Land application of vegetable processing wastes: Technical information for establishment and environmental monitoring of land application systems

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19 December 2008

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Scion

Date: 19 December 2008
Client: Gisbourne District Council (Funded by Envirolink)
Project No: 330-GSDC44

Executive summary

The "Land application of vegetable processing wastes: Technical information for establishment and environmental monitoring of land application systems" has been prepared to assist persons who design, set up, manage or monitor land application systems for vegetable processing wastes in New Zealand. It provides supporting information, serving as a technical reference on key issues related to designing, establishing, operating and monitoring land application systems. Topics covered in this document are outlined below:

Chapter 1. Introduction. Provides a brief introduction of vegetable processing industry in New Zealand and the purposes of this document.

Chapter 2. Characteristics of vegetable processing wastes. Describes the main constituents in wastes produced by vegetable processing industry.

Chapter 3. Benefits of land application of vegetable processing wastes. Highlights the beneficial effects of the land application systems for management of vegetable processing wastes.

Chapter 4. Site and crop selection. Summarises factors that can affect the selection of a land application site; provides basic information on selecting a crop to grow in a land application system.

Chapter 5. Loading rates and system design approach. Describes basic design approach and how to identify the limiting factors.

Chapter 6. Vegetable processing waste distribution system. Outlines distribution system planning and describes hardware technologies for safely distributing and applying vegetable processing wastewater, and their management.

Chapter 7. Site monitoring. Outlines the key areas to be included in a monitoring plan, and describes how monitoring can be used to help manage a land application system.

Chapter 8. Land application of solid residues. Summarises processes that lead to good management practices in land application of solids residue from vegetable processing industries.

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1. INTRODUCTION

There are approximately 53,000 ha of outdoor and 300 ha of greenhouse vegetables planted in New Zealand, with more than 40% of the vegetables being exported. Fresh vegetables ($205m) and processed vegetables ($291m) were exported 76 countries (HortResearch 2006). There are around 750 vegetable process growers and 110 potato process growers in New Zealand. The farm gate value of the process industry exceeds $100m. Potatoes, sweet corn, mixed vegetables, peas, and beans are the major processed and frozen vegetables exported (Table 1) (HortResearch 2006). The continued development of the vegetable processing industry in New Zealand has resulted in large quantities of industrial waste products needing to be treated and managed in a sustainable manner. In recent years there are increasing public, cultural and political pressure, and consequently more stringent environmental regulations are now in place, to protect water quality and develop sustainable alternatives to discharging into surface waters. The vegetable processing industry has developed and implemented effective waste management strategies to reduce, recycle and treat wastes. Wastewaters treated through conventional treatment processes in the vegetable processing industry usually need to be further polished through land treatment, which helps minimise pollutant loadings on surface waters.

Table 1. New Zealand processed vegetable export ($ million) (HortResearch 2006).

Year ended June	1965	1975	1985	1995	2005	2006
Processed vegetables						
Peas (frozen)	0.5	1.5	22.0	34.3	36.6	45.9
Potatoes (frozen)				14.1	54.3	59.5
Sweetcorn (frozen/dried)	0.2	0.8	9.5	30.6	42.7	38.9
Mixed vegetables (frozen)			4.6	23.9	36.0	40.7
Dried vegetables					25.5	38.2
Vegetable preparations					40.2	40.8
Other processed vegetables	0.8	2.4	20.9	75.6	28.4	27.4
Total processed vegetables	1.5	4.7	57.0	178.5	263.7	291.4

Land treatment is defined as the application of appropriately treated municipal and industrial wastewater to the land at a controlled rate in a designed and engineered setting (USEPA 2006). The purpose of land application is to obtain beneficial use of these waste materials, to improve environmental quality, and to achieve treatment goals in a cost-effective and environmentally friendly manner. In a land application system, the soil-plant ecosystem acts as a biofilter to effectively treat liquid and semisolid wastes derived from vegetable processing wastewater treatment. A well designed land application system can also improve soil productivity through reuse of nutrients and water in the wastes. The production and sale of crops can often partially offset the cost of the system.

Although the vegetable processing sector plays an important role in the New Zealand economy, there is little published information on effective management of wastes generated within the industry. To assist in the sustainable development of the vegetable processing industry, we have conducted a review of international literature to provide state-of-the-knowledge information for designing and operating a land application system to determine best management of vegetable processing wastes. In particular, we hope this document will help regulators and vegetable processing waste managers adapt methods for good practice in vegetable processing waste management.

2. CHARACTERISTICS OF VEGETABLE PROCESSING WASTES

Wastes are generated in the processing of vegetables. Most vegetable processing wastes contain valuable organic matter with macro and micro plant nutrients that may be beneficial to both soils and plants. Nutrients in vegetable processing waste may allow a reduction in fertiliser application to crops. Vegetable processing wastes may also contain solids, salts, and other minerals that can be detrimental to plants or the soil structure if their application is not properly managed.

When assessing the quality of vegetable processing wastes for land application, it is important to perform the following basic water quality analyses (Brown and Caldwell 2007): pH, total nitrogen, major nitrogen compounds, and phosphorus; total organics (measured as biochemical oxygen demand, or BOD, and chemical oxygen demand, or COD); total suspended solids (measured as TSS); salinity (measured as electrical conductivity, or EC); sodium adsorption ratio (SAR); cations and anions, such as calcium, magnesium, sodium, potassium, chloride, and sulphate (Brown and Caldwell 2007).

2.1 Organic components and suspended solids

Organic matter in soil contributes to increased soil fertility and crop production. The soil productivity benefits include increased water holding capacity, improved soil structure, increased micro-organism and macro-organism activity, and increased water infiltration (Whitehouse et al. 2000). Organic material consists of decomposed plant and animal residues. When organic matter is decomposed, it releases nitrogen, phosphorus, sulphur, and other nutrients that are useful to plants. Organic matter undergoing aerobic decomposition uses oxygen, and thus reduces the amount of soil oxygen available to plants. Soil oxygen depletion can result in anaerobic conditions, which can cause a reduction in infiltration capacity due to the sealing effect of gels and slimes secreted by anaerobic microorganisms (King 1986; Magesan et al. 2000).

Many land application systems are very efficient at removing biodegradable organics. Vegetable processing waste organic constituents that are easily biodegradable are traditionally measured using five-day BOD, although COD results can be obtained more quickly than BOD and can provide a better estimate of total ultimate oxygen demand if potential chloride interferences are addressed (Brown and Caldwell 2007). However, COD tends to somewhat overstate ultimate biological oxygen demand. Generally, BOD is used for measuring organics in vegetable processing wastes (Brown and Caldwell 2007).

Although total suspended solids are generally not a limiting design factor, solids concentration measurements are some of the most important physical characteristics to consider when evaluating vegetable processing wastes for land application (Borrie and Mcindeo 2000). Solids in water are composed of floating matter, settleable matter, colloidal matter, and matter in solution. Total suspended solids are a measure of the solids that can be filtered out of the water column. Excessive total suspended solids accumulation at the soil surface can adversely affect water infiltration rates, thereby causing prolonged ponding and odour problems (Brown and Caldwell 2007).

2.2 Nutrients

Vegetable processing wastes contain all plant nutrients with nitrogen (N) and phosphorus (P) among the major essential nutrients required by plants. Nitrogen in particular is vitally important and is the most frequently deficient of all nutrients (Tisdale et al. 1993). Nitrogen removal in land application systems is complex and dynamic as there are many forms of nitrogen (N_2, organic N, NH_3, NH_4, NO_2, NO_3) and it may change from one oxidation state to the next with relative ease (USEPA 2006). N is absorbed into plants as nitrate (NO_3^-) and ammonium (NH_4^+) with nitrate the most dominant available form of nitrogen in moist, well-aerated soils. The primary forms of nitrogen in vegetable processing wastes are organic nitrogen and ammonium. Nitrate concentrations in vegetable processing wastes are usually low (Brown and Caldwell 2007).

Nitrates may contaminate surface and groundwater sources because the nitrate ion is negatively charged and tends to be easily leached from soil (Whitehouse et al. 2000). Sandy soils are generally more susceptible to nitrate leaching than are clayey soils. To prevent or minimise groundwater degradation due to N leaching, it is important to analyse vegetable processing wastes for N before applying to crops. It is also important to measure soil and plant N to adequately assess nutrient requirements. The most common form of N assessment in water is by measuring concentrations of total nitrogen, nitrate and ammonium. To determine how much total N is in the organic form, ammonium N and nitrate N are measured and subtracted from total nitrogen (Magesan 2004).

Phosphorus is also an important nutrient for plants (Tisdale et al. 1993) and is mainly taken up by plants as orthophosphate ions ($H_2PO_4^-$ or HPO_4^{2-}). Phosphates are negatively charged ions and are repelled by negative charges on clay minerals and other organic compounds in soils. Phosphates react with iron and aluminium in acid soils and calcium and magnesium in neutral to calcareous soils to form solid materials that are not readily leached.

Many other nutrients are found in vegetable processing wastes in the forms of cations and anions. The major individual cations generally present include calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+). The major nutrient anions include chloride (Cl^-) and sulphate (SO_4^{2-}). These nutrients can have a profound impact on the physical and chemical properties of soils (California Fertilizer Association 1995) as well as affecting plant production.

Calcium and magnesium improve the physical properties of soils and increase water penetration if high concentrations of sodium are present. Because calcium and magnesium are salt ions that contribute to electrical conductivity (EC), the problems associated with high salinity are similar to those associated with high calcium and magnesium concentrations. Potassium is an essential plant nutrient. The potassium ion is water-soluble and positively charged, which can be adsorbed by negatively charged soil clay minerals and humus. Vegetable processing wastewater may contain high concentrations of potassium ions that can accumulate to potentially toxic levels in the soil (Brown and Caldwell 2007). Too much potassium may lead to deficiencies in magnesium and sometimes calcium.

As a micronutrient, boron is an element required by all plants, but in very small amounts. However, too much boron may result in severe toxicity problems (Goldbach et al. 2002). For example, excessive boron can cause leaf edges to die, leaves to lose chlorophyll, seeds to fail to sprout and restriction of root growth.

2.3 pH, salinity and sodicity

The pH of vegetable processing waste can have a major influence on crop production, functioning of soil microorganisms, and the fate and transport of waste constituents (Carnus et al. 1998; Sparks 2003). In a low pH environment, many metals are more soluble and thus can increase the movement of waste constituents. The ideal pH for many plants is slightly acidic, between 6.0 and 7.0. If the soil pH becomes too alkaline (pH>8.5), iron, manganese, zinc and other essential micronutrients are less available to plants. On the other hand, if the soil pH is too low (pH<4.20), aluminium (Al), iron (Fe) and manganese (Mn) toxicity to plants may occur (USEPA 2006).

Salts from vegetable processing wastes can affect crop health, soil productivity and groundwater quality. Although vegetable processing wastes often have high concentrations of organic materials, most of these organic substances are mineralised in the upper soil layer. Therefore, the mineral salts in the vegetable processing wastes are of interest in protecting plant growth, and soil and groundwater quality. Salinity becomes a problem when salts accumulate in soil to a concentration that is harmful to plants. To control this problem, there must be a sufficient excess of water above the plant requirements to leach salt below the rooting zone. Creating a net downward flow of water and salt through the root-zone is the only way to manage a salinity problem (Carnus et al. 1998). Additional irrigation needs to be applied if there is not enough natural drainage to leach out salts. Good drainage is essential to encourage leaching, but the leachate may have an adverse impact on groundwater quality due to excessive salt loading.

