supply functions which can then be used to predict N supply for plants. Even if these values can be determined the edaphic variable conditions associated with the addition of compost to soil would render these functions less useful.

2.3.4 Phosphorus

The amount of P in composts varies (e.g. 2.8-15 g/kg Table 2.4). The availability of this P to plants is difficult to predict as often it is present in organic forms and as there are no known tests for the availability of organic P (Tiessen et al. 1994). Only a few studies have examined the availability of P from compost. For composted city refuse, 11% of
total P was taken up by plants over 6 months (Iglesias-Jimenez et al. 1993). Similar quantities of total P in composted manure and biosolids were taken up by plants over 3 months (Chen et al. 1996). In contrast 40% of total P in non-composted sewage sludge was taken up by plants over 2.5 months (Fine & Mingelgrin 1996). For non-composted manure and sewage sludge a generalisation that 50% of P becomes available for plant uptake in the first year after application and that it becomes completely available in the longer term was made by Withers and Sharpley (1995). However, as composting results in changes in the proportion of different forms of P, this generalisation would not apply to composted waste. As for availability of N, predicting availability of P from compost requires the establishment of P availability functions determined from an experiment involving a range of composts, soil and plants from which P uptake was measured (Cai et al. 1997).

The application of compost to some soils can also indirectly affect availability of P to plants. In soils that have a high P fixing capacity, high rates of application of P need to be applied to ensure that P fixation sites are saturated. Application of compost to high P fixing soils can have a similar effect to that of high P fertiliser application rates, as humic ions present in the compost form chelates with the active Al(Fe) complex fixation sites restricting P adsorption (Iglesias-Jimenez et al. 1993).

2.3.5 Potassium and Sulfur

Composts have the potential to supply potassium to plants although the amount they can supply depends on the concentration of K in the composting substrate. Composted broiler litter applied at rates of between 400 to 1200 t/ha to a commercial potting mix supplied adequate K for the growth of lettuce (Flynn et al. 1995). Applications of 40 t/ha municipal solid waste compost to a sandy loam increased the concentration of K by 40 % from 350 to 525 ppm (Giusquiani et al. 1988). In contrast sewage sludge applications of between 330 and 1200 t/ha to a sandy soil increased concentration of K in petunia plants from 2% (control treatment) to 7% which is sufficient for maximum plant growth (Smith 1992). Thus certain types of compost have the potential to be used as a K source.

Little is known about the suitability of compost as a source of S for plants. Some composts contain between 4-5 g/kg S (Table 2.4) which will supply 100-200 kg/ha S
when compost is applied at 20-40 t/ha. These quantities of S have the potential to supply some or all of the S requirements for a crop but as for other elements, this depends on the availability of S from the compost.

2.3.6 Heavy metals

Composts, especially those made from sewage and manure wastes, contain heavy metals in various concentrations (Table 2.5). If the concentration of heavy metals is high, the application of the compost may have direct negative effects due to the phytotoxicity of elements such as Pb, Zn, Al, Cu, Mn, Cr and Cd at high concentrations or indirect effects through their concentration in plants and subsequent consumption by animals and humans (Stratton et al. 1995). However, some of these metals, (eg Zn, Cu and Mn) are essential plant nutrients and compost can be a useful source of these trace elements (Hue 1995).

Table 2.5 Heavy metal and Aluminium concentrations of various composts (expressed on a dry weight basis).

<table>
<thead>
<tr>
<th>Compost type</th>
<th>Pb</th>
<th>Zn</th>
<th>Al</th>
<th>Cu</th>
<th>Mn</th>
<th>Cr</th>
<th>Cd</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>broiler litter, wood shavings, peanut hulls</td>
<td>218</td>
<td>1803</td>
<td>153</td>
<td>244</td>
<td></td>
<td></td>
<td></td>
<td>Flynn et al. (1995)</td>
</tr>
<tr>
<td>broiler litter, pine bark, wood shavings</td>
<td>188</td>
<td>1649</td>
<td>213</td>
<td>241</td>
<td></td>
<td></td>
<td></td>
<td>Flynn et al. (1995)</td>
</tr>
<tr>
<td>paunch contents, vegetable waste</td>
<td></td>
<td>460</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Marchesini et al. (1988)</td>
</tr>
<tr>
<td>urban waste</td>
<td>263</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Giusquiani et al. (1988)</td>
</tr>
<tr>
<td>city refuse</td>
<td>224</td>
<td>1043</td>
<td>463</td>
<td>321</td>
<td>73</td>
<td>2</td>
<td>7</td>
<td>Iglesiasas Jimmenez et al. (1993)</td>
</tr>
<tr>
<td>sewage sludge and municipal refuse</td>
<td>748</td>
<td>898</td>
<td>401</td>
<td>474</td>
<td>192</td>
<td>7</td>
<td>13</td>
<td>Sims (1990)</td>
</tr>
<tr>
<td>sewage sludge</td>
<td>206</td>
<td>1100</td>
<td>1120</td>
<td>125</td>
<td>13</td>
<td></td>
<td></td>
<td>Smith (1992)</td>
</tr>
<tr>
<td>cattle manure</td>
<td>244</td>
<td>79</td>
<td>314</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Inbar et al. (1993)</td>
</tr>
</tbody>
</table>

26
2.3.7 pH

Composts generally have a neutral to basic pH (Table 2.4). Their application to acidic sandy soils often increases soil pH and improves plant growth (Smith 1992). For example, the application of municipal solid waste compost (MSW) at 125 t/ha/yr increased surface soil pH from pH 5.8 to 6.4 over 3 years (Maynard 1995). Similar increases in soil pH occurred when sewage sludge compost of pH 7.0 was applied at 135 t/ha to a loamy sand and soil pH increased from pH 4 to pH 6.7 (Tester 1989). In contrast, the application of 30 t/ha paunch compost (pH 7.4) to a sandy soil did not affect soil pH within 5 yrs (Marchesini et al. 1988). These studies demonstrate that compost can sometimes improve soil pH, especially if the soil is more acidic than that of the compost.

2.3.8 Effects of compost application on soil physical fertility

Compost application to soil may improve several physical properties of soil such as water holding capacity, bulk density, soil structure, soil strength and aggregation. Few studies have examined the physical effects of compost application on soil. Most statements relating to the impact of compost on soil physical conditions are inferences based on the measured role of native organic matter in soil.

Improvement in water holding capacity, especially of sandy soils, is an area where compost application may be highly beneficial. Applications of compost at 80 t/ha, increased water holding capacity of a sandy soil (in pot studies) by 43% and plant available water by 31% (Sabrah et al. 1993). The application of sewage-sludge compost at rates of 60, 120 and 240 t/ha increased water holding capacity by 47, 160 and 210% respectively of an evesboro loamy sand to a depth of 15 cm (Tester 1990). In contrast, the application of uncomposted sewage sludge did not increase plant available water in sandy soils (Clapp et al. 1986). Despite the potential for compost application to improve the water holding capacity of soil and increase the plant available water in soil, it is not currently possible to predict the extent to which compost application will improve these properties.

Soil bulk density is related to soil texture, porosity, hydraulic conductivity, aggregation, compaction and organic matter content (Clapp et al. 1986). High bulk densities can
reduce plant growth by impeding root development. Compost application is one method for reducing bulk density of soil if it is limiting plant growth. A reduction of bulk density by 13% occurred when compost was applied at 80 t/ha to a sandy soil in a pot experiment (Sabrah et al. 1993). The application of 240 t/ha of sewage sludge compost to a loamy sand reduced bulk density by 45% (Tester 1990). A reduction in bulk density due to compost application may occur because of the lower density of compost than soil. Compost application also reduces bulk density of clayey soils by increasing the volume of void areas due to increased soil aggregation (Hill and James 1995, Clapp et al. 1986).

Organic matter application to soil, including addition of compost, may improve soil aggregation by increasing the number, size and stability of aggregates. The rate of application required to increase aggregation may be large and depends on the soil type. Applications of 75 t/ha of manure had little effect on aggregation of a fine sandy loam soil but 40 t/ha of manure slightly increased aggregation of a loamy soil (Metzger and Yaron 1987, Clapp et al. 1986).

2.3.9 Effects of compost application on soil biological properties

The application of organic matter, including compost, to soil stimulates the microbial and faunal populations thereby changing soil biological properties (Syers and Craswell 1995). However, the relationship between these changes and plant response is difficult to quantify.

Application of organic municipal refuse to soil increased microbial biomass C, respiration and microbial quotient (Joergensen et al. 1996). The application of MSW compost increased microbial biomass C, P, N and S and increased activities of soil enzymes when applied at 2.5% w/w (Perucci 1990). An increase in organic matter content of 1.5% due to compost application increased microbial biomass carbon, basal microbial respiration rates and metabolic quotient (Pascual et al. 1997). The application of garbage compost at rates of 10, 20 and 40 t/ha increased soil microbial respiration and dehydrogenase activity (Werner et al. 1988). Urban refuse composted with sewage sludge applied at rates to supply 100, 200 and 300 kg/ha of available nitrogen increased mycorrhizal infection of maize at the two lower rates and the number of aerobic cellulolytic microbes increased when 200 and 300 kg/ha of compost were applied.
(Guidi et al. 1988). In all of these studies, no relationships between changes in biological properties and plant responses were identified. This lack of clear cause and affect relationships highlights the limitations of current techniques for assessing soil biological fertility and our poor understanding of the links between changes in biological properties and plant growth.

Although changes to biological properties of soil can be measured, it is not always clear whether these changes are beneficial or detrimental. Consideration of these changes in terms of soil health instead of plant response may provide a way of assessing the benefits of compost application on soil fertility. Soil health has been defined as ‘the continued capacity of a soil to function as a vital living system, within ecosystem boundaries to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health’ (Pankhurst et al. 1997). This definition recognises that soil microbes and fauna are important parts of the soil, as they affect ‘the capacity of the soil to function as a vital living system’ (Pankhurst et al. 1995). However, the baseline data required as a reference point for any given soil are unavailable.

2.4 Conclusions

Conditions required for composting organic waste have been examined by many researchers. Precise requirements for composting specific waste types have not been developed, partly as a consequence of the wide variety of wastes that are composted which differ considerably in chemical composition. The range of conditions discussed in this literature review provides a framework from which a composting process for pig and sewage waste can be developed. No robust test of compost maturity exists. Various analyses provide the basis for developing methods for testing the maturity of composts suited to individual composting processes.

The diversity of waste types used in composting causes problems for predicting the effect of compost additions on soil fertility and plant growth. The degree to which compost application affects soil fertility is primarily dependent on its composition and the soil type to which it is applied.
The first aim of the experimental work in this thesis was to establish a set of indicators for measuring changes in pig waste as it was composted and to use these indicators to assess the suitability of current composting techniques used by a piggery in Western Australia. The second aim was to assess the degree to which the application of composted pig waste influenced some components of soil fertility, with emphasis on its use as a soil conditioner for improving crop production on very sandy horticultural soils common to the Swan Coastal Plain of Western Australia.

Five areas were investigated in relation to the following hypotheses:

Temperature, moisture, carbon to nitrogen ratio, \( \text{NH}_4^+ \), total carbon, electrical conductivity (EC) and pH can be used as predictors of progress towards maturity for pig waste compost. Compost maturity can be assessed by measuring microbial biomass, carbon to nitrogen ratios and seed germination tests.

The amount of N and P lost by leaching from soil receiving compost will be minimal when compared to the N and P lost from readily soluble, inorganic fertilisers applied to sandy soils.

The addition of composted pig waste to a sandy soil will reduce soil bulk density, increase water holding capacity, increase microbial biomass and increase the total P and N content of the soil.

Composted pig manure can be used as a soil conditioner to increase water holding capacity and chemical fertility, for carrot production on a sandy soil without causing detrimental effects to carrot growth that are associated with the use of poultry litter.