The accumulation of salt in soil depends on the concentration of salt in the vegetable processing waste, the amount of water irrigation (hydraulic loading), and the rate at which salt is removed by leaching. If there is sufficient rain, soil salt will decrease during periods when no waste is applied to land. Under extremely dry conditions, accumulation of salt during the application season may be enough to affect plant growth until rainfall creates leaching. Therefore, an allowance for leaching should be considered to avoid salinity problems. This allowance is called a leaching fraction (LF) (Carnus et al. 1998).

Although the most accurate method for measuring total mineral salinity in vegetable processing waste is to measure and sum the concentrations of all the major mineral ions, this procedure is relatively expensive for frequent use. Electrical conductivity (EC) can be used as a "quick" measure of total salinity for comparative operational monitoring purposes for vegetable processing waste (Brown and Caldwell 2007).

When a soil is susceptible to salt accumulation, the amount of leaching required to prevent an unacceptable salinity level can be estimated by using a "leaching fraction" calculation. This calculation is based on the wastewater EC, hydraulic loading of the wastewater and rainfall, and the threshold soil EC at which growth of a specific plant may be negatively affected (Ayers and Westcott 1985; Carnus et al. 1998). Guidelines for the interpretation of water quality for irrigation and plants that will withstand various levels of salinity in the soil are provided by Rhoades and Loveday (1990), and Maas (1986) (Table 2). Sodium and chloride can cause direct toxicity to sensitive plants (see Rhoades and Loveday 1990, for a list of sensitive plants). However, for the most part salt affects plant growth by decreasing the osmotic potential in the root zone so that it is more difficult for the plant to extract water from the soil. Low osmotic potential acts similarly to low soil water potential found in dry soils and results in reduced plant water uptake (Carnus et al. 1998). Two management techniques for dealing with high salt in soil are to plant a salt tolerant species, and to deliberately leach salt from the soil. In practice, both methods are necessary if the EC of a vegetable processing waste is high (Carnus et al. 1998). Generally, New Zealand's humid climate in most areas promotes leaching of soils to a degree that prevents substantial accumulation of soluble salts (Tipler 2000).

Table 2. Salinity tolerance of selected crops (from Rhoades and Loveday 1990).

Tolerance class	Low	Medium	High
Species	Lucerne	Ryegrass	Barley
Critical soil EC threshold (dS/m)	2.0	5.6	8

In addition to effects on plant growth, high concentrations of soil sodium can cause swelling and dispersion of clay particles, leading to crusting and clogging of soil pores, and resulting in decreased permeability, infiltration, and drainage (Carnus et al. 1998). Sodium-affected (or sodic) soils are less suitable for irrigation and plant growth, and are therefore less efficient in the treatment of vegetable processing wastes. The sodium adsorption ratio (SAR) is commonly used as an indicator of the potential of vegetable processing wastes to cause a sodic soil (Carnus et al. 1998). The SAR describes the balance between the sodium (Na) ion and other most commonly available divalent ions, calcium (Ca), and magnesium (Mg) in the wastewater, and is calculated as:

$$SAR = \frac{[Na]}{\sqrt{[Ca]+[Mg]}}$$

where [Na], [Ca], [Mg] are the concentrations in mmol/L. Irrigation with wastewater having a high SAR can lead to increased sodium in the soil. The accepted limit for SAR for wastewater application to soils may be anything between 4 and 18 depending on the soil type (Rowe and Abdel-Magid 1995).

The soil sodicity is measured by its exchangeable sodium percentage (ESP). The ESP is the percentage of cation exchangeable capacity occupied by sodium ions.

ESP = 100 × (exchangeable sodium ÷ sum of all exchangeable cations)

The U. S. Salinity Laboratory Staff (1954) suggested an ESP of 15% as the critical level above which soil structure and therefore permeability could be deleteriously affected, assuming irrigation with water having an EC of 0.3-1 dS/m. However, the relationship between ESP and sodicity hazard is complex, and may be affected by soil type, wastewater salinity, and soil management. Although an ESP of 15% has been widely accepted as the critical level (Sumner 1993), it has also been considered too high by some scientists. For example, Hopkins (1997) studied the soil chemical properties at the Rotorua land treatment system receiving continuous sewage effluent irrigation for a number of years, and found that ESP values ranging from 7-30% in this sandy volcanic forest soil had no apparent effect on soil hydraulic conductivity. By contrast, McIntyre (1979), after studying a range of Australian soils, proposed an ESP of 5% as more appropriate for identifying sodic soils, although this was for irrigation with a very low salinity water (EC of 0.07 dS/m) or rainfall, which exacerbates sodicity (Carnus et al. 1998).

If a soil has a high ESP level, whether or not the soil is physically stable will be determined by other soil properties and by management practices. Soils will be more stable if they have a low pH, a low clay content, a high organic matter content, a high proportion of sesquioxides, and if the clay fraction contains more kaolinitic than smectitic or illitic clay minerals. In addition, a soil may be stable for a given high ESP level while undisturbed. But if the soil is disturbed (e.g., by cultivation), it may become unstable, disperse or swell and decline in permeability (Carnus et al. 1998).
When the sodicity causes detrimental effects on productivity, sodic soil conditions may be corrected by the addition of soluble calcium to the soil to displace sodium and remove it by leaching. This is most commonly achieved by the addition of gypsum (Rhoades and Loveday 1990). Assuming 100% efficiency of application and removal, for each tonne of sodium applied in the effluent, at least 3.7 tonnes of gypsum (depending on its purity) need to be applied to displace the sodium. More information on amendments for sodic soils may be found in Rhoades and Loveday (1990).

2.4 Pre-treatment

It is important to identify opportunities for reducing waste generation and/or strength; thereby minimising the potential impact of land application of vegetable processing wastes on groundwater. This approach can be used to help meet requirements for best management practices. Overall, source reduction and recycling efforts are consistent with the industry's goal for operating in an environmentally, socially, and economically sustainable manner. Sources and characteristics of vegetable processing waste will vary by facility depending on the type of product, nature of processing activities, size of the plant and other factors. Volume and chemical composition of vegetable processing wastes may vary seasonally. At most facilities, concentrations of organics (BOD), salts and nitrogen are the primary concerns (Brown and Caldwell 2007).

Methods for waste minimisation and best management practices to reduce the concentration and/or volume of waste streams can be summarised as follows (USEPA 1988):

1. Eliminate process water generation by process modifications, changing processes and operational changes;
2. Reduce the amount of process water produced by process modifications, changing processes and operational changes;
3. Recycle process water to other processes, or to offsite facilities;
4. Treat process water at the source, where constituents are more concentrated and easier to treat. This may facilitate further reuse of the effluent, and also reduces conveyance requirements;
5. Treat process water at the end-of-pipe (or route to a municipal treatment plant).

In addition, water conservation during facility cleaning may reduce waste volume substantially. Although water conservation methods are beneficial in conserving water supplies, they do not necessarily reduce the amount of constituents generated because the lower volume of water may carry a correspondingly higher concentration of constituents. However, with more concentrated effluent, recovery or treatment processes may be more efficient, which may reduce costs. Water conservation can also improve the feasibility or economics of other options such as recycling or disposal (Brown and Caldwell 2007).

3. BENEFITS OF LAND APPLICATION OF VEGETABLE PROCESSING WASTES

Land application is the method most widely used by the food processing industry to manage vegetable processing wastes. Application of such wastes to crop land is often the most economical waste management alternative to discharge waterways. Sustainable land application systems should aim to maximise nutrient use while minimising adverse environmental impacts.

Vegetable processing wastes are well suited to land application because the BOD can be readily converted into soil organic matter or mineralised (USEPA 2006). The applied BOD is filtered and adsorbed by the soil and biologically oxidised by soil microorganisms. The mechanisms in a land application system include the following processes:

- Removal of nutrients from the site. This includes nutrient and dissolved solids uptake by crops and subsequent removal by harvest. It also includes NH_3 volatilisation or nitrogen gas loss from denitrification.
- Long term storage in the soil, especially for the surplus phosphorus.
- Vadose zone retention. This includes some calcium and magnesium minerals with lower solubility precipitate in the vadose zone.
- Groundwater system. Groundwater can dilute and disperse percolated constituents, although groundwater quality should be monitored.

Most nutrients in vegetable processing wastes are absorbed, used by crops, and used by soil microorganisms, which keep them from percolating through the soil. The nitrogen cycle in soils allows for applied organic nitrogen to be converted into plant-available nitrogen, be lost to denitrification, immobilised by soil microbes and converted into stable soil humus (USEPA 2006). Phosphorus can be quickly retained in the soil by adsorption and precipitation, with some subsequent plant uptake. Potassium is also readily taken up by plants as a major plant nutrient. Dissolved mineral solids are removed by precipitation and crop uptake. However, some leaching of salts to groundwater is generally required to maintain appropriate chemical balances for good soil structure and crop production.

Land application of vegetable processing wastes potentially have many beneficial effects, such as avoidance of surface water discharge, crop irrigation, replacement of chemical fertilisers, improvement of soil fertility and productivity. Crop irrigation of vegetable processing waste provides valuable moisture, nutrients, and organic matter required to sustain and produce profitable crops. Therefore, the objectives of land application include:

- Provide cost-effective treatment of vegetable processing waste constituents in compliance with environmental regulations.
- Provide beneficial use of applied constituents such as nutrients and organic matter by producing a harvestable crop.
- Conserve water resource by substituting fresh water with vegetable processing waste to meet crop demand of water.

Land application systems can accommodate wide variations in the applied water content of organic materials, nitrogen, and other nutrients. Properly designed land application systems can intensively treat BOD, suspended solids, and nitrogen as effectively as advanced mechanical/biological treatment plants (Crites and Tchobanoglous 1998). The mechanisms for removal of organics and nutrients are robust so that the receiving groundwater is well protected. The buffering capacity of the soil can generally tolerate swings in applied pH without adverse effects on the soil, crop, or groundwater.

4. SITE AND CROP SELECTION

The characteristics of land application sites determine the potential for effective reuse of vegetable processing waste and its constituents. The site characteristics also directly affect the potential transport of vegetable processing waste constituents to groundwater. The procedure for site selection should include four steps (Robb et al. 2000): identifying the most suitable areas within reasonable distance of the effluent source, based on a broad-scale assessment of potential technical and environmental constraints; choosing potential sites from within the identified areas; evaluating potential sites based on readily available information including land use, climate, topography, soils information, location of groundwater aquifers and distance to surface waters, and knowledge that exists within territorial authorities and local communities; and conducting field investigations at the preferred site to verify the information and identify potential constraints that may affect the implementation of a land application system.

4.1 Climate

Climate influences many site characteristics because it affects soil formation, soil properties, crop establishment, and evaporation and evapotranspiration. Temperature and precipitation are the two main climatic factors that determine the rates of assimilation and conversion of vegetable processing waste constituents by soil microorganisms (USEPA 2006). For example, the rate of microbial conversion of organic carbon and nitrogen compounds decreases considerably with cool temperatures. Plant growth and uptake of nutrients increase with increasing temperature. Temperature can also affect evaporation and plant water use. The total annual rainfall and its distribution are important to land application systems because of the potential implications for surface runoff, soil erosion and leaching of waste constituents. In New Zealand, the National Institute of Water and Air Research (NIWA) coordinate a database of climate stations across the country providing information on local climate conditions.

4.2 Topography

Topography can affect soil depth, soil moisture content, crop growth conditions, and erosion and runoff potential. For example, steep slopes generally encourage surface erosion and allow less rainfall to infiltrate into the soil prior to runoff. It is recommended that the maximum slope for cultivated agriculture be 12 to 15 percent (Pettygrove and Asano 1985; USEPA 2006). However, it may be possible to grow crops that do not require cultivation, for example, grass-hay, to slopes of 15 to 20 percent or more, depending on site-specific runoff constraints. New Zealand regional or district councils usually have detailed information on topography.

4.3 Soils

Soil plays a significant role in land application of vegetable processing wastes. As a medium for plant growth, soil provides anchorage for vegetation, nutrient supply and water. Soil also provides a habitat for a multitude of organisms which help soil ecosystems to assimilate the vegetable processing waste constituents, an important process in the degradation and recycling of organic materials. Soils determine the quality of water passing over or through them. Wastewater passing through the soil may be cleansed of its impurities through a variety of soil processes, such as microbial digestion and filtration. Therefore, detailed descriptions of the physical and chemical characteristics of the soil within the entire rooting zone (or upper 1 m) should be made prior to land application of vegetable processing wastes. Initial information on soil types and characteristics may be obtained from the New Zealand soil database developed by Landcare Research.

Once a preferred site has been selected, it is important that soil survey information should be supplemented with an investigation by an experienced professional (e.g., a soil scientist) to evaluate the suitability of the soil on specific sites to adequately treat the vegetable processing waste. Soil characteristics that should be described include slope, microtopography, vegetation, depth, texture, different soil horizons in the soil profile, horizon thickness and boundary transitions, consistency, presence of rapidly draining materials, restrictive horizons or groundwater, drainage class, roots, estimated organic matter content, colour, structure and pH. Descriptions of other parameters such as infiltration rate, cation exchange capacity (CEC), type of clay minerals, available water capacity, type and amount of coarse fragments present, salinity, flooding potential, or soil erodibility may be needed. Detailed descriptions of some of these characteristics are provided in the following sections.

4.3.1. Texture

Soil texture is one of the most important characteristics determining fundamental soil properties such as fertility, water-holding capacity and susceptibility to erosion (Brady and Weil 2002). Soil textural classes are defined on the basis of the weight proportion of sand, silt and clay. Mineral soil particles with diameters ranging from 2 to 0.05 mm are classified as sand; those with diameters ranging from 0.05 to 0.002 mm as silt; and those with diameters less than 0.002 mm as clay. In some soils with high proportions of coarse materials, coarse fragment modifiers (greater than 2 mm), such as stony, gravely or cobbly are included as part of the textural class name (Soil Survey Staff 1993). Coarse-textured sandy soils can accept large volumes of water but do not retain much moisture. Clayey soils do not drain rapidly, but can retain larger volumes of water for long periods of time. Generally, deep, medium-textured (loamy) soils exhibit the best characteristics for vegetable processing waste irrigated systems.

4.3.2. Structure

Soil structure refers to the shape and degree of soil particle aggregation. The pattern of pores and aggregates defined by soil structure influences water movement, heat transfer, air movement, and porosity in soils (Hillel 2004). If soil aggregates resist disintegration when the soil is wetted or tilled, it is well structured. Well structured soils contain large pores that conduct water and air making these soils desirable for water infiltration, and generally more permeable than unstructured material of the same type (USEPA 2006).

4.3.3. Water holding capacity

Readily available water is defined as the portion of water in a soil that can be readily utilised by plant roots. The effective soil depth and texture has a significant impact on this soil property. Water in soils is held in pores ranging in size from large cracks or macropores to tiny interlayer spaces or micropores. When all of the macropores and micropores in a soil are filled with water, the soil is said to be saturated. Water is easily drained from a saturated soil because of gravitational forces. A soil is defined as being at *field capacity* when the soil is holding the maximum amount of water it can against the force of gravity (USEPA 2006). At this point, the water has drained from the macropores and is present only in micropores.

At field capacity, a plant will initially be able to extract water easily from the soil. However, soil water is held more tightly as the amount of water decreases and larger pores are drained. Eventually, plants are unable to extract sufficient water from the soil to survive, and the soil is said to be at its permanent wilting point. Although clay-textured soils may contain large amounts of water at the permanent wilting point, this water is held so tightly that it is unavailable to plants. As a result, the amount of water held between field capacity and the permanent wilting point, the available water-holding capacity, is more important for plant growth than the total soil water content (Brady and Weil 2002). The presence of organic matter increases the amount of available water directly, because of its greater water supplying ability, and indirectly, through beneficial effects on soil structure and total pore space. Ranges in the available water holding capacity for different soil types are summarised in Table 3.

Table 3. Available water holding capacity for different soil types (USEPA 2006).

Soil type	Moisture (%)		Depth of available water per unit depth of soil (mm/m)
	Field capacity	Permanent wilting point	
Fine sand	3-5	1-3	25-42
Sandy loam	5-15	3-8	42-108
Silt loam	12-18	6-10	58-133
Clay loam	15-30	7-16	100-183
Clay	25-40	12-20	167-292

4.3.4. Effective depth

Effective depth refers to the depth of soil to seasonal groundwater and/or a restrictive soil horizon that limits rooting depth. Adequate soil depth is needed for retention of vegetable processing waste constituents on soil particles, root development, and microbial activities. Most plants have the bulk of their roots in the upper 0.25-0.3 m of the soil as long as adequate moisture is available. Some perennial plants, such as lucerne and trees, have roots that are capable of growing to depths of greater than 3 m and are able to absorb a considerable portion of their moisture requirements from the subsoil. Retention of vegetable processing waste components is a function of their residence time in the soil and the degree of contact with soil particles. A soil depth of greater than 0.6 m is generally adequate for vegetable processing waste treatment (Pettygrove and Asano 1985; USEPA 2006).

4.3.5. Infiltration and percolation

The process by which water enters the soil pore spaces and becomes soil water is known as infiltration. The units of infiltration are generally mm per hour (mm/hr). The infiltration capacity is not constant with time, and generally decreases during an irrigation or rainfall event (Brady and Weil 2002). In soils with expansive clays, the initial rate of infiltration may be quite high as water enters the network of shrinkage cracks formed during periods of drying or desiccation. As infiltration continues, many macropores become filled with water and the shrinkage cracks swell shut. The infiltration capacity declines and then begins to level off, remaining fairly constant thereafter and is often called the saturated infiltration (Brown and Caldwell 2007). Once the water has infiltrated the soil, it moves downward into the soil profile by the process of percolation. Both saturated and unsaturated flows are involved in the percolation of water through the soil. Saturated flow occurs when the soil pores are completely filled (or saturated) with water, and unsaturated flow when the larger pores are filled with air, leaving only the smaller pores to hold and transmit water. Coarse-textured sandy soils have higher saturated permeability than fine-textured soils, because they typically have more macropore space. Medium-textured soils, such as loam or silt loam, tend to have moderate to slow saturated permeability.

If irrigation methods or application rates used on a site are high for the application of vegetable processing wastewater, infiltration rate testing may be warranted, especially for sites that could be prone to runoff, erosion, or extensive ponding. Infiltration tests can be conducted using cylinder infiltrometers, basin infiltration tests, or other methods (USEPA 2006). These tests can be a part of the site investigation. Irrigation systems should be designed to deliver water at a rate that is less than the infiltration capacity of the soil to minimise runoff or excessive percolation.

4.3.6. Chemical properties

Vegetable processing wastes often contain nutrients and/or organic matter that can improve soil chemical, physical or biological properties of agricultural land. However, there are several soil chemical characteristics that may need to be checked initially and/or monitored periodically during land application to ensure that soil quality is not degraded, and that toxicity to crops is prevented. These characteristics include: pH; cation exchange capacity (CEC); organic content; salinity; and micronutrient and macronutrient concentrations. Among all soil chemical characteristics, pH is the most important and influences various properties including nutrient availability, functioning of microorganisms and fate and transport of many contaminants. Typically, a soil pH between 5.5 and 7 is optimal for nutrient availability to plants. The ability of a soil to resist changes in pH as a result of land application of vegetable processing wastes or other activities is termed its buffering capacity. The buffering capacity of a given soil increases with increasing organic matter and the cation exchange capacity (CEC).

The CEC of a soil is the sum total of exchangeable cations that may be adsorbed, and therefore, represents the nutrient holding capacity of a soil. The CEC is primarily due to the clay minerals present and organic matter content. The contribution of organic matter to CEC, on a weight basis, is approximately four times as much as that from the clay fraction (Dubbin 2001). The CEC of soils tends to increase with increasing pH (Brady and Weil 2002). Checking the initial CEC of the soil is important in land application of vegetable processing wastes because leaching of cations from the applied water is more likely to occur in soils with low CEC (<5 cmolc/kg) (USEPA 2006). In contrast, leaching is reduced in soils with high CEC (>10 cmolc/kg). The organic matter content of soil influences the structure and formation of soil aggregates. Organic matter provides the energy substrate for soil microorganisms, which in turn aid in the formation of aggregates. In addition, the pH and buffer capacity of a soil is influenced by organic matter content. Soil organic matter has a high specific surface area and the majority of the surface soil CEC is attributed to organic matter. Because of the large amount of surface sites, organic matter is an important sorbent of plant nutrients, metal cations, and organic chemicals. The uptake and availability of plant nutrients, particularly micronutrients, is greatly affected by soil organic matter. Organic matter also forms stable complexes with polyvalent cations such as Fe^{3+}, Cu^{2+}, Ca^{2+}, Mn^{2+}, and Zn^{2+}, and decreases the uptake of metals by plants and the mobility of metals in the soil.

Soluble salts are generally composed primarily of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), chloride (Cl^{-}), bicarbonate (HCO_3^{-}), and sulphate (SO_4^{2-}). Sodium is the most problematic of all the ions released by soluble salts, because sodium disperses clay and organic matter, thereby degrading soil structure and reducing macropore space. Soils high in sodium, therefore, are poorly aerated and have reduced permeability to water. Soluble salts alter osmotic forces in soils and impede the uptake of water by plants. Deleterious effects of salts on plants are also caused by toxic concentrations of sodium and chloride. An indirect measure of soluble salt content in soils can be obtained by measuring the EC of saturation extract of the soil. An EC greater than 4 dS/m indicates a saline soil, and an EC of 2 to 4 dS/m indicates moderately high soil salinity. The threshold for yield effects for the most sensitive crops begins at about 1 dS/m (USEPA 2006). The EC of soil subject to land application of vegetable processing wastewater should be checked periodically as part of the soil monitoring program to ensure that potentially harmful and/or toxic concentrations of soluble salts are not present.

4.3.7. Nutrient concentrations

Concentrations of the macronutrients, nitrogen, phosphorus and potassium, and the micronutrients calcium, iron, magnesium, sulphur, manganese, molybdenum, zinc, copper, and boron should also be monitored in soils irrigated with vegetable processing wastewater (USEPA 2006). The purpose of this monitoring is to ensure that hazardous or potentially toxic levels of nutrients do not accumulate and that sufficient concentrations are available for plant growth. In addition, application of excess nitrogen can result in leaching of nitrate to groundwater. The recommended frequency of monitoring for these elements and compounds will vary depending on the characteristics of the soils and the chemistry of the vegetable processing wastewater being applied.

4.4 Hydrogeology

Hydrogeology is a critical component of the land application site (Brown and Caldwell 2007). It determines the fate of water and constituents that have leached through the soil profile. All readily available information on hydrogeologic factors should be compiled for a land application site, including: existence, depth, and characteristics of impermeable layers; depth and quality of the groundwater; depth, thickness, and characteristics of clay and sand/gravel layers down to and including the layers tapped by production wells in the area; publicly available regional hydrogeology reports; groundwater levels, quality, and beneficial uses for monitoring and production wells on or near the site (Brown and Caldwell 2007).

4.5 Crop selection

Vegetation plays an important role in a land treatment system, by recycling water and nutrients in the vegetable processing waste into a harvestable crop. Plant uptake is not the only form of nutrient transformation or removal from the soil-plant systems utilised in land treatment, but plant growth does impact on all mechanisms either directly or indirectly. Plants also play a role in providing cover, preventing erosion, stabilisation of the soil matrix and help maintain long-term infiltration rates. In slow rate systems designed for agricultural reuse, nitrogen generally is the limiting nutrient, which controls the design and establishes the required size and loadings for a particular land application system (Crites et al. 2000).