The availability of phosphorus to lettuce from sandy soil receiving composted pig waste can be predicted by measuring bicarbonate extractable soil P.
Chapter 3. Assessment of the composting process and product stability at Wandalup composting plant.

3.1 Introduction

Wastes produced from intensive animal production are often difficult to dispose of as they are produced in large volumes, contain concentrated levels of nutrients, may contain some toxic elements and often have a high water content (Weitman 1995). Aerobic composting is one method of waste treatment that has been used successfully to treat these waste types, producing a stabilised product that, in many cases, is suitable for use as a soil conditioner or fertiliser (Hill and James 1995).

The aim of aerobic composting is to provide optimal conditions for aerobic microbes, particularly thermophilic microbes. These microbes in turn rapidly convert unstable organic waste into a stabilised, nutrient containing soil conditioner and reduce odours and destroy human and plant pathogens (Van Oostrom and Cooper 1989). To ensure that rapid aerobic composting occurs it is essential to develop a monitoring system to identify management of the compost process to maintain suitable conditions for effective composting.

Environmental factors within a compost pile are generally used as indicators of the state of the compost. The main indicators used are temperature, moisture and C:N ratio. Other factors, such as pH and electrical conductivity (EC), can also be used (Finstein et al. 1986). Rapid stabilisation rates are characterised by high temperatures, declining moisture contents and narrowing of carbon to nitrogen (C:N) ratios (Finstein et al. 1986). Failure of the composting system is indicated by initial lack of increase in temperature, premature drop in temperature of the waste, excess or inadequate moisture contents (>70 % or < 40%) and a lack of decrease in the C:N ratio (Finstein et al. 1986).

Once a successful system is developed it is necessary to define an endpoint to the composting process. The endpoint occurs when the material being composted has stabilised to a point where the waste is highly uniform in structure, friable, brown to black in colour at which point the compost is suitable for use as a soil conditioner. When a compost has reached this stage it can be deemed mature (Mathur et al. 1993).
Many methods of assessing compost maturity have been developed, although no single method has been adopted due to the absence of a suitable qualitative measure. Measurements of microbial biomass (Mondini et al. 1997), seed germination (Harada et al. 1993) and C:N (Finstein et al. 1986) are used to define compost maturity. In addition to testing for maturity, it is necessary to determine chemical composition to assess nutrient levels and the presence of any potentially harmful compounds.

The major aim of this experiment was to examine how readily pig waste from Wandalup piggery could be composted. The three specific aims of this experiment were; i) to determine the usefulness of measuring temperature, moisture, carbon to nitrogen ratio, $\text{NH}_4^+$, total carbon, electrical conductivity (EC) and pH as predictors of the composting progress, ii) to assess compost maturity using microbial biomass measurements, carbon to nitrogen ratios and seed germination tests, and iii) to quantify the chemical composition of the compost.

3.2 Materials and methods

Composting process

Composting was conducted under commercial conditions in a pilot plant set up to compost solid pig waste at Wandalup piggery, 60km south of Perth, Western Australia (Plate 3.1). The compost plant used was an in-vessel tunnel system, 100m in length with 2m high cement walls (Roberts 1994). A purpose built compost turner was used, moving the material being composted 5-10 m along the composting tunnel with each pass of the machine. Composting material was turned twice a week. After waste had progressed 70m along the tunnel it was removed and stored in uncovered bays until sold.
Plate 3.1 Composting plant at Wandalup Farms piggery in the south-west of Western Australia.

Aeration produced by turning the compost was supplemented by side mounted fans which forced air through ventilation ducts set lengthways in the base of the composting tunnel. The initial substrate for composting consisted of separated pig solids, treated sewage waste and wheat straw. These wastes were mixed in a ratio of 3:2:10 by volume and added to the front of the composting tunnel. Approximately 50 m³ of material was added at the front of the tunnel whenever the compost was turned and moved along the tunnel.

Monitoring the composting process

Three replicate samples of composting material (4kg, wet weight), were taken at 10m increments along the 70 m of tunnel, corresponding with stages in composting and waste stabilisation. Samples were taken weekly for 6 weeks. Temperature was recorded at each sampling site and time using a 1.5 m temperature probe inserted to 50 % of the depth of compost at a given sampling point. All samples were dried at 105 °C and moisture content was recorded as weight loss after drying samples for 24 hours.
Electrical conductivity and pH were measured in 1:10, compost to deionised water, extracts. Extracts of 1:5 compost to deionised water did not provide sufficient solution for consistent use of pH and EC probes. Dried subsamples of 1g were also taken and ground to <0.5mm for carbon and nitrogen analysis using a LECO, CHN gas analyser (Sweeney and Rexroad 1987). Ammonium-N was determined in 2M KCl extracts using the method described by Reardon et al. (1966). Remaining ground material was bulked for commercial general nutrient analysis (K, Ca, Mg, Na, Cl, S, Cu, Zn, Mn, Fe and NO₃⁻).

Microbial ninhydrin positive nitrogen was determined on 2g subsamples using the fumigation-extraction method of Joergensen and Brookes (1990) which was adapted for compost by Mondini et al. (1997). Dried compost samples (20g) from weeks 1, 4 and 9 were re-moistened to 50% water content and incubated for 5 days at 20 °C (samples were not ground, unlike the procedure of Mondini et al. (1997)). Seed germination tests to assess compost maturity were conducted by determining the percentage of lettuce, Latuca sativa Oxley, seeds which germinated on a filter paper, soaked in a compost to deionised water (1:20) extract over 2 days at 20°C in the dark. Statistical analysis was conducted on data using ANOVA General Linear Model on Genstat™ (Payne and Arnold 2000).

3.3 Results

Temperature measurements along the composting tunnel fluctuated weekly (Figure 3.1). Initial temperature, 0 m, ranged from 30-55°C, while finishing temperature at 70m was between 40-55°C (Figure 3.1). Temperature along the tunnel in weeks 4 and 5 peaked at 70 °C at 20 m followed by a marked drop to 30°C at 30 m. During the rest of the weeks changes in temperature were less erratic with temperature increasing slightly or remaining relatively constant between 40 and 60 °C along the composting tunnel (Figure 3.1).
The percentage moisture of composting material decreased 62% at 0m to 35% at 70 m along the composting tunnel (Figure 3.2). Variation in moisture between weekly sampling was low over the first 10m of the composting tunnel, but from 20m to 70m weekly moisture content varied considerably (Figure 3.2). There was no correlation between compost moisture content and temperature (data not shown).
Carbon to nitrogen ratio of the composting material decreased from between 30-40:1 to 11.7-17:1, with a similar trend of reduction in C:N being observed for all 6 weeks (Figure 3.3).

![Figure 3.3](image)

**Figure 3.3** Variation in carbon to nitrogen ratio of composting material from mean values, along the composting tunnel (70m) over 6 consecutive weeks. (Line ‘av’ represents the 6 week mean.)

The mean total carbon concentration of the compost decreased over the course of composting, from 42% C to 37% C. There was little variation between sampling times at any given point along the composting tunnel (Figure 3.4).

![Figure 3.4](image)

**Figure 3.4** Variation in total oxidisable carbon concentration of composting material along the composting tunnel (70m), over 6 consecutive weeks. (Line ‘av’ represents the 6 week mean.)

The mean total nitrogen concentration of the compost increased over the course of composting, from 1.1% N to 2.5% N. There was little variation between sampling times at any point along the composting tunnel (Figure 3.5).
Figure 3.5 Variation in total nitrogen concentration of composting material along the composting tunnel (70m), over 6 consecutive weeks. (Line ‘av’ represents the 6 week mean.)

Electrical conductivity of compost, on average, decreased from 2500 µS/cm to 1800 µS/cm over the first 30m of the composting tunnel. EC then increased to 2500 µS/cm by 50m and declined to 1500 µS/cm by 70m. Over the five weeks, the pattern of change in EC during composting was consistent. At any given point along the composting tunnel, there was considerable variability in EC between weeks (Figure 3.6).

Figure 3.6 Variation in electrical conductivity of composting material along the composting tunnel (70m), over 5 consecutive weeks. (Line ‘av’ represents the 5 week mean.)
Compost pH changed little with position in tunnel increasing slightly over the first 20 m from pH 6.3 to pH 6.6, which was followed by a decline to pH 6.2 at 30m. Subsequently there was a gradual increase up to pH 6.4 at 70m (Figure 3.7). In comparison to the EC profiles during composting there was less of a repeatable pattern observed between the weekly measurements.

Figure 3.7 Variation in pH of composting material along the composting tunnel (70m), over 5 consecutive weeks. (Line 'av' represents the 5 week mean.)

The ammonium concentration in compost was highly variable at each sampling point. It also varied substantially along the composting tunnel, ranging from 25 μgNH₄⁺-N/g compost to 350 μgNH₄⁺-N/g compost. No trend was apparent with peak NH₄⁺-N levels occurring at different points for each weekly profile (Figure 3.8).
Figure 3.8 Variation in ammonium concentration of composting material, measured along the composting tunnel (70m), over 4 consecutive weeks. (Line ‘av’ represents the 4 week mean.)

Characterisation of compost maturity

Microbial NPC-N in the compost, decreased along the composting tunnel from 1114 μgNPC-N/g at 0m to 53 μgNPC-N/g by the end of the composting process (Table 3.1). There was no difference in microbial respiration of samples taken at 0, 40 and 70m along the composting tunnel (Table 3.1).

The seed germination test showed an increase in germination percentage with increasing time of composting. For the beginning of the composting process 4% of seeds germinated, increasing up to 87% for the end of composting at 70 m (Table 3.1).

Table 3.1 Maturity tests on compost taken from along the composting tunnel.

<table>
<thead>
<tr>
<th>Sampling distance along tunnel (m)</th>
<th>Microbial biomass (μgNPC-N/g)</th>
<th>Respiration rate (μgCO₂/g compost/h)</th>
<th>Germination (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1114 (89)</td>
<td>56 (8)</td>
<td>4 (1)</td>
</tr>
<tr>
<td>40</td>
<td>nm</td>
<td>47 (6)</td>
<td>78 (4)</td>
</tr>
<tr>
<td>70</td>
<td>53 (7)</td>
<td>54 (5)</td>
<td>87 (12)</td>
</tr>
</tbody>
</table>

(standard error of the mean in parentheses, nm = not measured)

There was no systematic difference in chemical composition, except previously discussed C and N, between uncomposted and composted pig waste although large standard errors of the mean were observed (Table 3.2).
Table 3.2 Chemical composition of composted pig waste before and after composting.