In general, crop varieties are selected depending on growing seasons, moisture availability, soil type, winter temperatures, and incidence of plant diseases, infrastructure for post-harvest processing and demand for harvested by-product. A regional approach, therefore, is usually recommended for selection and management of crops at land application sites (Jensen et al. 1973). Crops are often selected for their propensity for uptake of a certain nutrient or for use of large quantities of water. Ensuring good health and growth of the crop is vital to maximise nutrient removal and maintain soil productivity.

4.5.1. Nutrient uptake

A comprehensive nutrient management plan for a land application system is to balance between the nutrients required for plant growth and subsequent nutrient losses. Nutrient uptake is related to dry matter yield. Nutrient loading should be balanced to avoid yield reductions and environmental degradation. Nitrogen (N) is often the limiting design factor in a land application system. Some crops are heavy users of nitrogen. The relationship of nutrient availability and yield is non-linear (USEPA 2006). If the nitrogen loading is reduced to half of the expected uptake, it cannot be assumed that half the uptake will result. The actual yield and nutrient uptake will be a function of the initial soil reserve and resulting nutrient stress. Crop residue, straw, and other matter that is left in the field after harvest, will eventually contribute a portion of the nutrients back into the soil. Soil and plant tissue analysis can help determine nutrient deficiency and proper nutrient loading.

The highest uptake of nitrogen, phosphorus, and potassium can generally be achieved by perennial grasses and legumes. It should be noted that whereas legumes normally fix nitrogen from the air, they will preferentially take up nitrogen from soil-water solution, if it is present (USEPA 2006). The potential for harvesting nutrients with annual crops is generally less than with perennials because annuals use only part of the available growing season for growth and active uptake. The nutrient removal capacity of a crop is not a fixed characteristic but depends on the crop yield and the nutrient content of the plant at the time of harvest (USEPA 2006). Design estimates of harvest removals should be based on yield goals and nutrient compositions that local experience indicates can be achieved with good management on similar soils. The effectiveness of different crops in taking up soil nutrients depends on the total dry matter yield, plant ability to accumulate nutrients, and seasonality of production.

4.5.2. Salt uptake

In addition to nitrogen, crops also take-up other dissolved minerals including phosphorus, potassium, calcium, magnesium, and sulphur. These dissolved minerals can be measured as the portion of the ash content of the plant. The ash content is approximately 10% of the dry mass of the plant, so increased yield directly correlates to salt uptake (USEPA 2006). The uptake of the constituents that make up total dissolved salts is dependent on the crop type and the crop yield. To determine the salts removed by the harvested crop, test the tissue samples for ash (mineral) content and multiply the results times the yield.

4.5.3. Agricultural crops

Many common agricultural forage and field crops can be used in land application systems. For example, lucerne removes nitrogen and potassium in larger quantities and at a deeper rooting depth than most agricultural crops. Maize is an attractive crop because of its potentially high rate of economic return as grain or silage. The limited root biomass early in the season and the limited period of rapid nutrient uptake, however, can present problems for nitrogen removal. Prior to the fourth week, roots are too small for rapid uptake of nitrogen, and after the ninth week, plant uptake slows. During the rapid uptake period, however, maize removes nitrogen efficiently from applied waste (D'Itri 1982).

4.5.4. Forest crops

Tree crops can also be used land application systems. Vegetative uptake and storage of nutrients depend on the species and forest stand density, structure, age, length of season, and temperature. In addition, there is also nutrient uptake and storage by the understory tree and herbaceous vegetation. The role of the understory vegetation is especially important in the early stages of tree establishment. Forests take up and store nutrients and return a portion of those nutrients back to the soil in the form of leaf fall and other debris. Upon decomposition, the nutrients are released and taken up by the trees. During the initial stages of growth (1 to 2 yr) biomass production and nutrient uptake are relatively slow. To prevent leaching of nitrogen to groundwater during this period, nitrogen loading must be limited or understory vegetation must be established that will take up and store applied nitrogen that is in excess of the tree crop needs (USEPA 2006).

More information on selection of crops for a wastewater land application system may also be found in the New Zealand Guidelines for Utilisation of Sewage Effluent on Land (New Zealand Land Treatment Collective 2000).

5. LOADING RATES AND SYSTEM DESIGN APPROACH

Loading rates of vegetable processing wastewater in land application systems may be controlled by one of a number of factors (Crites et al. 2006): nitrogen, organic, hydraulics, or salt. Correct loading in a land application system should

- allow for sufficient retention time of the applied water in the aerobic zone of the soil to achieve oxidation of organics,
- manage salts to prevent build-up in the root zone and unreasonable degradation of underlying groundwater, and
- utilise the nutrients and process water while balancing optimum treatment capacity and reuse (Crites et al. 2006).

Nitrogen and/or organic materials are the common rate-limiting constituents for application of vegetable processing waste. The seasonal nitrogen loading must balance with crop uptake and other nitrogen losses from the system. Total organic (BOD) loading rate limits should be determined on a site specific basis after considering soil infiltration rates, resting time between applications, and the applied BOD. The goals of a proper design for organics are effective stabilisation of the organics, minimisation of reducing conditions that could mobilise trace metals and minimisation of the potential for nuisance odour and vector conditions (USEPA 2006).

Salt accumulation in the root zone needs to be managed so that crop production and groundwater quality are not adversely affected. Salinity in applied vegetable processing waste can be reduced by securing a better water supply, source control, alternative chemical usage, and/or treatment. Where supplemental water is necessary to meet the irrigation demand of a crop, its effect will typically reduce seasonal loadings and seasonal average concentrations. Acceptable suspended solids loadings vary with the method of application. Excess suspended solids loading can cause soil plugging and anaerobic mats on the soil surface with surface irrigation.

5.1 Design approach overview

The overall design approach for a land treatment system for vegetable processing waste is to determine the limiting factors and design a system that will adequately treat those limiting factors and/or will meet the standards of a desired risk category (USEPA 2006). The approach typically includes selecting a site and crops and designing pretreatment facilities and an irrigation system. Each of these elements may have an effect on the limiting factors.

5.2 Water quality risk

During the process of designing a land treatment system, many potential factors that may impact groundwater quality need to be considered. Loading rates of major constituents of concern are perhaps the easiest risk factors to quantify and measure (USEPA 2006). Risk factors can be used to establish the necessary intensity of planning, operational management, and monitoring for vegetable processing waste reuse systems. "Agronomic" loading rates mean constituents beneficial to crops applied in net amounts equal to what is utilised by the crops. The constituents not beneficial to crops are applied at rates comparable to local farming practices utilising fresh water.

5.3 Nitrogen loading

Nitrogen loading should always be evaluated as a potential limiting loading rate because of the relatively high total nitrogen content of vegetable processing waste, and the potential for nitrate to be transported into the groundwater. However, because of the potentially high carbon to nitrogen (C:N) ratio of vegetable processing waste, significant denitrification and immobilisation of nitrogen may occur in the soil (Whitehouse et al. 2000). The New Zealand drinking water standard for nitrate-nitrogen is 11.3 mg/L (Ministry of Health 2005).

When applied to the soil, nitrogen in vegetable processing wastewater goes through transformations - both chemical and biological, and they are a function of temperature, moisture, pH, C:N ratio, plant interactions, and equilibrium with other forms of nitrogen (USEPA 2006). Organic nitrogen in vegetable processing wastes will mineralise to ammonium after a period of a few weeks after application and lasting up to a few years. Nitrogen becomes available usually more slowly than nitrogen from chemical fertilisers. Therefore, nitrogen balances with vegetable processing waste are generally assessed on an annual basis. Soil solution nitrate monitoring is recommended to provide site-specific data on how quickly applied organic nitrogen is being converted to nitrate and leached.

Ammonium can be lost partially to volatilisation after becoming ammonia, especially if high concentration of ammonium is on the soil surface with a high pH value. The remaining ammonium can be oxidised to nitrate in the soil, adsorbed to soil, immobilised by bacteria, or taken up by plants. Under excessive loading conditions, some ammonium can be leached to shallow groundwater, particularly in sandy soils.
In oxygen deficient (anoxic) conditions, some bacteria will effectively take oxygen from available nitrate and release the nitrogen as nitrogen gas through the denitrification process (Parkin 1987). Nitrate may also be used by microorganisms and/or taken up by plants. Excess nitrate may be leached from the soil profile into the underlying groundwater. During and immediately after land application by flooding, soils become temporarily deficient in oxygen causing a large proportion of nitrate to be lost to the atmosphere through denitrification (Parkin 1987).

Sprinkler irrigation tends to keep soil more aerobic than flood irrigation, resulting in relatively less denitrification than with flood irrigation. Leach and Enfield (1983) found an average of 15% nitrogen removal by denitrification with rapid infiltration of municipal effluent using sprinklers on short cycles compared with 30% to 80% nitrogen removal by denitrification with surface flooding on two to seven day cycles. Some denitrification continues to occur in well-drained soils in water filled pores creating anoxic microsites in the immediate vicinity of the decomposing organics (Parkin 1987). Denitrification proceeds at a progressively slower rate at temperatures below 20°C and practically ceases at 2°C (Stevenson 1982). Denitrifying bacteria are sensitive to low pH environment and their activity in acidic soils (<pH 5) is greatly

restricted (Stevenson 1982). The denitrification process is dependent on carbon availability and has been correlated to the amount of mineralisable carbon during seven days of incubation (Paul and Clark 1996).

Soil microbes metabolise the organic materials in the vegetable processing wastes. Microbes are about eight parts carbon to one part nitrogen. Because of the metabolic inefficiencies, about 1 part nitrogen is required to metabolise every 24 parts of carbon. When the C:N ratio exceeds 24:1, microbes tend to keep most available nitrogen in their bodies and leave little inorganic nitrogen available in the soil (Magesan et al. 1999). While the limited available nitrogen will reduce the risk of nitrate leaching, it can also limit plant growth (Brady and Weil 2002).

Microbial growth on readily available carbon in vegetable processing wastewater normally leads to an increase in active soil organic matter, which supplies readily mineralisable nutrients. Continued cycling of carbon generates more complex enzymes and other polysaccharides that are precursors to stable humic material, or soil organic matter (Paul and Clark 1996). Soil humus is relatively resistant to decay and contains a significant portion of immobilised organic nitrogen. The soil humus has a half-life of hundreds of years and is 60 to 90% of the soil organic matter (Brady and Weil 2002). Soil humus also helps to improve soil structure, enhance percolation in clay soils and moisture retention in sandy soils, and increases the cation exchange capacity and metal retention capacity in all soils. A soil with 1.5% organic matter, consisting of 80% humus with a C:N ratio of 10:1, will have nearly 1,200 mg/kg of immobilised nitrogen (USEPA 2006). As more research becomes available on practices that optimise the conversion of organic matter into soil humus, these practices should be incorporated into vegetable processing waste application site management.

5.4 Organic loading

The soil ecosystem removes biodegradable organics in vegetable processing wastes through filtration, adsorption, and biological reduction and oxidation (Whitehouse et al. 2000). Most of the biological activity occurs near the surface where organics are filtered and adsorbed by the soil, and where oxygen is present to support biological oxidation. However, biological activity will continue with depth even under oxygen deficient or anaerobic conditions if a food source and nutrients are present, but at slower rates (USEPA 2006). The acclimation of soil microbial populations for assimilation and treatment of waste-derived organics is essentially not a limiting factor in well aerated soil conditions.

Generally, excessive organic loading can result in odorous anaerobic conditions, incomplete removal of organics in the soil profile, mobilisation of iron, manganese, and other elements, and increases in bicarbonate concentration in the soil solution via carbon dioxide dissolution (USEPA 2006). Maintaining an aerobic upper soil profile between irrigations is managed by organic loading, hydraulic loading, drying time, and cycle time; not organic loading alone. However, if nitrate reduction is a treatment objective, some duration of anoxic conditions during each irrigation cycle is desirable.