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Chemical composition of compost</th>
<th>Nutrient/pH/EC</th>
<th>Chemical composition of compost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>before</td>
<td>after</td>
<td>before</td>
</tr>
<tr>
<td>N%</td>
<td>1.14 (0.36)</td>
<td>2.53 (0.35)</td>
<td>S%</td>
</tr>
<tr>
<td>C%</td>
<td>41.6 (2.2)</td>
<td>37.1 (1.2)</td>
<td>Cu μg/g</td>
</tr>
<tr>
<td>P%</td>
<td>0.72 (0.03)</td>
<td>1.2 (0.25)</td>
<td>Zn μg/g</td>
</tr>
<tr>
<td>K%</td>
<td>0.23 (0.05)</td>
<td>0.26 (0.08)</td>
<td>Mn μg/g</td>
</tr>
<tr>
<td>Ca%</td>
<td>4.70 (0.43)</td>
<td>4.82 (0.56)</td>
<td>Fe μg/g</td>
</tr>
<tr>
<td>Mg%</td>
<td>0.42 (0.03)</td>
<td>0.33 (0.03)</td>
<td>NO₃ μg/g</td>
</tr>
<tr>
<td>Na%</td>
<td>0.25 (0.05)</td>
<td>0.18 (0.02)</td>
<td>pH (1:10 DI)</td>
</tr>
<tr>
<td>Cl%</td>
<td>0.19 (0.05)</td>
<td>0.22 (0.08)</td>
<td>EC μS/cm</td>
</tr>
</tbody>
</table>

Before = sample taken before composting. After = sample taken after composting, (standard error of the mean in parentheses)

3.4 Discussion

The relative ease with which the pig waste composted during this study indicates that composting systems could be readily set up at any piggery, as long as the process is monitored and appropriate adjustments to aeration, temperature, moisture and C:N ratio are made according to a set of guidelines such as those evaluated in this experiment (Table 3.3).
Table 3.3 Summary table of measurements taken during composting and their suitability as predictors of composting progress.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Usefulness</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature</td>
<td>basic predictor but highly variable between weeks at the same point of composting</td>
</tr>
<tr>
<td>moisture</td>
<td>basic predictor but highly variable between weeks at the same point of composting</td>
</tr>
<tr>
<td>C:N</td>
<td>useful predictor with low variability between weeks at the same point of composting</td>
</tr>
<tr>
<td>C concentration</td>
<td>basic predictor indicating a reduction in C through microbial breakdown.</td>
</tr>
<tr>
<td>N concentration</td>
<td>useful predictor increasing as C is lost through microbial respiration during OM degradation. Less variable than change in C%, although hard to define a N% when composting has finished.</td>
</tr>
<tr>
<td>electrical conductivity</td>
<td>not useful as a predictor</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>not useful as a predictor</td>
</tr>
<tr>
<td>pH</td>
<td>not useful as a predictor</td>
</tr>
</tbody>
</table>

The considerable variation and lack of a discernible pattern of temperature profiles during 6 weeks of composting suggests that temperature alone could not be used as an indicator of progress towards maturity. Thus, if temperature was measured at any given point along the composting tunnel it would not provide a clear indication of the state of waste degradation. This is in contrast to findings of other research where temperature has been found be a useful indicator of composting progress, with temperature generally increasing rapidly followed by a gradual decline towards ambient temperature as the waste becomes stabilised (Inbar et al. 1993).

The variability in temperature profiles during composting can be explained by a sub-optimum level of process control due to manual determination of aeration and turning frequency. It is useful to monitor temperature during composting to indicate whether microbes are operating efficiently and hence producing high temperatures. Continuous monitoring of temperature is useful to indicate when adjustments to the composting pile, such as turning, need to be made to maximise the efficiency of the composting process (Van Oostrom et al. 1988, Finstein et al. 1986, McPhail and Van Oostrom 1993 and Lau et al. 1993).
Despite the high variability, the temperatures achieved during composting appeared to be sufficient to destroy pathogens and weed seeds. Further tests may be required as the temperatures are only just within the range for pathogen destruction (50-60°C) (Gotaas 1956). The temperatures reached are also those that are optimal for maximal rates of other types of waste decomposition (MacGregor et al. 1981 and Finstein et al. 1993). Thus, this pig waste is highly suitable for composting.

The lack of a substantial decline in composting temperature from the initial 50-60°C by the end of composting suggests that despite the system being successful in achieving optimal composting conditions the process is not carried out for long enough for all of the readily available microbial substrates to be utilised. Further composting may be required to produce a highly stable product for use in sensitive applications, such as a potting mix (Sikora and Sowers 1985, Lau et al. 1993 and Harper et al. 1992). For this pig waste composting plant, a continuous flow design was used so it was difficult to extend the time that compost spent in the composting tunnel. If further composting was required it could be carried out in a pile outside the tunnel.

The general decline in moisture content along the composting tunnel is similar to that found by other researchers (Finstein et al. 1986, MacGregor et al. 1981, Lau et al. 1993). There was a high level of variability between weekly profiles which can be attributed to different rates of moisture loss from various positions along the compost tunnel, depending on its proximity to the aeration fans. Subsequent turning and mixing of low and high moisture containing materials would result in fluctuations in weekly moisture values.

Despite the fact that moisture content has been used as a general indicator of composting progress (Finstein et al. 1986), at this composting plant monitoring of moisture content along the tunnel did not provide a clear indication of the level of waste stabilisation. However monitoring of moisture content, as for temperature, is recommended to enable sufficient levels (>40% water) to be maintained to sustain a high rate of microbial activity (Gotaas 1956).

In contrast to temperature and moisture, the measurement of compost carbon to nitrogen ratio was a robust indicator of stages in the composting progress. The C:N ratio of the
composting substrate narrowed towards the end of the composting tunnel. Similar trends were observed for all weekly measurements. Fluctuations observed in temperature and moisture were less apparent for C:N. The consistency of C:N measurements between weeks indicates that C:N measurements could be used to assess progress towards a stabilised product as was also found by other researchers (Gotaas 1956, Finstein et al. 1986).

A narrowing of the C:N ratio indicates that C is being lost from the waste material, through microbial metabolism and consequent respiration, while little or no N is being lost (Finstein et al. 1986). In association with C loss, N is converted to stable inorganic forms incorporating some C. The waste thereby progresses toward stabilisation. Thus, C:N measurements are predictive of stages in the composting process and, in this case, indicated that the tunnel composting process was creating a product with consistent carbon and nitrogen contents, in spite of fluctuations in temperature and moisture. In comparison, total carbon content of the compost varied little and would not be a useful indicator of composting performance.

The measurements of EC and pH during composting are not normally used to monitor composting progress as they do not directly indicate the decomposition of the waste. However, similarities between weekly profiles of EC and pH demonstrates that consistent composting conditions are achieved as each batch moves along the composting tunnel. The similarity between weekly profiles for EC, and to some extent pH, indicated that the composting system at Wandalup is consistent although the level of process control was limited. A consistent product is continuously produced. Ammonium content of the compost was the least useful indicator of composting progress.

The attempt to estimate compost maturity by comparing the microbial biomass of compost before and after composting (Mondini et al. 1997) was partially successful. There was a considerable decrease in NPC-N, an indicator of microbial population, between un-composted and composted samples, suggesting that the compost is becoming microbiually stable by the end of the process. Unusually low respiration rates were measured in samples taken from the beginning of the composting process, suggesting low microbial activity when high microbial activity would be expected (Mondini et al. 1997).
The low respiration rates may be due to the samples being air dried after collection and then re-incubated before respiration analysis. This may not have allowed the microbes to recolonise the sample adequately. Measuring respiration rates and NPC-N on fresh samples is probably the preferable method, undried samples are also preferred for the determination of soil microbial-NPC in soil (Sparling et al. 1993). Thus it is important to carry out NPC microbial analysis on compost samples as soon as possible after sample collection to get an accurate and meaningful result.

In general, the nutrient composition of the compost appeared suitable for use of this material as a fertiliser. Levels of potentially toxic metals, such as Cu and Zn were below the limits for application to cropland, according to USEPA guidelines for sewage sludge applications (Lue-Hing et al. 1994, Richard et al. 1993).

### 3.5 Conclusions

Composting of the pig waste from Wandalup Piggery was a relatively simple process. The determination of C:N ratio was the best indicator of composting progress. Temperature and moisture fluctuated considerably and did not provide an accurate indicator of the stage in the composting process. The determination of compost maturity using a method of measuring microbial NPC-N was successful, providing an indication of the size of the microbial population. Simpler methods of C:N determination and the seed germination test would be the most appropriate for infield testing due to the simplicity of the tests. Composted pig waste had a suitable chemical composition to be used as a soil conditioner or fertiliser.
Chapter 4. Application of composted pig waste increases phosphorus and nitrogen leaching in Bassendean sand.

4.1 Introduction

The loss of nutrients from horticulture on the Swan Coastal Plain of Western Australia is a major concern and contributes to the pollution of surface and groundwater (Weaver et al. 1988, and McPharlin et al. 1994(a)). To alleviate this problem attention has been focused on better management of inorganic fertiliser inputs, especially phosphorus and nitrogen (McPharlin and Luke 1989 and McPharlin et al. 1994(a)). Recent attention has been paid to changing the practice of applying organic amendments such as poultry litter which is now regarded as a major source of flies.

Horticulturists on the Swan Coastal Plain apply poultry litter (up to 40 t/ha/crop) to improve the fertility of sandy soil types. At these rates of application, more N (up to 600 kgN/ha/crop) is applied than is required by the crop. High amounts of P are also applied (up to 200 kg/ha/crop). Since N and P in poultry litter are contained in highly soluble forms, their application to sandy soil types has the potential to further exacerbate N and P pollution of surrounding water bodies (McPharlin and Luke 1989).

To minimise pollution while maintaining the fertility of sandy soils it is advantageous to use organic soil amendments that have low water soluble N and P contents. Composted wastes are ideal for use as soil conditioners, as composting results in a large proportion of soluble nutrients being microbially immobilised into organic, insoluble forms rendering them less susceptible to leaching (Sims 1990, Paul and Beauchamp 1994).

It was predicted that the amount of N and P lost from compost applications by leaching would be minimal when compared to the N and P lost from readily soluble, inorganic fertilisers. This was expected to highlight the potential of compost to be used as a soil conditioner without contributing to nutrient leaching problems. This hypothesis was tested in a column leaching experiment comparing the amounts of $\text{PO}_4^{2-}$, $\text{NH}_4^+$ and $\text{NO}_3^-$ leached from Bassendean sand (SCP 11) (McArthur 1991) collected from Lancelin, Western Australia. The sand was amended with compost and inorganic nitrogen and phosphorus fertilisers.
4.2 Materials and methods

The experiment was conducted over 12 days, using 1.5 L leaching columns set up in a constant temperature room set at 22°C. Bassendean sand (SCP11) (McArthur 1991) from Lancelin Western Australia was packed into columns 10cm in diameter with 1kg sand/column. Four levels of composted pig waste from Wandalup farms equivalent to 0, 10, 20, 80 t/ha (0, 116, 232 and 930 kgP/ha and 0, 190, 380, 1520 kgN/ha respectively) were added. Each treatment was replicated 6 times. Nitrogen and phosphorus fertilisers were applied to half of the replicates for each treatment as superphosphate (320 kg P/ha) and ammonium nitrate (680 kg N/ha (340 kg as NH₄⁺-N and 340 kg as NO₃⁻-N). Soil and amendments were thoroughly mixed with the sand and packed back into the leaching columns. Columns were leached at a rate of 28mm H₂O/day (14mm in the morning and 14 mm in the afternoon) to a total of 336 mm. Leachates were collected daily and combined every two days. Samples were frozen until analysed.

Leachates were analysed for P by a manual colorimetric method (Murphy and Riley 1962). Ammonium-N and Nitrate-N were measured by automated colorimetry; ammonium-N by the salicylate chlorine method (Reardon et al., 1966) and nitrate-N by reduction, diazotization and coupling with N-1-naphthyl-ethylene diamine dehydrochloride (Best, 1977). Electrical conductivity and pH of the leachate were also measured using appropriate meters.

Analysis of data was conducted using analysis of variance from which least significant differences and standard errors of the mean were determined. Statistical analysis was conducted on data using ANOVA General Linear Model on Genstat™ (Payne and Arnold 2000).
4.3 Results

The amount of P leached increased with increasing rates of compost addition. Up to 10 kgP/ha, 80 t/ha compost, was leached over 12 days (Figure 4.1). The rate at which P leached from compost was relatively constant for each compost level for the duration of the experiment (Table 4.1).

Figure 4.1 Cumulative phosphorus leached from Bassendean sand amended with composted pig waste, 0, 10, 20, 80 t/ha (0, 116, 232, 930 kgP /ha), in the absence of N and P fertiliser. (Vertical bars show LSD (0.05) for differences between rates, individual error bars are standard errors of each mean.)

Table 4.1 Regression equations between P leached versus time for the amount of phosphorus leached from Bassendean sand amended with composted pig waste.

<table>
<thead>
<tr>
<th>Compost rate (t/ha)</th>
<th>Regression equation</th>
<th>$r^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 t/ha</td>
<td>$y = 0.041x - 0.111$</td>
<td>95.6</td>
</tr>
<tr>
<td>10 t/ha</td>
<td>$y = 0.41x - 1.11$</td>
<td>98.4</td>
</tr>
<tr>
<td>20 t/ha</td>
<td>$y = 0.58x - 1.35$</td>
<td>98.4</td>
</tr>
<tr>
<td>80 t/ha</td>
<td>$y = 1.01x - 2.46$</td>
<td>99.1</td>
</tr>
</tbody>
</table>
Leaching soil fertilised with superphosphate, (320 kgP/ha), over 12 days resulted in 62 kgP/ha being leached (Figure 4.2). Compost application to this soil resulted in increased amounts of P being leached with up to 13% more P being leached when compost was applied at 80 t/ha (Figure 4.2).

![Cumulative phosphorus leached from Bassendean sand amended with composted pig waste in conjunction with superphosphate (320 kgP/ha). (Individual error bars are standard errors of each mean)](image)

**Figure 4.2** Cumulative phosphorus leached from Bassendean sand amended with composted pig waste in conjunction with superphosphate (320 kgP/ha). (Individual error bars are standard errors of each mean)

The application of compost doubled the amount of NH$_4^+$-N leached from Bassendean sand. In the absence of compost, 3.5 kg NH$_4^+$-N/ha was leached while 7.7-9 kg NH$_4^+$-N/ha was leached in the presence of compost (Figure 4.3). There was no systematic difference in the amount of NH$_4^+$-N leached for different compost application rates (Figure 4.3). N loss was highest between days 2 and 4 after which the rate of loss declined.
Figure 4.3 Cumulative ammonium-N leached from unfertilised Bassendean sand amended with 4 rates of composted pig waste. 0, 10, 20, 80 t/ha (0, 190, 380, 1520 kgN/ha). (Vertical bars show LSD (0.05) for differences between rates, individual error bars are standard errors of each mean).

The greatest amount of nitrate leached from unfertilised Bassendean sand occurred when no compost was applied (10 kgN/ha) (Figure 4.4) and most was leached in the first 4 days (Figure 4.4). Nitrate losses after compost was applied were 41 to 54 % less than when no compost was applied (Figure 4.4).

Figure 4.4 Cumulative nitrate-N leached from unfertilised Bassendean sand amended with 4 rates of composted pig waste. (Vertical bars show LSD (0.05) for differences between rates, individual error bars are standard errors of each mean)

The application of compost increased the amount of NH$_4^+$-N leached by up to 20% when 80 t/ha compost was applied in conjunction with 680 kgN/ha of ammonium nitrate. The most rapid loss of ammonium-N occurred during the first 4 days after which the rate of loss decreased significantly (Figure 4.5).
Figure 4.5 The effect of compost application on Ammonium-N leached from a Bassendean sand to which 680 kgN/ha (340 kg NH₄⁺-N) had been applied. (Individual error bars are standard errors of each mean).

Application of compost in conjunction with ammonium nitrate (680 kgN/ha) resulted in increased NO₃-N being leached. Up to 19% more NO₃-N was leached when 80 t/ha compost was applied than when no compost was applied. Most of the N loss occurred in the first 4 days (Figure 4.6).

Figure 4.6 Cumulative nitrate-N leached from N and P fertilised Bassendean sand amended with composted pig waste. (Error bars are standard errors of the mean).

The application of compost to fertilised Bassendean sand reduced the amount of ammonium-N retained after 12 days of leaching. In contrast, the application of compost in the absence of N-fertiliser had no effect on soil ammonium concentration (Figure 4.7). Increasing the rate of compost had no effect on the amount of nitrate in the soil.
after leaching in the absence of N fertiliser. When fertiliser was applied, compost application decreased nitrate content of the Bassendean sand (Figure 4.7).

**Figure 4.7** Total ammonium-N and nitrate-N remaining in fertilised, compost amended sand (680 kg N/ha NH₄NO₃) and unfertilised compost amended Bassendean sand, after 12 days of leaching. (Individual error bars are standard errors of each mean).

### 4.4 Discussion

It was predicted that the amount of N and P lost from compost applications by leaching would be minimal when compared to the N and P lost from readily soluble, inorganic fertilisers. This was expected to highlight the potential of compost to be used as a soil conditioner without contributing to nutrient leaching problems. This hypothesis was tested in a column leaching experiment comparing the amounts of PO₄²⁻, NH₄⁺ and NO₃⁻ that were leached from Bassendean sand (SCP 11) (McArthur 1991) from Lancelin, Western Australia, amended with compost and inorganic nitrogen and phosphorus fertilisers.

Despite large amounts of P being applied in the compost, most of this P was sparingly soluble. Only 1% of P applied as compost at 80 t/ha was leached which is in marked contrast to the 20% P leached from superphosphate. Despite the low percentage of P leached from compost, the actual amount leached needs to be taken into consideration. Up to 13% more P was leached when compost was applied in conjunction with superphosphate. This highlights the importance of considering the amount of P added in soil conditioners in horticulture as they still have a potential result in increased P leaching. However the amount of P leached in this study occurred in the absence of
plants. For extrapolation to horticultural conditions, P leaching in the presence of plants needs to be measured. Plants have the potential to take up a significant proportion of P that would otherwise be leached depending on its availability and the amount in excess of plant requirement.

The increase in P leached in the presence of compost and superphosphate was the same as the amount leached when only compost was applied. This indicates that there was no interactive effect of the compost and superphosphate resulting in more P being mobilised from the compost then leached. Conversely this also indicates that compost application did not increase the P buffering capacity of this soil reducing the availability of P for leaching.

The constant rate of P loss from compost amended soil demonstrates that this compost could act as a slow release fertiliser, with some leachable P becoming available for plant uptake. However, to further assess the potential of compost as a slow release P fertiliser a longer leaching period would be required to determine whether P becomes soluble at the same rate for a longer period of time or whether the rate declines. A constant P loss rate for 2-3 months would show that the compost could be used to supplement or replace crop P requirements. A rapid decline in rate of P loss might mean that the compost would not be suitable as a P source for horticultural crops.

The amount of N lost from compost through leaching only represented a small percentage of total N applied as compost (0.5% as NH₄-N and 0.25% as NO₃-N) when compost was applied at 80 t/ha. However, application of compost resulted in up to 19-20% (when applied at 80 t/ha compost) more ammonium (35 kgN/ha) and nitrate (39kgN/ha) leached when both compost and an ammonium-nitrate fertiliser were applied together. The amount of ammonium and nitrate leached when compost and the N fertiliser were applied together was more than the sum of the amount leached when either the compost or N fertiliser were applied separately, suggesting a positive interaction between the compost and the N fertiliser. This response shows that application of the N fertiliser stimulated the mobilisation of NH₄-N and NO₃-N from the compost. Compost application may increase N leaching losses when applied at high rates and this needs to be taken into account when considering the effects compost application may have on the environment. Similar responses have been observed for
composted municipal waste at rates above 50t/ha which cause NO₃-N contamination of
ground water (Iglesias-Jimenez and Alvarez 1993).

4.5 Conclusions

The amounts of P and N leached from a sandy soil increased with increasing rates of
compost application. When compost was applied in conjunction with conventional rates
of N application there was an interactive effect resulting in more N to be leached than
the sum of N leached when each was applied separately. No interaction effect was
observed between compost and P fertiliser on P leaching. Overall, this experiment
illustrated the importance of taking into account the potential for N and P to be leached
when compost is applied to horticultural crops that are already heavily fertilised.
Chapter 5. Composted pig waste applied to sandy soils increased phosphorus, microbial biomass, soil carbon and reduced bulk density.

5.1 Introduction

The application of organic amendments to soil as soil conditioners is a common practice worldwide. Many different types of organic amendments can be used, although manure and compost are the two most commonly applied forms of organic matter. These materials are generally applied to supply some plant nutrients and to improve soil structure and other physical properties. Due to the wide range of types and compositions of compost and manure, generalised conclusions as to their effect on soil fertility may be misleading.

The amount of nutrients that an application of compost will supply is difficult to predict and depends on the forms of nutrients, the rate at which nutrients become available for plant uptake, and the rate within the composted material at which the nutrients are immobilised. These characteristics vary widely between waste types and depend also on how the waste has been treated. Despite these difficulties, compost can be a valuable source of nutrients, especially N and P. The plant availability of N from sewage sludge may be up to 55% of total N per year while it is suggested that 40% of total N in farm yard manure is available annually for plant uptake (Clapp et al. 1986, Hue 1995, Eck and Stewart 1995). P from organic amendments, such as composts and sewage sludge may have a similar availability to N of approximately 40-50% of P applied per year (Withers and Sharpley 1995, Chen et al. 1996).

Soil bulk density can be improved by organic matter application (Hill and James 1995). The application of 240 t/ha sewage compost reduced bulk density by 50 % (Tester 1990). Organic matter is also important for maintaining biological fertility of soils. A microbial community in soil is essential for degrading organic matter and mineralisation of organic nutrients. For heterotrophic microbes to survive they require a carbon source, therefore, addition of organic matter will increase soil microbial biomass. The application of municipal compost at 40 t/ha to a sandy loam increased soil biomass C over 100% (Perucci 1990). Similarly an application of 300 t/ha municipal compost to an arable soil increased biomass C by 100 % (Joergensen et al. 1996).
The sandy soils of the Swan Coastal Plain (SCP) of Western Australia represent a situation where organic matter application is likely to improve horticultural productivity due to the inherently very low organic matter contents of these soils. The aim of this experiment was to compare the effects of applying a variety of organic amendments, composted pig waste, poultry litter and peat, on the fertility of a Karrakatta sand, on which horticulture is commonly practiced in Western Australia. This experiment specifically aimed to determine how a newly produced pig compost compared with other more traditional organic soil conditioners in relation to its ability to improve total soil P, bicarbonate extractable P status, bulk density and microbial biomass.

5.2 Materials and methods

A field experiment was set up on Karrakatta sand at University of Western Australia’s research station, Shenton Park, Western Australia. The experiment was established in a completely randomised design, with three organic amendments (pig compost, poultry litter and peat). These materials were applied at 3 application rates (0, 20 and 80 t/ha on a dry weight basis). Each treatment was replicated 3 times.

Composted pig waste was obtained from the Wandalup composting plant (Chapter 3) Poultry litter and peat were purchased from a commercial supplier of soil conditioners. Organic amendments were applied to plots 2m x 2m, which were arranged with a 1m buffer between each plot. No organic matter was applied to the buffer. Organic amendments were incorporated to a depth of 30 cm by rotary cultivation in each plot.

The experiment was conducted over 300 days, starting in January. Weeds were removed by hand as they germinated. Five soil cores were randomly taken from the top 10 cm of each plot and bulked at each sampling time (0, 30 (for microbial biomass measurements only), 60 and 300 days). Samples were then air dried and a 50 g sub-sample of soil was ground for total C, N and P analysis.

Ground soil samples were analysed for total C and total N using a LECO CHN analyser (Sweeney and Rexroad 1987). Total P was determined in nitric perchloric acid digests of ground soil samples. Bicarbonate extraction of P was used to determine available P in soil samples (Colwell 1963). Phosphorus concentration in the acid digests and
bicarbonate extracts was determined using colorimetry (Murphy and Riley 1962). Microbial biomass-N measurements were made on fresh soil samples using a fumigation extraction method (Joergensen and Brookes 1990). Chemical properties of composted pig waste, poultry litter and peat was determined by a commercial soil and plant analysis laboratory (CSBP Wesfarmers). Statistical analysis was conducted on data using ANOVA General Linear Model on Genstat™ (Payne and Arnold 2000).

Table 5.1 Chemical properties of composted pig waste, poultry litter and peat.