5.4.1. Organic loading rate risk categories

The acceptable BOD loading rate for a site can be affected by soil type and permeability, soil drainage, method of application, depth to groundwater from the soil surface, temperature, and presence or absence of a cover crop (Crites, et al. 2000). Soil type and permeability are important because the faster the drainage of soil pores after an application, the sooner the oxygen can re-enter the soil and re-establish aerobic conditions. Soil temperature influences the activity of soil microorganisms (Crites, et al. 2000). Vela (1974) found that although soil microbial activity drops in colder weather, the number of soil microbes can increase so that overall organics removal is still effective.

Compared with flood irrigation, sprinkler application is more conducive to re-oxygenation of the soil because the distribution is more uniform, can be much shorter in duration and does not necessarily result in saturated soil conditions. On the other hand, fallow land will generate less oxygen demand than cropped land. Some special situations, such as heavy and/or compacted soils, may reduce oxygen transfer substantially.

5.5 Hydraulic loading

When vegetable processing wastewater has been adequately treated at the facility, the hydraulic loading rates for slow rate land application systems are generally similar to loading rates for clean irrigation water. Slow rate land application systems may have periods during the year when hydraulic loading rates exceed crop needs, but during most of the year the goal is to satisfy crop needs (USEPA 2006). Providing adequate water for plant needs is accomplished by maintaining a soil moisture content of between 50% and 100% of field capacity between irrigations (USEPA 2006). The design hydraulic loading rate is a function of crop evapotranspiration, irrigation efficiency, and desired leaching rates. Some factors that can limit hydraulic loading of vegetable processing wastewater to below normal irrigation rates are: the depth applied in a single irrigation; a very high BOD concentration. Standing vegetable processing wastewater for extended periods of time creates an oxygen deficit in the root zone, potentially odorous conditions and environments for mosquito breeding.

5.6 Salt loading

Vegetable processing waste usually contains elevated concentrations of total dissolved solids. They are typically a result of the products themselves and are utilised in the production of foodstuffs. Typically 40 to 70% of the dissolved solids are organic (Brown and Caldwell 2007). These organic dissolved solids in vegetable processing waste include proteins, carbohydrates and organic acids from the raw products. Organic dissolved solids are readily decomposed in the soil profile, as contrasted with inorganic dissolved solids that are conservative in nature. Conversely, some of the carbon dioxide from the breakdown of organics can increase concentrations of bicarbonate in soil solution (USEPA 2006).

Plant macronutrients, such as ammonium and nitrate, phosphorus, potassium, calcium and magnesium, are part of the inorganic dissolved solids and to a significant degree are removed in land application systems that incorporate growing and harvesting of crops. Sodium, chloride, sulphate, and other ions are also taken up by crops in varying amounts. The remaining inorganic dissolved solids are either leached from the soil profile or precipitate out into non-soluble forms. When inorganic dissolved solids accumulate in soils, they increase the osmotic stress in plants. This can reduce yields and prevent seed germination (USEPA 2006).

Salts in excess of crop uptake are applied even in good practices in a land application system, because there is no reasonable way to control the salt sources. Therefore, leaching of these excess salts is required to limit salt build-up in the root zone. The leaching requirement is the ratio of deep percolation to the applied water. The same ratio exists between the concentration of conservative mineral salts applied and the concentration of conservative mineral salts in the percolate. Sometimes EC values can overstate the potential for impact on groundwater salinity in food vegetable processing waste because of degradable conductive organic acids present in the wastewater that will be decomposed in the soil.

In addition to crop sensitivity considerations, groundwater quality impacts from the salinity of drainage water may need to be monitored, especially for vegetable processing waste with significantly elevated salinity. Groundwater uses, quality and flux beneath the site should be reviewed to assess the potential impact of leachate.

Usually some mineral ions have greater impacts on beneficial uses than others. For example, sodium in water used for irrigation can be particularly damaging to soil structure while calcium and magnesium can actually be beneficial. Vegetable processing waste that is relatively high in calcium, bicarbonate, and sulphate will also tend to encourage the precipitation of those minerals in the soil, reducing the total salinity of percolate by 30% or more for up to several decades (Jury and Pratt 1980). Potassium can be beneficial for irrigation and other uses, being an essential nutrient for both plant and animal health. Where minerals are added to vegetable processing waste for specific purposes (such as in cleaning products), substituting minerals with beneficial characteristics (such as potassium, calcium, and magnesium) for minerals with adverse characteristics (e.g., sodium) can help in making the project environmentally acceptable by reducing the concentrations of the least desirable ions that actually applied to soil.

5.7 Settleable and suspended solids

Land application systems are effective for the removal of settleable and suspended solids through filtration. Settleable solids may include coarse solids, such as peelings and chips, or fine solids such as silt and clay. Settleable solids only limit sprinkler or drip irrigation to point that they may clog nozzles and drippers. When border strip irrigation is used, suspended solids often deposit heavily within the first 3 to 5 m down the strip (USEPA 2006). The high deposition of solids forms a mat that prevents oxygen diffusion and results in odour-causing anaerobic conditions. Because of the potential for solids matting, border strip irrigation should not be employed when total settleable solids exceed 10 ml/L (USEPA 2006). In practice, sprinkler irrigation is best for high concentrations of settleable solids.

5.8 Acidity loading

Most plants grow well with the soil pH near a neutral condition. Wastewater with a range of pH between 3 and 11 has been applied successfully to land application systems (USEPA 2006). Extended duration of low pH (<5.5) can change the soil fertility and lead to leaching of metals (Sparks 2003). When the acidity is comprised of mostly organic acids the soil water will be neutralised as the organics are oxidised. The acidity of vegetable processing wastewater can be characterised with total acidity using units of mg $CaCO_3$/L. The total acidity represents the equivalent mass $CaCO_3$ required to adjust the pH to a specific pH, commonly defined as 7.0. The buffer capacity represents the soils ability to neutralise an equivalent amount of acidity, and is reported as mg $CaCO_3$/kg. A balance between the total acidity applied in vegetable processing wastes and the buffer capacity of soil can indicate the capacity of the soil to effectively neutralise the acid in the wastewater. Most field crops grow well in soils with a pH range of 5.5 to 7.0. Some crops, such as asparagus and cantaloupes, with a high calcium requirement prefer a soil pH greater than 7.0. If the pH of the soil begins to drop, liming materials are required to return the pH to the desirable range for optimal crop production. Because of the soil's ability to treat large amounts of organic acids, it is recommended that pH adjustment of vegetable processing waste only be considered for extreme pH conditions (pH < 4.5 or > 8.5) (USEPA 2006). On the other hand, the effects of additional salt loading should be evaluated if chemicals are used for pH adjustment.

5.9 Incorporating loading rates into design

The planning and design of land application systems is not a linear process because of the interrelated elements and site specific conditions (USEPA 2006). It is a common practice that the designer performs estimates based on initial assumptions and then refines each element of the land application system until the total system design is optimised. The potential water quality risks should be taken into account during all phases of system planning and design.

5.9.1. Hydraulic loading rate evaluation

A preliminary hydraulic loading rate evaluation is usually the initial step in a planning or design process. This should be performed using typical crops grown in the region. The hydraulic evaluation (also known as "water balance") should be performed on an average month-by-month basis. The result of this initial evaluation is an estimate of the land area required for vegetable processing waste flows.

5.9.2. Pretreatment selection

For vegetable processing wastewater, a minimum level of pretreatment with parabolic static screen or rotary drum screens is usually economically justified. Therefore, screening of vegetable processing effluent should be a component of the system design for initial solids removal. The organic reductions from this level of pretreatment should be considered in the estimate of organics in the land applied vegetable processing wastes.

5.9.3. Organic loading rate evaluation

An initial land area calculation should be performed for BOD. In some situations, lower target loading rates may be desired to reduce the risks with potential for less intensive management and monitoring.

5.9.4. Site selection

The irrigation site for vegetable processing waste reuse is typically selected based on size, proximity to the factory, soil, depth to groundwater, proximity to residences, and ownership considerations. The required size of the site can be initially estimated from the greater of the areas in the initial hydraulic and BOD loading rate calculations given above. One or more potential sites with sufficient size should be identified for further evaluation. Any site suitable for irrigated agriculture is feasible for land treatment of food vegetable processing waste. The availability of supplemental irrigation water can also be an important consideration in site selection.

5.9.5. Crop selection

Crops are typically selected to maximise water usage, maximise nutrient uptake and have good marketability locally. Crop cultural practices should also not conflict with the seasonality of wastewater flows from the vegetable processing facility. Several crops with promising characteristics should be selected during the evaluation.

5.9.6. Irrigation plans

One or more potential initial irrigation methods should be selected based on the initial crop selection and irrigation practices in the region. The selection of an irrigation method may also be dictated by the irrigation facilities pre-existing on the site. Settleable and suspended solids concentration and pretreatment process will also affect the choice of an irrigation system.

5.9.7. Refinement of design

A convergent trial-and-error process can be employed to derive an appropriately designed and sized land application system. After initial alternatives for the site, crops and irrigation systems have been identified, detailed calculations of limiting loading rates should be performed using the factors appropriate for the site (e.g. infiltration rate, field capacity, etc.). The costs of each reasonable combination of alternatives should be estimated. When a limiting factor is identified for each combination of alternatives, the designer can investigate additional ways to reduce the limiting constituent and the associated costs of reduction. Risks associated with major constituents should be considered because lower loading rates may reduce ongoing regulatory compliance related costs while providing better utilisation of water and nutrients. A preferred combination of pretreatment-site-crop-distribution alternatives should become apparent and decided.

6. VEGETABLE PROCESSING WASTE DISTRIBUTION SYSTEM

Once a land application system has been designed conceptually, the detailed engineering aspects of system layout, configuration, and construction follow standard engineering practices. Crites et al. (2000) have provided a guidance document for municipal and industrial land application systems that may be used as a reference. The New Zealand Guidelines for application of sewage effluent onto land (Whitehouse et al. 2000) provides a comprehensive guide to determine irrigation requirements and adequate equipment. Commonly used equipment for successful operation of land application system for vegetable processing wastes are described below.

6.1 Distribution system planning

Irrigation system selection and operation are generally treated in the same way for conventional irrigated agriculture and vegetable processing waste land application (Whitehouse et al. 2000). The difference between these two systems is the requirement of nutrient/salt loading restrictions of vegetable processing waste. Vegetable processing waste discharge often occurs over a longer season than conventional irrigation, resulting in waste application in the autumn and winter (or year-round) when irrigation requirements are usually low (USEPA 2006). In addition, maximizing irrigation efficiency is not always the optimum approach for managing vegetable processing waste. Environmental monitoring, in addition to agronomic monitoring, is generally required for land application systems.

A critical factor for existing processing facilities considering land application is identifying available area with suitable soils near the facility. Irrigation rates and the recommended frequency of application generally differ between vegetable processing waste land application and conventional irrigated agriculture (USEPA 2006). Crop selection is often determined by operational needs of the land application system. For example, forage grass for silage or hay may be chosen over crops with a higher rate of financial return because forage management is more flexible and will not interfere with irrigation schedules.

6.1.1. Land area requirement

A preliminary evaluation of vegetable processing waste quantity and quality is used to assess land area requirements at the planning stage. The method used to assess land area required involves determining the limiting factor for land application (Crites et al. 2000). For vegetable processing waste, the limiting factor is generally hydraulic loading, nitrogen application, or organic (e.g., BOD) loading.

Vegetable processing facility flow can vary throughout the year. The designer must determine the season in which the most restrictive flow conditions exist. Area planning should take into account additional capacity requirements for future facility expansion. A conservative water application rate should be assumed during the preliminary area calculations. As discussed previously, other vegetable processing waste constituents may limit loading and require a higher minimum area. If another constituent is limiting, then the area calculation for that constituent should also be used for preliminary estimation of land area requirements.

It is a common practice to increase the minimum estimated required area by up to 25% to account for buffer zones, unsuitable areas, and other factors. It is prudent to have an additional 25% of the minimum area available so that crop rotation, use of fallow seasons, resting periods between irrigation cycles, accommodating long return period wet year runoff, and use of crops that will not accept vegetable processing wastewater can be part of the cropping strategy for the facility (USEPA 2006). In addition, irrigation area could be sized to accommodate future projected flows from the facility. This is particularly important in situations where availability of suitable area may become scarce in the future.

6.2 System components

The system components of the vegetable processing waste distribution system include: an in-plant collection system that routes water to a common collection point; pretreatment and storage devices; a pumping station to move water from the facility to the irrigation system; primary transmission lines to carry wastewater from the facility to the land application fields; cropping areas used for land application; a distribution system (pipelines, ditches, or both) including booster pump stations, if required; in-field irrigation system (Brown and Caldwell 2007). Each of these components should be designed using standard engineering practices and should also address regulatory and operational safety requirements. In some situations, additional transport may be necessary, particularly when the land application site is far from the facility.

6.3 Irrigation systems

A variety of irrigation systems may be used to distribute vegetable processing wastes. Irrigation systems fall generally into four broad categories: surface application, spray irrigation, drip irrigation, and direct injection. Each of these system types has a place in vegetable processing waste land application programmes, although drip irrigation is limited in applicability (USEPA 2006).

6.3.1. Surface application systems

Surface application systems are commonly used when initial capital expense and energy consumption needs to be minimised. A basic requirement for the surface irrigation method is a land area that must be generally flat. Most systems operate best at slopes of less than 2%, although slopes up to 8% can be accommodated with appropriate design (Brown and Caldwell 2007). Common surface irrigation methods include flood irrigation, border-strip irrigation and rill or furrow irrigation.

Flood irrigation. This is the most basic method in which wastewater is turned out into a field with minimal distribution or control of the flows. Water is allowed to move downward through the soil and across the field, until irrigation is completed. The lack of control with flood irrigation systems makes their use inappropriate for vegetable processing waste management.

Border-strip irrigation. These systems are refined from flood irrigation by adding an element of control to the application amount and locations within the field. Border irrigation fields are smooth or levelled to create a favourable environment for surface water flow, and are at slopes of 2 percent or less (USEPA 2006). Irrigation water is applied to the field at one end and it flows due to gradient through the field to the far end. Border strips are typically 12 m wide and 150 to 300 m long (Borrie and Mcindeo 2000). Border irrigation is best suited for continuous canopy crops (not row crops), such as pasture, grasses, and trees. Careful management and supervision of the application operation is required to provide adequate results, including uniform applications over the irrigated area and determination of the actual amount applied.

6.3.2. Spray irrigation systems

Spray irrigation systems are a flexible alternative to surface irrigation systems. These systems deliver water under pressure to the land surface via nozzles that provide a relatively uniform distribution of water (USEPA 2006). Spray irrigation systems are often regarded as an improved irrigation system with respect to surface irrigation methods because they cover the entire field surface, do not require land levelling, have higher irrigation uniformity and efficiency, and do not have a tailwater collection requirement. Spray systems require pressure to operate, are affected by wind, may require buffers in populated areas, and have higher capital and energy costs than surface irrigation systems (USEPA 2006). The common types of spray irrigation systems used in land application are solid set sprinklers, movable systems, “Big gun” systems, and mechanical move irrigation systems.

Solid set sprinklers. These sprinklers and associated piping are placed permanently in fields to provide the necessary water supply for crop production, so that no equipment needs to be moved. Generally, all pipes are buried below ground, and sprinklers are placed on permanent risers. Irrigation application rate for these systems is controlled by selection of appropriate nozzles to deliver the required irrigation amount. Based on the system pressure (in the range of 35 – 85 psi) and sprinkler characteristics, the spacing of nozzles with respect to each other can be calculated (USEPA 2006). In general, common spacing for sprinkler heads ranges from 10 m on centre to 27 m on centre (USEPA 2006). Depending on design details, these systems can deliver up to 25 mm/hour over a field. Designs should be performed by professionals following conventional methods (Pair 1983). Because solid set systems are always in place in the field, the labour required to implement irrigation is low. However, the presence of permanently installed sprinklers creates challenges for crop management and harvest.

***Movable sprinkler systems*.** There are a wide variety of movable sprinkler systems that operate in a way similar to that of solid set sprinklers. These sprinklers can be moved from location to location in the field, and, while the sprinkler is in a single position, irrigation of that area can be accomplished.

Long-lateral systems (also known as bike-shift or long-line systems) consist of permanently buried mainlines and movable sprinklers on sleds connected to the mainline with polyethylene hose. The sprinklers are moved manually around a number of positions to cover the area. K-line systems consist of moveable sprinkler lines that are connected to permanently buried mainlines. These sprinkler lines consist of a polyethylene pipe with sprinklers spaced at approximately 15 m intervals. The movable sprinkler irrigation systems have the advantages of less capital expense for irrigation equipment and they provide unimpeded access for cropping. The disadvantage is that the system requires labour for movement to irrigate an entire field.

***"Big gun" systems*.** These systems rely on a very large sprinkler nozzle operating at a high pressure to apply irrigation water to a relatively large area. For a relatively low capital expense, a relatively large area can be irrigated. In addition, big guns have the capacity to irrigate non-level ground. Big gun irrigation systems can be constructed with fixed gun locations in an irrigated field or can be movable. Movable systems include the big gun are moved manually to different irrigation risers. Another popular movable irrigation system is the 'travelling big gun.' A hose reel attached to the big gun is laid out and the sprinkler, when activated, returns along the hose line path by means of either hydraulic pressure or an additional motor supplying power to roll up the irrigation hose and move the sprinkler.

Centre pivot and linear move irrigation systems. Centre pivot irrigation systems operate from a central water supply with a movable irrigation lateral that travels in a circle around the pivot point (USEPA 2006). The lateral is supported above the crop on wheeled towers approximately 50 m apart. Such irrigation systems are moderately expensive for initial capital cost, but have very low maintenance and manpower requirements and can be simply operated from a central location. Centre pivots may be fixed permanently in one position or towed to various positions. They can be easily automated and controlled from a central point. Because of the potential for high frequency applications, centre pivots often provide the most aerobic soil conditions of all vegetable processing waste application techniques. Centre pivots also have relatively high instantaneous application rates, making them unsuitable for use on some low permeability soils (USEPA 2006).

Spray irrigation technology is quite popular in the agricultural sector, and operating guidelines and practices are well developed. Sprinkler systems provide both good irrigation efficiency and irrigation uniformity when compared with surface irrigation systems. Spray systems require pressure for efficient operation. However, low pressure systems are increasingly being developed to increase energy efficiency and decrease water losses.

6.3.3. Drip irrigation systems

Drip irrigation system makes use of small irrigation nozzles operating at low pressure and placed adjacent to crops. Drip irrigation systems are frequently used in areas where water supply is scarce. They are especially appropriate for row crops and tree crops where locations for irrigation do not cover the entire land area. Drip irrigation systems commonly operate at low pressures and relatively low flow rates, relying on longer sets to supply needed irrigation amounts (USEPA 2006).

There are two types of drip irrigation, namely surface drip and subsurface drip. Both surface and subsurface drip systems have buried mainline pipes. Laterals for surface drip irrigation are placed on top of the ground, while laterals for subsurface drip irrigation are buried from 100 mm to 900 mm below the surface depending on the crop type (Borrie and McIndeo 2000). Even highly treated vegetable processing waste may have sufficient solids to cause line or nozzle plugging, making drip irrigation less common for vegetable processing wastewater irrigation (USEPA 2006).

6.3.4. Direct injection systems

Direct injection of vegetable processing wastes involves the use of a specialised tine implement that is towed by a tractor unit. As the tines are pulled through the soil a cavity is created into which the vegetable processing waste is injected. The waste is supplied to the tines either from a tank attached to the tractor unit or from a flexible pipe connected to a stationary tanker.

Direct injection systems are most suited to situations where there is odorous and high strength vegetable processing wastes. Direct injection systems have negligible potential for the creation of odours and aerosols. However, these systems require high energy and operating expenses. The number of repeat applications to an area of land is limited by the need to avoid disturbance to the growing crop (Borrie and Mcindeo 2000).

6.4 Site characteristics

Design of land application system for vegetable processing wastewater can be influenced by a number of site- and facility-specific factors. The key site layout factors are field size, field shape, and slope. Surface irrigation methods are only suited to relatively flat sites because they rely primarily on gravity flow. Sprinkler and drip systems do not have particular limitations related to slope. Field size is limited for these systems because, if fields become too large, supply pipelines and pumping capacity also become expensive. The important soil properties that influence system selection are infiltration rate, soil texture, and soil water storage capacity. Application rates need to be matched to the soil infiltration rates for both sprinkler and surface systems. Soil water storage capacity is required to hold irrigation water in the crop root zone. Fine textured soils with a large storage capacity can be irrigated less frequently than coarse textured soils. Climate is also a key factor in determining irrigation strategy, because it affects overall irrigation requirements and also affects timing and duration of irrigation. Generally, any irrigation method must account for precipitation as well as evapotranspiration (Whitehouse et al. 2000).

6.5 Irrigation system management

The challenge for irrigation scheduling is to manage irrigation to meet but not exceed both hydraulic and constituent loading rates. The challenge for crop management is to produce marketable crops while meeting the requirements of environmental protection. While typical agriculture generally sets a crop plan based on projected sale price and potential to make a profit, land application systems have this goal as a secondary priority. It may be optimised by having a crop mix that allows the farm manager to irrigate all the vegetable processing wastewater without damaging crops or overloading any fields in the process (USEPA 2006).

7. SITE MONITORING

To ensure an effective land application system and protection of groundwater, site monitoring is a critical part of operating and managing a vegetable processing waste land application system. Routine land application site monitoring and documentation for key system components should be established. Ongoing data management, evaluation, and record keeping for key system components are critical to the success of a monitoring programme (USEPA 2006). For best results from a monitoring programme, data collected from both short-term and long-term observations should be integrated and evaluated over time (USEPA 2006), which can provide guidance for operational adjustments and modifications where necessary.

7.1 Monitoring programme framework

A number of land application system design documents (e.g., Crites et al. 2000; USEPA 2006; Brown and Caldwell 2007) may be used as references for developing detailed monitoring programmes. Each of these addresses monitoring in a general way. Operational monitoring and compliance monitoring are two objectives of a monitoring programme. Operational monitoring is typically conducted by the personnel responsible for operating the land application system, and includes both quantitative and qualitative observations and other data required to document process control (Brown and Caldwell 2007). These observations may include details regarding functioning of the physical infrastructure, as well as crop management issues, including both field management and irrigation. During the course of monitoring, the observer will learn more about the behaviour of the land application system, and this often leads to developing improved operating procedures or adjusting equipment to improve system performance. Common modifications based on operational monitoring can include changing irrigation practices; scheduling harvest, replanting, and other crop management activities; scheduling preventative maintenance and repair; and expanding or improving the system. By providing system feedback on a regular basis, operational monitoring serves an important “early warning” function. Minor problems that are identified quickly can be corrected before groundwater or cropping impacts are incurred.

Compliance monitoring is intended to provide system operations documentation for regulatory oversight and compliance with the regulatory requirements. This typically identifies points of compliance for monitoring both the vegetable processing waste and groundwater. Vegetable processing waste is monitored to allow determination of loading rates. Groundwater monitoring is conducted to assess whether water quality impacts have occurred that could be attributable to the applied water.