<table>
<thead>
<tr>
<th>Nutrient/pH/EC</th>
<th>compost</th>
<th>poultry litter</th>
<th>peat</th>
</tr>
</thead>
<tbody>
<tr>
<td>total N %</td>
<td>2.53</td>
<td>3</td>
<td>1.1</td>
</tr>
<tr>
<td>total P %</td>
<td>1.2</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>total K %</td>
<td>0.26</td>
<td>1.3</td>
<td>0</td>
</tr>
<tr>
<td>pH (H₂O)</td>
<td>6.4</td>
<td>6.4</td>
<td>4.11</td>
</tr>
<tr>
<td>EC uS/cm</td>
<td>1500</td>
<td>nd</td>
<td>nd</td>
</tr>
</tbody>
</table>

5.3 Results

Compost increased total soil P to a greater extent than did the other two organic amendments. The rate of 80 t/ha compost increased soil P from 130 kgP/ha to 860 kgP/ha while 20 t/ha increased it to 335 kgP/ha (Figure 5.1). Poultry litter increased total soil P but to a lesser extent than compost (Figure 5.1). Over 10 months, total soil P decreased most under the poultry litter treatments (20 % and 56% respectively) when applied at 20 and 80 t/ha. In contrast, there was only a 14 % decrease in total P for 20 t/ha compost and only 30% at 80 t/ha compost (Figure 5.1). The application of peat had a negligible effect on total soil P (Figure 5.1).
Figure 5.1 The effect of organic amendment addition at 20 (A) and 80 (B) t/ha on total soil P, measured over 10 months. (Error bars indicate least significant difference (LSD) between treatments (p<0.05), no error bar indicates no significant difference between treatments.)

The application of all organic amendments at 20 t/ha appeared to increase bicarbonate extractable soil P (80% increase for compost, 50% for poultry litter and, 20% for peat) but this was not significant (Figure 5.2). Application of compost and poultry litter at 80 t/ha further increased bicarbonate extractable P with increases of 150% for compost and 350% for poultry litter (Figure 5.2). The concentration of bicarbonate extractable P for all amendments and rates of application declined over the first 2 months. The greatest decline was observed for poultry litter at 80 t/ha. Other treatments showed a more gradual decline (Figure 5.2).
Figure 5.2 The effect of organic amendment addition at 20 (A) and 80 (B) t/ha on bicarbonate extractable P, measured over 10 months. (Error bars indicate least significant difference (LSD) between treatments (p<0.05), no error bar indicates no significant difference between treatments.)

Applications of organic amendments at 20 t/ha had no effect on total soil C (Figure 5.3). Applications of 80 t/ha of organic amendments increased soil C by up 4 times (Figure 5.3). Soil C levels declined rapidly over the first two months for compost and poultry litter treatments but soil C for peat treatments remained constant over the 10 months of the experiment (Figure 5.3).
Figure 5.3 The effect of organic amendment additions at 20 (A) and 80 (B) t/ha on total soil carbon, measured over 12 months. (Error bars indicate least significant difference (LSD) between treatments (p<0.05), no error bar indicates no significant difference between treatments.)

Compost application at 80 t/ha was the only, of the two tested, treatment that increased soil microbial biomass-N (Figure 5.4). After 10 months, microbial biomass-N had declined to 2 ugN/ g soil for the compost treatment. The application of organic soil conditioners at 20 t/ha had no effect on microbial biomass-N (Figure 5.4). A comparison with poultry litter is not shown as the high level of N compounds contained in the litter interfered with the highly sensitive technique used to determine microbial biomass, even when the samples were highly diluted (100 000 times).
5.4 Discussion

The composted pig waste used in this study has the potential to be used as a soil conditioner on sandy soils to increase soil P, N, other nutrients, soil water holding capacity, and microbial biomass and to reduce soil bulk density. For the soil properties measured, comparisons between compost and poultry litter showed that compost could be used as a substitute for poultry litter which is currently used as a soil conditioner in Western Australian horticulture on sandy soils on the Swan Coastal Plain.

The increased total soil P concentrations following the addition of compost and poultry litter indicated that both organic treatments can increase total soil P. However, their potential to supply P for plant utilisation depends on the form of P. Bicarbonate extractable soil P is the standard determinant for assessing plant response to soil P in Western Australian soils. Plant response to bicarbonate extractable P is calibrated for most horticultural crops and soil conditions on inorganic P sources (McPharlin et al. 1992). Carrots and lettuce require 100 kgP/ha and 177 kgP/ha bicarbonate extractable P when grown on a Karrakatta sand to achieve 95% of maximum yield (McPharlin et al. 1992, McPharlin et al. 1996). At an addition of 80 t/ha compost, there is potential to supply adequate P for a carrot crop in this soil. Before recommendations of the P fertiliser value of composted pig waste can be made, calibrations between bicarbonate...
extractable P from compost amended soils and plant response are needed. Organic amendments will contain P in different forms to that of an inorganic P fertilisers and the rate of P dissolution would also be different.

It is well known that the application of organic matter to soil can increase soil carbon concentrations. The amount of time that this increase lasts is important for improving soil fertility. For compost and poultry litter 60% of the initial increase in total soil C is expected to be maintained for a least a year. The initial rapid decline in organic C reflects the breakdown, by microbes, of readily available organic matter fraction in the compost and poultry litter (Jarvis et al. 1997). Horticulturalists can expect that annual applications of compost or poultry litter onto sandy soil types will contribute positively to soil carbon levels and will increase it with yearly applications. This compounding effect of continuously increasing soil total C will affect related soil properties such as bulk density, microbial biomass and water holding capacity.

Microbial biomass-N is a reflection of the size of the microbial population. The increase in microbial biomass-N due to compost application can be explained in two ways: 1) after composting a significant amount of readily available microbial substrates was still present in the compost, which microbes utilised resulting in population growth and 2) added organic matter would improve the environment for microbial survival. The application of peat, known as a highly microbi ally stable form of organic matter, even resulted in an increase in soil microbial biomass-N. This may be a result that supports explanation 2) in which the peat has provided an improved environment for microbial survival in the sandy conditions which have very few suitable sites for microbes to reside due to their coarse non-porous nature.

The high microbial biomass-N increase due to compost application could potentially be deleterious as it would be correlated with increased microbial community. This community may in turn compete for nutrients with roots, potentially reducing plant yield. The rapid decrease in microbial biomass-N 30 days after 80t/ha compost application demonstrates that the high initial level of microbial-N temporarily reflects a change in relative abundance of members of the microbial community, creating a new equilibrium suited to the increased organic matter in the soil (Ritz et al. 1997). Few studies have examined the effect of organic matter application on microbial biomass-N although cattle manure application to organic production systems in Scotland has also
been observed to have a similar effect as compost on increasing microbial biomass-N (Ritz et al. 1997).

5.5 Conclusions

Application of composted pig waste has the potential to supply P for plant growth as well as to increase total soil C, microbial biomass-N and reduce soil bulk density. These preliminary results indicate that composted pig waste has the potential to be used as a substitute for poultry litter, currently used as soil conditioner in Western Australia. Before composted pig waste can be used as a P source, the relationship between bicarbonate extractable P and crop response needs to be determined so its effectiveness can be predicted and compared to other P sources. Increases in total soil C and microbial biomass N and a reduction in soil bulk density suggest that general improvements to soil fertility can be made by applying composted pig waste. These assessments are qualitative and a direct correlation with increased crop production has not been determined. Further controlled experiments assessing the benefit of compost on crop production are required.
Chapter 6. Effects of the addition of composted pig waste and poultry litter on carrot yield, quality and soil properties.

6.1 Introduction

Carrot production is an important part of Western Australian horticulture, providing 90% of Australia’s export carrots (Galati & McKay 1996). To maintain this high level of productivity it is essential to maintain and improve soil fertility especially for the sandy soil types on which a large proportion of WA’s carrots are grown. These soils are characteristically low in organic matter (< 0.5 % organic carbon) and have low nutrient retention capacities and low water holding capacities (McArthur 1991). Additionally, high moisture loss during summer results in soil moisture deficits, which reduce yields (Plate 6.1) and increase the proportion of deformed roots (Orzoleck and Carroll 1978).

Plate 6.1 Severe plant loss on the perimeter of irrigated area of summer grown carrots due to moisture stress at Guilderton, north of Perth.
The application of organic soil conditioners is often carried out to improve the fertility and productivity of sandy soils (Sabrah et al. 1993). In Western Australia, poultry litter is the main soil conditioner used in horticulture; approximately 200 000 t is applied annually (Tingay and Associates 1997). Poultry litter is not normally used on carrot crops due to grower perceptions that it causes deformation and splitting (Galati & McKay 1996). Deformity and splitting are thought to be due to a variety of factors, including high inorganic nitrogen content in the soil, especially ammonium (Bienz 1964), although this has not been fully evaluated. In contrast, composted pig waste is low in inorganic N (Chapter 3) (approximately 100 mg/kg NH₃-N, 40 mg/kg NO₃-N, compared to 280 mg/kg NH₄⁺ and 880 mg/kg NO₃⁻ for composted broiler litter (Flynn et al. 1995)) and can have beneficial effects on soil fertility under laboratory and controlled field conditions (Chapters 4 and 5). As composted pig waste has the potential to be used as a substitute for poultry litter in horticulture, it is important to examine its effect on carrot production, one of Western Australia’s major horticultural crops (Galati & McKay 1996).

The aim of this experiment was to assess the effects of composted pig waste and poultry litter on carrot yield and quality. Carrot quantity and quality were measured as indicators of soil fertility as well as chemical and physical properties that may enhance plant growth. It was hypothesised that composted pig waste could be used as a soil conditioner to improve carrot production on a sandy soil.

6.2 Materials and methods

The experiment was conducted on a horticultural farm at Guilderton, north of Perth. A completely randomised design was used, with 4 application rates of compost: 0, 2.5, 5 and 10 t/ha (dry wt) and 2 application rates of poultry litter, 5 and 10t/ha (dry wt). Each treatment was replicated 3 times. Higher rates of compost were not used due to concern from the grower of long term effects on his carrot production.

Composted pig waste was obtained from the Wandalup composting plant and poultry litter was bought from a commercial supplier of soil conditioners. The rates of compost used are dry weight equivalents of what large scale producers would be willing to use under present economic conditions.
Table 6.1 Chemical composition of pig waste compost and poultry litter.

<table>
<thead>
<tr>
<th>nutrient (%)</th>
<th>Poultry Litter</th>
<th>nutrient (µg/g)</th>
<th>Poultry Litter</th>
<th>compost</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>3</td>
<td>2.53</td>
<td>NO₃⁻</td>
<td>Nd</td>
</tr>
<tr>
<td>P</td>
<td>1</td>
<td>1.2</td>
<td>NH₄⁺</td>
<td>6000</td>
</tr>
<tr>
<td>K</td>
<td>1.25</td>
<td>0.26</td>
<td>Fe</td>
<td>2000</td>
</tr>
<tr>
<td>Ca</td>
<td>5</td>
<td>4.82</td>
<td>Cu</td>
<td>20</td>
</tr>
<tr>
<td>Cl</td>
<td>1</td>
<td>0.22</td>
<td>Mn</td>
<td>300</td>
</tr>
<tr>
<td>Mg</td>
<td>0.75</td>
<td>0.33</td>
<td>Zn</td>
<td>300</td>
</tr>
<tr>
<td>Na</td>
<td>0.5</td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(data from; EPA (undated), Barker and Zublena (1995) and chapter 1, nd = not determined).

The experiment was conducted within a summer crop of Nantes (cfco8) carrots grown under standard horticultural cropping conditions on Karrakatta sand. Plots, 2m x 1m, were randomly distributed along two standard rows, 70m long and 1.5m wide beds. There were 1m buffer strips left between each treatment to which no organic matter was applied. Compost and poultry litter were applied after bed formation then incorporated to a depth of 30 cm by rotary cultivation. Seed beds were then reformed. Fertiliser was applied in late December at commercial rates of 250 kgP/ha, 230 kgN/ha, 400 kgK/ha. The beds were seeded a week after compost application at a density of 658 000 seeds/ha, with four twin rows, 6.3 cm apart, in each bed. The trial was irrigated fertilised and sprayed for weeds and insects according to practices for the surrounding commercial carrot crop.