The scopes of monitoring activities for operational control and compliance overlap are often complementary. Compliance monitoring generally requires documenting system performance on a monthly or annual basis, while operational management observations are often gathered more frequently for short-term evaluation and decision-making. In addition, for a land application site with more than one field, field-by field flows and timing are recorded to determine loading rates for compliance monitoring. For operational monitoring, irrigation amounts are usually measured daily so that a decision about where to apply facility flows for the following day can be made. This decision relies on the additional information for a more in-depth analysis that takes into account time of the last irrigation, soil moisture status, current and projected weather conditions, cropping patterns, and scheduling needs for other fields within the land application programme.

Sampling plan. A well managed land application system is usually monitored according to a site-specific sampling and analysis plan (Brown and Caldwell 2007). This plan is developed to document and provide detailed guidance regarding monitoring requirements, analytical methods, sampling frequency, analysis, and reporting. The plan should contain a description of both measurement protocols for regulatory compliance and operations monitoring. The sampling plan should also address the key areas to be monitored, which usually includes soil, water, groundwater, and crops. For each of these, the plan should specify required measurements, frequency of measurements, location of sampling, and other special instructions. The sampling plan should also include procedures, instrument calibration, sample shipping and chain-of-custody procedures, review of data upon receipt, etc. Detailed supporting material, such as standard procedures for sampling, sample handling, and equipment calibration instructions can be included as appendices.

7.2 Water monitoring

7.2.1. Flow and volume measurements

Measurements of wastewater flow are required to determine irrigation volumes and field constituent loading rates. In addition, monitoring wastewater in storage and tracking climatic factors will enable a site water balance to be calculated (Brown and Caldwell 2007).

7.2.2. In-field irrigation wastewater measurement

For land application systems, total facility flow and the distribution of vegetable processing wastewater among irrigation fields (for facilities with multiple fields) should be measured. This is useful for calculating hydraulic and other constituent loadings for the land application area and to avoid application rates that would result in excessive leaching. The type of application method (surface irrigation, spray irrigation, drip or injection) influences the choice of in-field distribution monitoring method (Brown and Caldwell 2007). Flow measurement methods typically involve either direct or indirect measurement.

Direct measurement. For systems where vegetable processing waste is pumped to the field(s), the direct measurement flow meters are appropriate for in-field flow measurement. Use of hour-meters and estimation of flow from pump discharge and system pressure data is also feasible for estimating in-field distribution of water. Use of on-going pressure measurements in conjunction with this method is recommended (Brown and Caldwell 2007) because vegetable processing waste suspended solids may affect system pressures and water delivery by restricting flow in the pipelines or plugging sprinkler nozzles or gated pipe openings. Monitoring pressures in the field can be combined with performing on-going, routine maintenance/inspection of the irrigation system. When a surface irrigation method is used, flow measured in major distribution system pipes or ditches can be proportioned by area irrigated assuming that gated pipes or siphon tubes are set in a reasonably uniform manner.

Indirect measurement. Indirect measurement methods measure or estimate "net irrigation" or the amount of water actually reaching the field. Net irrigation accounts for losses between the point of discharge to the irrigation system (called "gross irrigation") and actual application in the field.

7.2.3. Climate monitoring

Climate data, particularly, precipitation and evapotranspiration information, are used to schedule irrigation and as input to some of the indirect methods of applied water monitoring discussed above. Local climate data can usually be obtained from the national weather service stations and other sources.

7.2.4. Vegetable processing wastewater quality monitoring

The requirements for vegetable processing wastewater quality data specified in the facility's monitoring programmes generally focus on data needed to calculate field loadings and for evaluating potential impacts to groundwater quality. The compliance monitoring programme must specify analytical procedures and frequency of monitoring (Brown and Caldwell 2007).

The sampling frequency should ensure a good characterisation of the applied wastewater. Generally, variability is an important factor in calculating permit limits, determining compliance and setting the monitoring frequency. With low variability in a data set, less monitoring is acceptable.

Sampling locations must be representative of the flow to be monitored. Vegetable processing wastewater quality can change from point to point within the distribution system, especially when storage is required. This variability needs to be considered when selecting sampling points. Samples can be collected as either grab or composite samples, depending on monitoring requirements and objectives. Grab sampling involves filling containers manually. When samples are intended to represent daily, weekly, or monthly conditions, 24-hour composite sampling is often used (Brown and Caldwell 2007). In a composite sample, vegetable processing wastewater is collected at several times or continuously with an automated device over the course of the sample collection period. These individual samples are combined into the composite sample, and a subsample is submitted for analysis.

7.3 Vadose zone monitoring

The vadose zone is the unsaturated subsurface zone that lies above the groundwater table. Land application sites need to be designed and managed such that the most effective soil chemical and physical treatment processes occur within the root zone. Some constituents may move downward into the lower vadose zone where monitoring data may be desired. The best use of vadose zone monitoring data is for trend analysis of constituents of concern throughout and below the root zone. However, this monitoring is difficult to accomplish in a consistent, reliable manner due to the variability of subsurface conditions (Brown and Caldwell 2007). Therefore, monitoring wells are the primary means of assessing groundwater quality for land application system compliance purposes, except for situations where well installation would be impractical from a cost and data utility perspective. For example, when the groundwater table is deeply below the land application site so that the groundwater quality would not likely be affected by surface activities for many years. In such cases the relatively more intensive soil monitoring in the vadose zone to provide an indication of ongoing effectiveness of land application to avoid unintended water quality impacts. Soil monitoring should also be conducted.

7.3.1. Soil monitoring

Soil analysis is an important part of land application site operational monitoring, especially for the vadose zone. Soil information is commonly used for a number of purposes: estimation of nutrient supply for crops; assessment of treatment efficiency of the soil plant system; evaluation of soil chemistry suitability for crop vigour and soil structure maintenance; soil water monitoring to support irrigation scheduling and soil water balance calculations; and assessment of the land application site condition over time. Soil monitoring results can be highly variable. For soil monitoring, samples should be collected at several depths within the crop root zone. At each depth, several samples should be taken to make a representative composite sample. Site conditions, variability, crop rooting depth, and management practices are also factors to consider when developing a soil monitoring programme (Brown and Caldwell 2007).

The basic soil chemistry analyses are general soil chemistry (organic C, pH and electrical conductivity, or EC), nutrient (e.g., nitrogen, phosphorus and potassium) accumulation, salinity and cation balance. Soil parameters can be compared with generally acceptable ranges. When values for soil parameters are outside these ranges, operational changes may need to be considered to assure ultimate protection of groundwater quality and crop productivity.

7.3.2. Soil water sampling

The soil water or soil solution is invariably defined as the soil interstitial water, its solutes, and dissolved gases (Litaor, 1988). In a land application system, the leaching of nutrients, especially nitrate and phosphate, through soil has been the subject of interest for many years because of its economic and environmental importance. Soil solutions sampled in the field by different methods may vary in volume and also in solute concentrations because they are held by the soil aggregates at different tensions, and various physical and chemical processes occur next to the solid-liquid interfaces (Magesan et al. 2008). The applicability of a certain method and device may depend on the purpose of the sampling. For example, when soil solution is related to mobile water in the soil environment, then soil solution composition can be used to predict the forms and amounts of chemicals that may reach ground and surface water through transport from the soil environment (Wolt 1994).

Different soil solution sampling methods and devices have been used extensively for almost a century (Litaor 1988; Wolt, 1994). The methods can be divided broadly into two groups: *ex situ* and *in situ*. Soil solution collected from soil samples that have been removed from the field is *ex situ* soil solution. Soil solution that is collected from the field by porous cup, pan, or wick type solution sampling (Goulding and Webster 1992), or through direct sampling of the drainage from lysimeters or mole-pipe drainage systems (Magesan et al. 1994) is *in situ* solution.

The suction cup sampling methods are designed to measure concentrations of constituents in the water in the vadose zone soil pores. Soil solution samples are collected from the device by applying a vacuum (generally for 24 hours prior to sampling), which draws soil solution into the suction cups and samples can then be collected. The sample is analysed to determine concentrations but interpretation of this result is complex.

Concentrations of constituents in samples from suction samplers are considerably affected by the moisture content of the soil. Samples taken from soil at saturation are much more representative of mobile water in the soil profile, while samples taken from partially drained or dried soil are more representative of tightly bound, immobile pore water (Brown and Caldwell 2007).

Suction samplers often appear to be a low cost monitoring choice because the basic sampling equipment is relatively inexpensive. This is often not the case when replicate installations to provide representative results and the requirement to provide an accompanying soil moisture content measurement are included in the cost of monitoring.

The more capital intensive pan, basin, and wick samplers offer some improvements over the suction samplers because they provide a solution sample that has been collected as a result of downward flow of water. They provide both a sample for chemical analysis and an estimate of water flow based on the volume of water collected. Depending upon soil characteristics and installation, these types of samplers can also be adversely affected by soil-water flow bypass and/or preferential flow. A comparison of vadose zone water sampling techniques may be found in a recent publication titled "Monitoring and sampling of soil solution in land based waste treatment systems" (Magesan et al. 2008).

7.4 Groundwater monitoring

The need for groundwater monitoring is dependent upon facility type and size, wastewater characteristics, management, loading rates, and aquifer and site characteristics. Groundwater monitoring provides a more reliable and accurate indication of conditions at the point of compliance. Groundwater monitoring programmes, which include sampling frequency and the required analytical parameters, may be established in direct consultation with the regulatory agency. Details regarding the establishment of a programme and methods for monitoring well construction, hydrogeologic evaluation and monitoring are based on agency guidelines and industry standards (Brown and Caldwell 2007). The general objectives of a groundwater monitoring programme are to develop a monitoring network to document background groundwater quality, depth to groundwater, and flow direction in the local area; to provide up-gradient and down-gradient groundwater monitoring locations so that potential facility impacts to groundwater can be assessed. There are circumstances where groundwater quality monitoring may not be necessary, for example when wastewater constituent loading rates are below levels of regulatory concern. A small facility with low-strength wastewater loaded at low discharge rates would have a limited potential to contaminate groundwater, therefore may not need as extensive a monitoring program as a larger facility that applies high-strength wastewater at high rates to land.

Generally, the number, locations and construction details for monitoring wells will depend on the size of the application area, loading rates and hydrogeologic conditions underlying the application site. Typically at least one up-gradient and two down-gradient wells are necessary, with a point of compliance near the down-gradient boundary of each contiguous land application area (Brown and Caldwell 2007). Monitoring well screens should also be placed to accommodate fluctuations in the groundwater table. For sites in sensitive areas (fragile groundwater resources, shallow water tables, etc.), monitoring wells are likely to be mandatory.

When determining well locations, approximate groundwater elevations and grab samples can provide useful information. The grab samples can provide important information on the range and variability of pre-existing or up-gradient groundwater quality. The number of monitoring wells needed at an application site generally correlates with the water quality risk potential on that site, which depends on the size of the area used for land application, regulatory requirements and the nature of the underlying aquifer. When groundwater monitoring is difficult, soil analysis may be used as a surrogate for groundwater monitoring (Brown and Caldwell 2007).

Routine chemical monitoring of groundwater at land treatment facilities applying vegetable processing wastes may includes the following general parameters: pH, electrical conductivity (EC), and nutrient analyses for nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), total nitrogen (TN), and dissolved reactive or total phosphorus (Brown and Caldwell 2007).

7.4.1. Groundwater data evaluation

Although groundwater quality data typically forms the basis for permit compliance, the proper evaluation of groundwater quality data is often difficult. Establishing a cause and effect between vegetable processing waste loadings and groundwater quality results requires an understanding of transport conditions gained by watching trends of key parameters over time.