The experiment was conducted over four months (27/12/95 - 22/4/96). Five soil cores were randomly taken from the top 10 cm of each plot and bulked at sowing and harvest. Samples were air-dried and a 50g sub-sample of soil was ground for C, N and P analysis.

Ground soil samples were analysed for total C and total N using a LECO CHN analyser (Sweeney and Rexroad 1987). Total P was determined in nitric perchloric acid digests of ground soil samples using manual colorimetry (Murphy and Riley 1962). Bicarbonate
extractable P was determined using the Colwell (1963) procedure on unground soil samples.

Carrots were harvested from randomly selected 1m² quadrats within each plot, one day before the commercial crop was due to be harvested (22/4/96). Carrots were washed and graded into 5 categories: i) export, ii) prepac, iii) smalls, iv) splits and v) forked. The export category was defined as those carrots suitable for export market, prepac were smaller than export quality but greater than 10 cm in length, smalls were <10cm in length, splits were those carrots which were split and the forked category took into account deformed carrots of which > 90% were forked (pers comm. A. Galati, 1997). The weight of each category was determined and the sum of export and prepac yields was used to determine total marketable yield. Statistical analysis was conducted on data using ANOVA General Linear Model on Genstat™ (Payne and Arnold 2000).

6.3 Results

Application of compost had no effect on carrot yield when applied at rates of 2.5 and 5 t/ha. At 10 t/ha, carrot yield was significantly reduced from 70.1 t/ha to 62.9 t/ha (Table 6.2). Similarly, the application of poultry litter at 5 t/ha had no effect on yield but at 10 t/ha, yield decreased to 65.7 t/ha. (Table 6.2). Marketable yield declined with applications of 10 t/ha of compost and poultry litter from 59.7 t/ha with no organic amendments to 43.8 t/ha compost and 50.9 t/ha poultry litter. Carrot density was not affected by the application of compost or poultry litter (Table 6.2). The average individual carrot weight was not affected by application of compost or poultry litter (Table 6.2).

The most pronounced detrimental effect of compost application was on export yield. Export yield declined from 46.6 t/ha to 32.2 t/ha carrots when 10 t/ha compost was applied (Table 6.3). In contrast, poultry litter had no effect on export yield (Table 6.3). A large variation in response to compost and poultry litter application was observed for prepac carrot yield (Table 6.3).
### Table 6.2 Yield and density of carrots grown in Karrakatta sand amended with compost or poultry litter.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Total yield (t/ha)</th>
<th>marketable yield (t/ha)</th>
<th>carrot density (carrots/m²)</th>
<th>average carrot wt (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>70.1 (0.58)</td>
<td>59.7 (1.28)</td>
<td>56 (1.2)</td>
<td>125 (2.7)</td>
</tr>
<tr>
<td>Compost 2.5t/ha</td>
<td>72.8 (2.27)</td>
<td>63.0 (2.70)</td>
<td>51 (2.2)</td>
<td>142 (7.9)</td>
</tr>
<tr>
<td>Compost 5 t/ha</td>
<td>72.0 (2.54)</td>
<td>58.0 (0.87)</td>
<td>52 (2.3)</td>
<td>139 (8.8)</td>
</tr>
<tr>
<td>Compost 10 t/ha</td>
<td>62.9 (3.45)</td>
<td>43.8 (5.29)</td>
<td>49 (3.8)</td>
<td>128 (2.7)</td>
</tr>
<tr>
<td>Poultry litter 5 t/ha</td>
<td>74.3 (0.48)</td>
<td>67.1 (0.45)</td>
<td>50 (1.7)</td>
<td>149 (5.6)</td>
</tr>
<tr>
<td>Poultry litter 10 t/ha</td>
<td>65.7 (1.80)</td>
<td>50.9 (3.05)</td>
<td>44 (4.1)</td>
<td>153 (15.4)</td>
</tr>
<tr>
<td>LSD</td>
<td>6.03</td>
<td>7.93</td>
<td>nsd</td>
<td>Nsd</td>
</tr>
</tbody>
</table>

(LSD = least significant difference at p < 0.05, nsd = no significant difference between treatments, standard error in parentheses).

### Table 6.3 Yields of export and prepac carrots grown in Karrakatta sand amended with compost or poultry litter.

<table>
<thead>
<tr>
<th>treatment</th>
<th>export yield (t/ha)</th>
<th>prepac yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>46.6 (0.94)</td>
<td>13.1 (1.89)</td>
</tr>
<tr>
<td>Compost 2.5t/ha</td>
<td>51.0 (4.18)</td>
<td>12.0 (1.95)</td>
</tr>
<tr>
<td>Compost 5 t/ha</td>
<td>48.4 (2.33)</td>
<td>9.6 (1.46)</td>
</tr>
<tr>
<td>Compost 10 t/ha</td>
<td>32.2 (4.47)</td>
<td>11.6 (0.81)</td>
</tr>
<tr>
<td>Poultry litter 5 t/ha</td>
<td>53.3 (2.08)</td>
<td>13.8 (1.64)</td>
</tr>
<tr>
<td>Poultry litter 10 t/ha</td>
<td>42.9 (4.73)</td>
<td>8.0 (2.44)</td>
</tr>
<tr>
<td>LSD</td>
<td>9.7</td>
<td>nsd</td>
</tr>
</tbody>
</table>

(LSD = least significant difference at p = 0.05, nsd = no significant difference between treatments, SE in parentheses).

In contrast to marketable fractions of carrot yield, non marketable fractions, split and forked carrots, generally increased for higher compost application rates. An increase in the yield of split carrots from 2 t/ha to 6 t/ha occurred at 10 t/ha compost (Table 6.4). Similarly, the yield of forked carrots increased when application of compost was increased from 2.7 t/ha to 8 t/ha (Table 6.4). The application of poultry litter had no effect on split carrot yield but had a similar effect to compost on the yield of forked carrots (Table 6.4). An opposite trend was observed for the small carrot category with an apparent decline in yield of small carrots with higher compost and poultry litter application rates (Table 6.4).
Table 6.4 Yield of split, deformed and small carrots grown in Karrakatta sand amended with compost or poultry litter.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>split carrot yield (t/ha)</th>
<th>deformed carrot yield (t/ha)</th>
<th>small carrot yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>1.6 (0.91)</td>
<td>2.7 (0.87)</td>
<td>6.1 (0.94)</td>
</tr>
<tr>
<td>Compost 2.5 t/ha</td>
<td>2.7 (0.12)</td>
<td>4.8 (1.06)</td>
<td>3.9 (1.19)</td>
</tr>
<tr>
<td>Compost 5 t/ha</td>
<td>1.3 (0.78)</td>
<td>8.0 (2.00)</td>
<td>4.5 (1.04)</td>
</tr>
<tr>
<td>Compost 10 t/ha</td>
<td>6.0 (0.61)</td>
<td>7.5 (0.43)</td>
<td>4.9 (0.43)</td>
</tr>
<tr>
<td>Poultry litter 5 t/ha</td>
<td>1.8 (0.43)</td>
<td>2.3 (0.20)</td>
<td>3.1 (0.15)</td>
</tr>
<tr>
<td>Poultry litter 10 t/ha</td>
<td>3.0 (0.51)</td>
<td>8.4 (2.66)</td>
<td>3.0 (0.60)</td>
</tr>
<tr>
<td>LSD</td>
<td>1.74</td>
<td>4.19</td>
<td>nsd</td>
</tr>
</tbody>
</table>

(LSD = least significant difference at p < 0.05, nsd = no significant difference between treatments, SE in parentheses).

There was no effect of compost or poultry litter applications on soil bulk density (Figure 6.1).

![Figure 6.1](image)

**Figure 6.1.** Soil bulk density of Karrakatta sand amended with compost or poultry litter. (Error bars represent standard errors of the mean)

For soil samples taken at the time of sowing total soil P was increased from 183 ugP/g soil, up to 281 and 289 ugP/g soil for 10 t/ha compost and poultry litter, respectively (Table 6.5). This trend was maintained to the end of the experiment. Total soil phosphorus content for each treatment declined over the duration of the experiment. In contrast, for soil samples taken at both sowing and harvest, there was no effect of application rate on bicarbonate extractable P (Table 6.5). Bicarbonate extractable P declined over the course of the experiment (Table 6.5).
Table 6.5 Changes in total soil phosphorus and soil bicarbonate extractable P due to the application of composted pig waste and poultry litter.

<table>
<thead>
<tr>
<th>treatment</th>
<th>total P (µg/g soil)</th>
<th>bicarbonate extractable P (µg/g soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>seeding</td>
<td>harvest</td>
</tr>
<tr>
<td>none</td>
<td>183</td>
<td>158</td>
</tr>
<tr>
<td>compost 2.5 t/ha</td>
<td>202</td>
<td>167</td>
</tr>
<tr>
<td>compost 5 t/ha</td>
<td>232</td>
<td>166</td>
</tr>
<tr>
<td>compost 10 t/ha</td>
<td>281</td>
<td>239</td>
</tr>
<tr>
<td>poultry litter 5 t/ha</td>
<td>202</td>
<td>191</td>
</tr>
<tr>
<td>poultry litter 10 t/ha</td>
<td>289</td>
<td>175</td>
</tr>
</tbody>
</table>

LSD nsd Nsd nsd nsd

(nsD = no significant difference between treatments, p<0.05, standard error of the mean in parentheses.)

For soil samples taken at the time of sowing, applications of 10 t/ha of compost and poultry litter increased soil carbon from 0.45% to 0.60% (Table 6.6). A similar pattern, for both amendments was observed for soil nitrogen, which increased from 0.03% N to 0.05% N (Table 6.6). Over the course of the experiment, there was a slight decline in percentage soil carbon for each organic matter application rate (Table 6.6). In contrast, the concentration of soil nitrogen generally increased over the course of the experiment for most treatments (Table 6.6). The C:N ratio was not affected by either organic matter source. By the end of the experiment, the C:N ratio for each treatment had declined from values of 12:1-21:1 to 11:1-12:1 (Table 6.6).

Table 6.6 Total carbon and nitrogen in Karrakatta sand amended with compost or poultry litter.

<table>
<thead>
<tr>
<th>treatment</th>
<th>total C (%)</th>
<th>total N (%)</th>
<th>C/N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>seeding</td>
<td>harvest</td>
<td>seeding</td>
</tr>
<tr>
<td>none</td>
<td>0.4 (0.04)</td>
<td>0.4 (0.03)</td>
<td>0.03 (0.004)</td>
</tr>
<tr>
<td>compost 2.5 t/ha</td>
<td>0.5 (0.01)</td>
<td>0.4 (0.03)</td>
<td>0.02 (0.002)</td>
</tr>
<tr>
<td>compost 5 t/ha</td>
<td>0.6 (0.07)</td>
<td>0.5 (0.09)</td>
<td>0.04 (0.006)</td>
</tr>
<tr>
<td>compost 10 t/ha</td>
<td>0.6 (0.10)</td>
<td>0.5 (0.07)</td>
<td>0.05 (0.008)</td>
</tr>
<tr>
<td>poultry litter 5 t/ha</td>
<td>0.5 (0.04)</td>
<td>0.5 (0.06)</td>
<td>0.02 (0.004)</td>
</tr>
<tr>
<td>poultry litter 10 t/ha</td>
<td>0.6 (0.10)</td>
<td>0.5 (0.07)</td>
<td>0.05 (0.014)</td>
</tr>
</tbody>
</table>

LSD nsd nsd 0.007 nsd

(LSD = least significant difference at p < 0.05, nsd = no significant difference between treatments, standard error of the mean in parentheses.)
6.4 Discussion

In contrast to expectations, the composted pig manure was not suitable for use as a soil conditioner for carrot production as it induced declines in carrot yield and quality similar to those caused by the application of poultry litter. An increase in total soil nitrogen was the only effect that application of compost or poultry litter had on soil fertility.

Both compost and poultry litter reduced total yield and marketable yield of carrots. Compost application increased carrot splitting and forking and poultry litter increased the number of forked carrots. Thus, both organic amendments can have detrimental effects on carrot root development, with greater amounts of compost and poultry litter having greater effects.

Forking of carrots can be caused by numerous abiotic and biotic factors which kill or damage the apical meristem of the carrot root (Galati and McKay 1996). Carrot forking has been associated with high levels of ammonium compounds in the soil, when N rates greater than 360 kgN/ha were applied (Bienz 1964), soil compaction (White 1978), fresh manure applications (Singh 1989, Peirce 1987, Ware and McCollum 1968), Pythium fungi, wind damage, waterlogging and nematodes (Galati and McKay 1996). Splitting of carrots has also been associated with high soil N levels, especially ammonium, as well as high levels of chloride (Bienz 1964).

The increased forking and splitting of carrots by the application of the compost suggests that a generalisation that composting can minimise the effect organic soil conditioners have on causing carrot forking and splitting is not correct in this case. Despite a reduction in ammonium concentration by composting it appears that other factors in the compost may cause forking and splitting. The compost may contain phytotoxic organic acid compounds which have been found to inhibit plant growth (Mathur et al. 1993, Stratton et al. 1995). If this compost is to be used as a soil conditioner for carrot production it may be necessary to incorporate it into the soil well before seeding. This is the general recommended practice for fresh manure applied to other horticultural crops, providing time for the compost to begin decomposing in the soil and a breakdown of any phytotoxic compounds (Singh 1989, Peirce 1987, Ware and McCollum 1968).
The application of compost and poultry litter up to 10 t/ha had no effect on soil water holding capacity or soil bulk density. Application rates higher than 10 t/ha would be required to improve physical soil conditions. The use of compost as mulch at rates up to 10 t/ha may be more appropriate. This would reduce the evaporative loss of water from sandy soil and improve the water availability beneath the soil surface for plant uptake. Compost mulching has reduced detrimental effects associated with compost application (Mathur et al. 1993), potentially reducing the number of deformed carrots.

The lack of detectable increase in total soil phosphorus with compost and poultry litter application indicates that much higher rates are required to increase soil phosphorus to a level where other P inputs could be reduced while still providing adequate phosphorus supplies for crop production. Increases in total soil N with compost and poultry litter application show that nitrogen fertiliser rates could be reduced to take into account N supplied from the soil conditioners. Increases in soil N for some treatments over the course of the experiment were due to the frequent applications of inorganic N to maintain soil N levels at adequate levels for carrot growth.

**6.5 Conclusions**

The composted pig waste was not suitable for use as a soil conditioner for the production of carrots in this study because it increased the quantity of deformed and split carrots and decreased total carrot yield. A similar effect was observed for the application of poultry litter. This confirms anecdotal evidence that poultry litter causes deformities in carrots.
Chapter 7. Lettuce growth response to the application of compost as a phosphorus source.

7.1 Introduction

High application rates of phosphorus (P) fertilisers are essential for the production of all horticultural crops grown on the Swan Coastal Plain of Western Australia. The soils have very low phosphorus retention capacities and soluble P is readily leached although most horticultural crops have high P requirements (Weaver et al. 1988). Phosphorus requirements of crops are conventionally met by applying readily soluble P fertilisers which often results in high P leaching losses (McPharlin et al. 1994). Other less soluble P fertilisers and soil conditioners have the potential to be used instead of, or in conjunction with, superphosphate (Withers and Sharpley 1995).

The composted pig waste used in this study contained 1.2% total P, which is mostly less soluble and less plant available than P in inorganic P fertilisers such as superphosphate (Chapter 4). The rate and amount of P that is solubilised from compost are not known and depend on rates of P mineralisation. A lack of understanding of availability of P from composted pig waste has the potential to limit its use as a fertiliser. It has been estimated for compost in general that 50% of total P is readily available for plant utilisation (Withers and Sharpley 1995). In practice, the availability of P from composts is likely to vary considerably depending on waste type and the treatment process that it has undergone. The amount of microbial immobilisation of inorganic P to organic P as well as the pH alterations due to the addition of liming or acidifying compounds will all affect the amount of plant available P (Withers and Sharpley 1995).

The availability of P from a specific fertiliser can be measured directly or indirectly (Cai et al. 1997). The direct method involves assessing plant response to the application of the fertiliser when nutrients other than P are not limiting. Predictive estimates of crop response to P application are developed based on indirect methods which involve estimating plant available P using a soil extractant which theoretically extracts only plant available P (Cai et al. 1997). Extraction methods have some limitations but have
been found to be successful when calibrated for plant species and soil type (Cai et al. 1997, McPharlin et al. 1996).

On the Swan Coastal Plain the most commonly used method of soil testing for plant available P is the indirect Colwell (1963) bicarbonate extraction method (McPharlin et al. 1996). This method is effective for predicting the yield response of many horticultural crops to P application. For lettuce grown on Karrakatta sand, 80 ugP/g soil of bicarbonate extractable P is required to achieve 95% of maximum yield (McPharlin et al. 1996). Similar amounts are required for other sandy low organic matter soils (McPharlin et al. 1996). Although this method is effective for estimating yield response to inorganic P, its effectiveness has not been determined for soils that have received organic amendments such as composts.

It is hypothesised that compost can be used to supply all the P requirements of a lettuce crop. In comparison to superphosphate as a P source, it is expected that the total amount of P applied as composted pig waste will be much greater than that for superphosphate to achieve the same yield. The critical amount of bicarbonate extractable P to achieve the same yield should be similar for both treatments. The aim of this experiment was to assess the capacity of compost to supply phosphorus to lettuce.

7.2 Materials and Methods

The experiment was set up at the Medina Field Station (Plate 7.1), Agriculture Western Australia, using a completely randomised design with two phosphorus sources (compost and super phosphate) and five application rates (0, 25, 50, 100, 200 t/ha dry weight of compost and 0, 50, 100, 200, 400 kgP/ha of superphosphate). Each treatment was replicated 3 times.

Composted pig waste was obtained from the Wandalup composting plant. The experiment was conducted on a yellow Karrakatta sand which had not been previously fertilised. Compost and superphosphate were applied to plots, 2m x 1.2m, with a 1m buffer between each plot. Trace elements were broadcast over all plots at 25 kg/ha MnSO₄, 50 kg/ha MgSO₄, 18 kg/ha FeSO₄, 18 kg/ha CuSO₄, 16 kg/ha ZnSO₄ and 2 kg/ha Na₂MoO₄. Fertilisers were incorporated to 20 cm depth by rotary cultivation. Lettuce seedlings, Lactuca sativa L. cv ‘Oxley’, were planted, 1 week after fertiliser and
compost application, in four rows 30 cm apart with 40 cm between plants (Plate 7.1). N was fertigated at 20 kgN/ha/week as NH₄NO₃, 3 kgN/ha/week as Ca(NO₃)₂ and 15 kgN/ha/week KNO₃. K was fertigated at 40 kgK/ha/week as KNO₃ while Mg was broadcast at 2 kgMg/ha/week as MgSO₄.

The experiment was conducted over two and a half months. Soil sampling was conducted monthly during which five soil cores were randomly taken from the top 15 cm of each plot and bulked. Soil samples were then air-dried and a 50 g sub-sample of soil was ground for total C, N and P analysis.

![Plate 7.1 Lettuce seedlings after planting in raised beds at Medina](image)

Ground soil samples were analysed for total C and total N using a LECO CHN analyser (Sweeney and Rexroad 1987). Total P was determined in nitric perchloric acid digests of ground soil samples while bicarbonate extraction of P was used to determine available P in soil samples (Colwell 1963). Phosphorus concentration in the acid digests and bicarbonate extracts was determined using manual colorimetry (Murphy and Riley 1962).

Plants were harvested 2.5 months after establishing the experiment. Thirteen lettuce heads per plot were collected as well as root systems from 5 of the harvested plants. The
fresh weights of lettuce heads and roots were recorded. Subsections from the center of each head were weighed, then dried to determine dry matter yields. Complete root systems were also dried and dry weights were recorded. After weighing, dried samples were ground. Total plant P was determined in nitric perchloric acid digests of ground plant samples using manual colorimetry (Murphy and Riley 1962). A general tissue test was carried out on lettuce heads by a commercial laboratory (CSBP Wesfarmers). Statistical analysis was conducted on data using ANOVA General Linear Model on Genstat™ (Payne and Arnold 2000).

7.3 Results

Lettuce yield, expressed as fresh head weight, responded to superphosphate application and reached a plateau at 50 kgP/ha of superphosphate (Figure 7.1). Lettuce yield also responded to compost application with maximum yield being achieved when compost was applied at 100 t/ha (Figure 7.1). The maximum yield for superphosphate treatments was 17% higher than for compost treatments, 980g for superphosphate compared to 800g for compost (Figure 7.1).
Figure 7.1 Average yield response of lettuce head to compost and superphosphate as phosphorus sources. (LSD represents least significant difference at p<0.05, error bars represent standard errors of the mean.)

Phosphorus concentration in lettuce leaf tissue increased with higher rates of superphosphate P, reaching 0.6% P when 400 kgP/ha was applied. In contrast, leaf tissue P concentration reached a maximum of 0.4% P, at an application rate of 50 t/ha of compost. Higher compost application rates up to 200 t/ha had no effect on P concentration (Figure 7.2a). There was no difference in phosphorus concentration in lettuce root tissue among rates of superphosphate application (Figure 7.2 (b)). The rate of compost applied also had no effect on phosphorus concentration in root tissue. Similar root tissue phosphorus concentrations were observed for both compost and superphosphate treatments (Figure 7.2 (b)).
Figure 7.2 Phosphorus concentration in lettuce leaf (a) and root (b) tissue in response to compost and superphosphate application. (Error bars represent standard errors of the mean.)

The amount of P taken up by whole lettuce plants increased with increasing applications of superphosphate. Increases in P uptake were greatest between application rates of 0 and 100 kgP/ha after increases in P uptake began to plateau (Figure 7.3). A similar trend of increased P uptake was observed for increasing rates of application of compost. P uptake plateaued at 25 t/ha compost. The amount of P uptake was higher for all superphosphate treatments (Figure 7.3).
Figure 7.3 Total P uptake by lettuce plants in response to compost and superphosphate application. (Error bars represent standard errors of the mean.)

A comparison of lettuce yield with total soil P for soil where superphosphate had been applied indicated that the greatest yields were achieved when total soil P concentration was above 150 ugP/g soil (Figure 7.4). In contrast, much higher total soil P concentrations were required before lettuce yield reached a maximum when compost treatments were applied (Figure 7.4).
Figure 7.4 Relationship between total soil P and lettuce yield in response to superphosphate application and compost application. (Error bars represent standard errors of the mean.)

The increases in lettuce yield corresponded with increased concentrations of bicarbonate extractable soil P for superphosphate treatments (Figure 7.5). Lettuce yield increases also corresponded to increased bicarbonate extractable soil P for compost treatments (Figure 7.5). The response curves were different for the two forms of P (superphosphate and compost). Bicarbonate extractable P from soil with compost applied was about half as effective in supporting yield as bicarbonate extractable P from superphosphate treatments (Figure 7.5).
7.4 Discussion

Composted pig waste can be used as a P source for growing lettuce in soil. However, extremely high compost application rates did not achieve lettuce yields equivalent to those that received high levels of superphosphate. In contrast to expectations, bicarbonate extractable P levels were not comparable between P sources at similar lettuce yields and therefore predictive models for bicarbonate extractable P levels developed for soils fertilised according to conventional practices cannot be used when high rates of composted pig waste are applied.