Background groundwater quality. "Background" applies to groundwater that is representative of conditions in and around the site, but has not been affected by vegetable processing waste application on the site. Establishing "background" groundwater quality can be very important for both compliance purposes and for the proper interpretation of ongoing monitoring results. Background samples can be collected solely from monitoring wells or from a combination of monitoring wells of the site. Alternatively, samples can be collected from any location within or surrounding the site if an adequate number of temporally independent samples can be collected prior to the application of vegetable processing waste to the site. Statistical procedures are used for establishment of the upper limit of background groundwater quality (Whitehouse et al. 2000).

Trends. Groundwater quality trends should be plotted over a number of years to determine if there are ongoing trends. Increasing concentrations of some constituents of concern may indicate the need for changes in loading rates or operational practices. Seasonal trends in both groundwater elevation and quality should also be evaluated for water quality in shallow monitoring wells.

Permit exceedance. Groundwater quality limitation violations occur when a compliance sample analysis result exceeds a level specified in the permit for a constituent. An exceedance may be treated as a warning signal that prompts further actions such as an acceleration of monitoring frequency, assessment of wastewater management practices, evaluation of the treatment capabilities and maintenance of the land application system, and assistance from qualified experts.

7.5 Crop monitoring

Crop monitoring is a critical factor in operating and maintaining a land application system. A healthy and productive crop is required to remove nutrients and salts as part of soil-plant treatment of vegetable processing wastes. The value of crops harvested from the site may provide an additional incentive to assure that proper attention is paid to the land application fields (Brown and Caldwell 2007).

Activities to monitor and control insect and disease problems, promote crop growth, and maintain adequate nutrient balance within the plants should be a standard part of the management of any crop. Nutrient shortages, ion toxicity, and diseases may exhibit specific responses in plants that can be recognised by agronomists or experienced farmers. Attention to crop needs including irrigation water and nutrients will result in better management for agricultural production, process water treatment, and environmental protection objectives.

Daily visual observations are important for ongoing management activities and should be maintained in a field log for reference. The actual measurements required for crop monitoring are simple. These include biomass removal (harvest weight) and samples of the crop to determine the amount of constituents removed (Brown and Caldwell 2007).

Because nutrient uptake is a primary function of the crop for land application purposes, analysis for nitrogen is recommended. Total and available nitrogen in vegetable processing wastes differ because the organic nitrogen is not entirely available to crops and some is lost in conversion processes (Crites et al. 2000; EPA 2006). Available net nitrogen loading and crop uptake should be nearly equivalent, at least when averages over several years are being considered.

7.6 Routine maintenance, inspection and record-keeping

Routine monitoring, including thorough daily inspections, is recommended to identify operational problems at an early stage and gather data to make irrigation and cropping decisions. Routine inspection forms also commonly incorporate collection of meter readings, pressure checks, times that various activities take place, etc. This is an appropriate combination of tasks and should be encouraged. It is inherently dependent on many variables, and observations used to adjust management according to actual field conditions are important. In addition, results and observations made during inspection are an appropriate topic at periodic facility staff meetings or informal meetings of field or maintenance personnel (Whitehouse et al. 2000).

Inspection forms and other operational and compliance records associated with the monitoring activities should be maintained in a central file that allows for easy future reference. Careful record-keeping on an ongoing basis is critical to data evaluation, identification of short- and long-term trends, and operational fine-tuning. Facility files should also include process-related records, such as the volume of chemicals used for cleaning, energy consumption and other pertinent data (Brown and Caldwell 2007).

7.7 Combined data evaluation

Data from each monitoring technique and all media should be evaluated as a whole to get a better picture of the overall effectiveness of the land treatment site. For low risk sites, verifying loading rates, verifying good agronomic conditions, and watching trends are generally sufficient. For higher risk sites, the effectiveness of the land application system should be periodically evaluated in greater detail. This could include estimations of deep percolation, fate of constituents in the vadose zone, transport of constituents to groundwater, and the rate of movement of groundwater

(Brown and Caldwell 2007). These values can then be used to evaluate the trends and changes seen in groundwater well monitoring results.

7.8 Operational adjustments and modifications

When monitoring results show trends towards undesirable conditions, changes should be considered. The uncertainty associated with interpreting sodicity data emphasises the need to monitor soil ESP and, if that has increased, soil physical properties in order to detect and correct deleterious changes that may have occurred as a result of vegetable processing wastewater irrigation (Brown and Caldwell 2007).

8. LAND APPLICATION OF SOLID RESIDUES

8.1 Background

Vegetable processing facilities often generate significant quantities of by-product solids (called residuals) as part of their operations. Sources of residues may include initial screening of vegetable processing waste, material removed from sedimentation basins, and solids that settle in lagoons or other water storage locations. These wastes usually contain high levels of organic matter, nutrients, moisture, and sometimes salts. Land application is the method most widely used by the food processing industry to manage these solid wastes because it is often the most affordable waste management alternative that can provide plant nutrients and act as a soil conditioner (Carnus et al. 1998). The purpose of this section is to provide a summary of good management practices for land application of vegetable processing wastes.

8.2 Application methods

Surface spreading and subsurface injection are the most commonly used land application methods for vegetable processing solid wastes. To meet the objectives of maximum nutrient use with minimum environmental effect, a number of guidelines for spreading and injection need to be followed (Carnus et al. 1998; Hillel 2004):

- Characterise waste to determine nutrient and contaminant contents and select an application rate that does not exceed crop nutrient requirements, avoids harming or contaminating crops, and avoids groundwater contamination.
- Calibrate the spreader to obtain the desired application rate.
- Check soil moisture before applying liquid wastes and adjust the application rate to avoid overland runoff or groundwater contamination through preferential flow.
- Incorporate fresh wastes as soon as possible to prevent odours and reduce nitrogen losses.

Spreading. Semisolid wastes (up to 4% solids) can be pumped into a spreader, and special equipment can be used for wastes with up to 15% solids (Mancl, K. 2007). When spreading semisolid waste it is important to limit each application to bring the soil moisture just up to field capacity. Too much liquid application at one time needs to be avoided. Application of waste may also be limited by soil conditions. Hauling waste in a tank through a wet field may cause soil compaction, but the weight of the tank can be eliminated completely by using a flexible hose to deliver waste to the spreader in the field.

Incorporation and injection. Generally, spreading/incorporation or injection of vegetable processing solid waste is the most appropriate methods for applying food processing waste. It can add plant nutrients and organic matter to the soil. Fresh waste should be incorporated immediately to prevent odours and reduce nitrogen loss. Surface-applied waste can be ploughed under; waste can also be injected about 0.1-0.2 m below the surface, which places it beneath the soil surface without turning the soil over. This minimises disturbance of vegetation, which is particularly important on pasture.

8.3 Potential issues

Similar to the wastewater, vegetable processing solid wastes normally contain high concentrations of organic materials (e.g., high BOD value) and nutrients (e.g., nitrogen, phosphorus, potassium, etc.) which could be assimilated by soil-crop systems. However, sometimes these wastes may contain high concentrations of salts or other chemicals (e.g., caustic or acidic compounds) added during the processing or cleaning stage. These salts and chemicals may have an adverse effect on crop growth or soil properties.

There are short- and long-term environmental effects associated with land-applied vegetable processing wastes (Carnus et al. 1998).

Short-term effects can be odour and vector attraction (e.g., insects and rates), and dramatic changes in soil pH and salinity. Odour and vector attraction may be minimised by injection below the surface of the land or incorporation into soil, which relies on the soil as a barrier. This may also be reduced through waste stabilisation processes such as aerobic or anaerobic digestion, composting, and pH adjustment.

Longer-term effects are likely to be on- and off-site effects related to salt accumulation in soil, nutrient imbalance, and nutrient leaching. Soil salinity and sometimes sodicity because of high levels of sodium salts induced by waste application may cause soil structure damage as well as crop growth reduction. Suggestions for dealing with salt-related problems are detailed in the Technical Review document published by the NZ Land Treatment Collective (Carnus et al. 1998). As for the wastewater, nitrogen is the most commonly monitored nutrient associated with land application of vegetable wastes. To minimise nitrate leaching and contamination of water bodies, it is important that the application rate should be based on crop nitrogen requirements, i.e., based on an agronomic rate. If waste is applied to a soil with high phosphorus level and in a sensitive environment (e.g., close to significant fresh water lakes), phosphorus loading also needs to be taken into account.

8.4 Solid residue monitoring

If the vegetable processing wastewater land application site is also used for solids land application, or solid wastes are repeated applied onto same land areas, routine monitoring of residues is necessary for operational management to determine loading rates. Monitoring parameters may include:

Material quantity. Weight of material should be recorded, along with date of generation.

Material quality. Prior to land application, residues from stockpiles should be analysed for potentially limiting constituents, which are likely to be nitrogen or phosphorus. A composite sample should be collected for analysis for total solids, nitrogen species (organic-N, ammonium-N and nitrate-N), and total phosphorus.

Soil analysis. Soil should be analysed to provide an estimate of soil capacity for additional nutrient loading.

Record keeping. When solid residues are land-applied, date, amount applied, application method, incorporation methods (if materials are mixed with the soil), and other field observations should be recorded. Residues are often applied on a wet weight basis, so that analytical data must be converted using measured moisture content (Brown and Caldwell 2007).

8.5 Good management practices

Application of vegetable processing solid wastes to crop land is encouraged by regulators in many countries. Compared with other industrial wastes, restrictions on land application of vegetable processing wastes are usually more relaxed (e.g., New York State Department of Environmental Conservation 1999). The extent of regulation is generally governed by the potential for adverse impacts on the environment, particularly on water quality. Where water quality impacts are likely to occur, operators should be required to prepare and follow proper management plans. Management plans should establish application rates appropriate to the property of the waste, the crop or land being used, and other appropriate agronomic factors. Monitoring should be required as necessary to evaluate compliance with applicable requirements.

The following points may be used as a guide to planning and implementing on-farm management practices for land application of vegetable processing solid wastes as fertilizers and soil conditioners on agricultural land (New York State Department of Environmental Conservation 1999).

- A detailed site management and operation plan needs to be in place before vegetable processing wastes are used in farm operations.
- Quality of the vegetable processing wastes applied to agricultural lands must meet relevant regulations.

- The chemical and physical characteristics of vegetable processing wastes should be analysed when planning to apply the wastes.
- Suitable soils should be selected for land application of vegetable processing solid wastes. The most suitable soils are those with few limitations that restrict incorporation of the wastes and/or prevent the on-site use of nutrients in the organic waste (e.g., soil wetness, slope, and texture).
- Application rates of vegetable processing solid wastes should be based on optimising crop growth and at the same time minimising environmental impacts. The actual application rate is calculated based on the most limiting factor, which is likely to be nitrogen. However, the limiting factor can also be a waste characteristic (e.g., pH, salt content, etc.) or a soil property (e.g., phosphorus, pH, organic matter).
- Special management practices need to be in place when wastes with high levels of salts are applied to land.
- The wastes may be incorporated evenly within the top soil or injected into the subsurface soil; this can reduce odours, ammonia volatilisation, and vector attraction.

Annual soil testing is recommended to account for residual nutrients in the soil and help determine crop needs and nutrient management decisions. To assess the potential risk to water quality, concentrations of total nitrogen, the carbon to nitrogen (C:N) ratio, and concentrations of plant-available phosphorus in soil are good indicators. For optimum crop production, additional soil testing is recommended, e.g., pH (indicator of soil acidity or alkalinity), electrical conductivity (indicator of soil salinity), and concentrations of exchangeable potassium, sodium, calcium and magnesium.

9. ACKNOWLEDGEMENTS

The author wishes to thank the FRST for funding support (Envirolink programme), and Dr. Guna Magesan for reviewing the document.

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