The lower yield maximum obtained when compost was used as a P source indicates that there is a limitation to lettuce plants induced by the compost or due to the form of P present. Similar differences in comparisons of readily soluble P sources with slowly soluble P sources such as rock phosphates have also been observed (Bolland and Barrow 1988). This may be related to the effectiveness of the slowly soluble source, relative to the soluble source. The decrease in the rate of P dissolution with increasing application rates, can be caused by a feedback effect in which increasing the concentration of the P source in the soil increases the proximity of P containing particles.
which decreases the rate of dissolution of P (Barrow and Bolland 1990). Further support
of the feed-back theory can be drawn from this experiment in that the maximum relative
effectiveness of compost was reached at 100 t/ha, after which any increase in P supply
did not result in greater yield despite tissue testing indicating that P concentration was in
the marginal sufficiency range (0.4-0.6%P) (Reuter and Robinson 1986).

Other factors that may limit P uptake by plants from soil include soil pH, nutrient
deficiencies and high C:P ratio. In this experiment it is unlikely that any of these factors
affected P uptake. Soil pH remained below the critical level (pH 7.5-8) where
availability of P is greatly reduced due to chemical immobilisation (Glendinning 1999).
Tissue testing indicated that lettuce plants had no nutrient deficiencies (data not shown)
and the soil C:P ratio was below 60 indicating that P immobilisation is unlikely to occur
(Smith et al. 1992). This highlights the complex effects that compost application can
have on soil fertility.

The commonly used sodium bicarbonate extractable P test for estimating plant response
was not suitable for soils that had received compost if a calibration developed for
conventionally fertilised soils was used. There was a completely different relationship
between plant response and bicarbonate extractable P for superphosphate and compost.
The critical levels of soil P for lettuce on Swan Coastal Plain sands previously
developed for chemical fertilisers cannot be used when compost is applied. The soil test
needs to be re-calibrated for composted pig waste. Differences between soil test P and
plant response have also been found between superphosphate and rockphosphate
(Bolland et al. 1989)

The utilisation of composted pig waste to supply all the P requirements of a lettuce crop
is unlikely to be successful due to the limitation in availability of P observed in this
study. A combination of commercial P fertiliser and compost is likely to be effective
and practical. The compost would act as a soil conditioner as well as a source for some
of the P requirements of the crop. Use of composted pig waste as a P fertiliser may be
more suited to horticultural crops with lower P requirements such as cabbage
(McPharlin et al. 1996). Although compost was not able to supply all the P
requirements for maximal lettuce growth, yield was increased by 30% at low rates of
compost application similar to the rates of poultry litter used in horticulture. Therefore,
this compost could be a valuable substitute for poultry litter which is becoming phased out of horticulture in Western Australia.

7.5 Conclusions

Composted pig waste can be used as a P fertiliser for growing lettuce in sandy soils, but there are limitations to the amount of P that it can supply to crops. Supplemental P would be required for growing lettuce. The compost may be more suitable for other horticultural crops with lower P requirements than lettuce (Mcpharlin et al. 1996). The current bicarbonate soil test calibration for estimating plant response to soil P levels is not suitable for predicting response where compost has been applied in these soils.
Chapter 8. General Conclusions

The concept of composting wastes, including pig waste, is not new. This research represented a study conducted for the Australian pig industry to establish a composting method applicable to Australian production conditions. The prototype system that was investigated in this thesis demonstrated that by composting pig waste with other readily available wastes, such as straw and sewage sludge, a highly valuable product can be produced which is suitable for use in horticultural industries to improve soil fertility and potentially to increase crop production and quality.

One of the aims of this research was to assess how readily pig waste could be composted, to identify problems that may arise and to develop a set of guidelines for monitoring and ensuring that any pig waste composting process is operating efficiently and producing a mature product. Other studies have been conducted on composting pig waste (Collins and Parson 1993, Lau et al. 1993, Pandey et al. 1993) but they have generally examined only one or two factors affecting pig waste composting performance, such as the height of the composting reactor, or the most suitable C:N ratio of the raw materials. Thus, by examining a wider range of factors and assessing maturity tests, this study has consolidated sufficient information for pig producers to develop their own composting process, to suit their own conditions. This is a significant outcome for the pig industry as it provides another option of treating the large volumes of solid waste produced daily at piggeries in a sustainable way with minimal infrastructure requirements.

The research supported observations for other waste types in relation to conditions required for composting organic waste, demonstrating that pig waste composts in a similar fashion to other common wastes types (Mathur 1991, Gotaas 1956, Harper et al. 1992). No special considerations are required for composting pig waste as have been identified for some wastes such as seafood.

The second objective was to assess the degree to which application of composted pig waste influenced some components of soil fertility, (Table 8.1) particularly its use as a soil conditioner for improving crop production on the very sandy horticultural soils common to the Swan Coastal Plain of Western Australia.
### Table 8.1 Summary of main findings in this study.

<table>
<thead>
<tr>
<th>Experimental Objective</th>
<th>Main findings</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment of composting process and product stability.</td>
<td>C:N ratio was the best indicator of composting progress. C:N ratio and seed germination tests were the best indicators of compost maturity.</td>
<td>Composting of pig waste can be readily conducted using the Wandalup process to produce a mature product.</td>
</tr>
<tr>
<td>Quantify the amount of N and P leached when compost was used in horticulture and to compare to conventional inorganic fertilisers.</td>
<td>Significant amounts of N and P are available for leaching from compost and potentially available for crop uptake.</td>
<td>Composted pig waste has a high potential to supply N and P for crop growth or leaching.</td>
</tr>
<tr>
<td>Comparison of the effects of applying pig waste, poultry litter and peat on the fertility of a sandy horticultural soil.</td>
<td>When compost was applied in conjunction with inorganic fertilisers the amount of N and P leached was higher than if the fertiliser was applied alone.</td>
<td>It is important to take in to consideration the amount of N and P leached from compost when applied in conjunction with fertiliser, inorganic fertiliser inputs could be reduced accordingly.</td>
</tr>
<tr>
<td>Compost application resulted in increased quantities of deformed and split carrots and decreased yield. These effects were similar to those observed when poultry litter was applied.</td>
<td>Composted pig waste compared favorably with poultry litter as a soil conditioner increasing soil total P, soil total C and microbial biomass N and reducing soil bulk density.</td>
<td>Composted pig waste has the potential to be used as a substitute for conventionally used poultry litter in W.A. horticulture.</td>
</tr>
<tr>
<td>Need to determine the relationship between bicarbonate extractable P and crop response for compost amended soil.</td>
<td>Compost application resulted in increased quantities of deformed and split carrots and decreased yield. These effects were similar to those observed when poultry litter was applied.</td>
<td>Composted pig waste was not a suitable soil conditioner for carrot production, having similar detrimental effects as that of poultry litter</td>
</tr>
</tbody>
</table>
Table 8.1 Summary of main findings in this study, continued.

<table>
<thead>
<tr>
<th>Experimental Objective</th>
<th>Main findings</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determination of the amount of P that can be supplied by composted pig waste for growing a high a crop with high P requirements, lettuce.</td>
<td>High rates of compost application supplied most of the P requirements for lettuce production.</td>
<td>Composted pig waste has the potential to supply large quantities of P for horticultural crop production.</td>
</tr>
<tr>
<td>The current soil test used for predicting lettuce response to soil P was not suitable for predicting lettuce response to P supplied by the compost.</td>
<td>Soil tests for crop responsiveness to application of P in organic soil conditioners needs to be determined.</td>
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</table>

Two of the major problems facing horticulturalists on the Swan Coastal Plain are 1) the banning of poultry litter use, and 2) fertiliser pollution of river and ground waters (Tingay and Associates 1997). A major focus of the rest of this study was to assess whether pig waste compost could be used as a substitute for poultry litter and to gain an understanding of some of the nutrient dynamics associated with the application of composted pig waste to soil.

In the leaching experiment (Chapter 4) only a small percentage of total N and P contained in compost was leached, 0.75 and 1% respectively. Despite these low leaching proportions the amount leached is still considerable if the compost is used as a soil conditioner on soils to which horticultural industry standard rates of inorganic fertiliser are applied. Compost application, 80 t/ha, resulted in 13% more P and 20% more NO₃-N and NH₄-N being leached, when applied in conjunction with a conventional rate of fertiliser used for growing lettuce. Thus it is important to adjust fertiliser rates accordingly if compost is applied before sowing a crop. However, predicting the effectiveness of the compost as a nutrient source is difficult due to the complexities involved in determining the availability of nutrients from organic sources.

The general benefits of using composted pig waste as a soil conditioner for sandy soils, common to Western Australian horticulture, were examined in Chapter 5. At rates up to 80 t/ha of compost soil P, soil water holding capacity, and microbial biomass all
increased and soil bulk density was reduced. For the properties measured, compost compared favourably with poultry litter.

The benefits of composted pig waste identified in Chapter 5 were tested in a field experiment for impacts on carrot production. Carrots were chosen as they are a crop for which the addition of soil conditioners, such as poultry litter is not practiced due to detrimental effects on carrot formation. It was hypothesised that it was the volatile compounds present in the poultry litter that caused this problem hence it was thought that composted pig waste, with most volatile compounds having been broken down, could be used successfully for carrots. Unfortunately compost applications, even at the very low rates of 2.5, 5 and 10 t/ha increased carrot splitting and forking and reduced marketable yield. Therefore, it is recommended that composted pig waste is not used on sensitive root crops, such as carrots. There is no other research on the effect of compost on carrot growth therefore it is difficult to conclude whether this is a specific effect of composted pig waste. Both poultry litter and sewage sludge cause similar detrimental effects so it is likely that it is a general response to addition of organic amendments (Galati and McKay 1996, Bienz 1964). These preliminary findings suggest that further work to determine the mechanisms by which some organic wastes effect carrot development would be highly beneficial.

Composted pig waste was effectively used for lettuce production, in particular to supply P (Chapter 7). Little work has been conducted on the ability of composts to supply specific nutrients under high production cropping systems. The findings of this experiment provide an insight into potential limitations to using compost to supply the total P requirements of a high P demanding crop. Soil conditioners with moderate nutrient levels, such as pig waste compost or poultry litter, will supply a significant amount of nutrients when applied at rates of approximately 20 t/ha. This needs to be taken into account when calculating the nutrient requirements of a crop. The second major finding is that there can be limitations in use of compost to supply all the P requirements of a crop as the effectiveness of the compost as a P source is less than the equivalent amount of fertiliser P. Furthermore, there was a different relationship between bicarbonate extractable soil P and lettuce yield when compost was used as a P source. Caution is required when using common soil tests to predict P yield response when high levels of soil conditioner are applied. Further investigation of appropriate
soil tests, for P and other macro nutrients, to predict crop response to composted waste application would be very useful.

The work conducted in this thesis has provided an overview of how pig waste can be composted as well as information on its effects on biological, physical and chemical soil fertility. General areas that require further investigation include, (1) the capacity of composted pig waste to supply plant nutrients in different soil types and (2) the mechanisms involved in the release of nutrients from compost and how nutrient release rates can be predicted. The effect that compost application has on biological fertility was only briefly investigated in this thesis, hence there are also further opportunities to examine what effects compost have on soil biology.

In summary, composting of pig waste can be easily conducted to create a highly useful compost that can be readily used in horticulture. The compost has the potential to supply N and P for crop growth reducing inorganic fertiliser requirements for a given crop. Composted pig waste compares favorably to poultry litter as a soil conditioner and thus has the potential to be used as a substitute for it in Western Australian horticulture. The compost may not be suitable for use on crops that are sensitive to organic matter applications, such as carrots. Despite finding that composted pig waste can supply large amounts of P it is difficult to predict the precise P fertiliser value of the compost as conventional soil tests for plant responsiveness to P application will not work when high amounts of organic matter are added to the soil.
9.1 References


Singh, S.P. (1989). Production Technology of Vegetable Crops. Agricultural Research Communications Centre Sadar (India), 120-128


