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EFFECTS OF AIR-DRYING AND STORING SEWAGE SLUDGE BIOSOLIDS ON ENTERIC PATHOGENS, INDICATORS AND NUTRIENTS

A Review of Literature for Smart Water Fund, Victoria, Australia

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EXECUTIVE SUMMARY

The majority of sewage sludge produced in Victoria is treated by mesophilic anaerobic digestion followed by storage/air-drying or by storage/air-drying after wastewater treatment by lagooning. The produced biosolids are accumulated in lagoons or stockpiles within the curtilage of the wastewater treatment plant (WwTP). This is not a sustainable approach to sludge management in the long-term and alternative methods and outlets for the sludge need to be identified. One of main options available for managing sewage sludge is treating the sludge for use on agricultural land as a soil improver and fertiliser replacement product. In this way, significant agronomic benefit is gained from the beneficial use of the nutrients and organic matter contained in sludge. The storage time for sludge specified in Victoria for land application is determined by the Guidelines on *Biosolids Land Application*, which specify the processes capable of achieving a required level of pathogen reduction. The minimum storage period for sludge recommended in Victoria is 3 years. This project aimed to evaluate whether the 3-year duration time for sludge storage is justified in terms of pathogen reduction rates and to indicate the impact of storage/air-drying treatment on the nutrient content of sludge.

Sludge storage has been widely practiced as a method of stabilising sludge and reducing its pathogen content. Storage for 14 days following primary anaerobic digestion, or for 3 months if the sludge is untreated, reduced indicator, pathogen and parasite (eg *Taenia saginata*) concentrations by >2 $\log_{10}$ and the sludge is suitable for use as an agricultural fertiliser. The rate of pathogen removal during storage increases with increasing ambient temperature. Therefore, removal rates are higher during the warmer summer period compared to the winter. The potential risk to health depends on the initial numbers of pathogens in the sludge. The risk of infection from *Salmonella*, for example, is negligible for 'conventionally treated' sludge achieving ≥2 $\log_{10}$ removal and ≤5 $\log_{10}$ g^{-1} dry solids (DS) of *E. coli*. Multi-barriers are adopted to prevent the spread of infectious disease when sludge is treated to this standard and land-use restrictions also therefore apply and are important when considering the potential risk of infection. Parasites are the most resistant types of infectious enteric microorganism with the helminth, *Ascaris* able to survive for long periods at cool ambient temperatures. However, helminth infections are extremely rare in modern society. *Ascaris* is recommended as an indicator of the efficacy of sludge treatment at pathogen destruction in developing countries, where its prevalence in the population is potentially high. It is also specified in the rules for sludge treatment for land application in the regulations of certain developed countires. However, its relevance is questionable if human roundworm infections are limited in the population. Drying sludge is also very effective at pathogen removal and the complete destruction of parasites and pathogens can be achieved when sludge is desiccated to ≥80 % DS.

The overall reduction in indicator and pathogen numbers is increased by treating sludge prior to air-drying and storage, eg by mesophilic anaerobic digestion, which is the main practice in Victoria. Pre-treatment and storage/air-drying process modifications such as drying of sludge in thin layers can ensure 100% inactivation of even the most persistent types of parasites.

The report concludes that secondary digestion storage of liquid sludge following primary mesophilic anaerobic digestion, or long-term lagooning sludge, followed by air-drying to >80 % DS and storage are highly effective at removing pathogens from sewage sludge. Storage after anaerobic digestion for 14 days produces sludge that is suitable for application to agricultural land for food crop production with accompanying land use provisions. Storage of air-dried sludge for 6 – 12 months

further increases the level of hygienisation and the literature reviewed here indicated that product treated to this standard under Australian conditions could be used without restriction.

GLOSSARY

Air-drying is the process of drying sludge by evaporation in a drying bed or lagoon.

Biosolids refer to sewage sludge that is treated to a standard suitable for recycling on land.

Drying bed is a structure constructed with a permeable drainage media for drying sewage sludge by evaporation and drainage, which is collected by an underdrainage system.

Drying pan is a term occasionally used to describe a sludge drying lagoon.

Fresh refers to sludge in its present, 'as sampled' condition and may be used to distinguish analytical data that may be reported on a fresh or dry solids basis.

Lagoon is an excavated cavity lined with a membrane or impermeable material to prevent seepage and may be used for storing and/or drying sewage sludge; in the case of drying this is by evaporation.

Long-term storage is defined as a period exceeding 1 month.

Parasite is an organism that lives in another host and derives its nutrition from and potentially causes disease in the host.

Pathogen is a microbiological agent that can cause infection and disease.

Sewage sludge is the residual solids produced by urban wastewater treatment.

Short-term storage is defined as a period for up to 3-4 weeks.

Storage refers to the practice of holding sludge without active management in liquid, mechanically dewatered cake or dryer forms for different periods of time for stabilisation and pathogen reduction.

CONTENTS

1. INTRODUCTION

1.1 Background

Sewage sludge consists of the organic and inorganic solids derived from wastewater treatment. It has been termed 'biosolids' when treated to a standard that is suitable for beneficial use, such as for land application as a fertiliser replacement and soil improver in agriculture. Globally, recycling biosolids to farmland is by far the most widely practised method of sludge management and is regarded as the most sustainable option under most circumstances. Other methods include sea dispersal, landfill disposal or incineration with the disposal of the residual ash in landfill. However, disposal at sea has ended in Europe and the US, disposing of biodegradable waste in landfill is not regarded as a long-term sustainable option due to the contribution to greenhouse-gas emissions and is being reduced, and in many countries incineration is very unpopular with the public. In Europe, sea disposal of sludge was banned by the Urban Wastewater Treatment Directive 91/271/EEC in 1998 (CEC, 1991) and this practice is also unacceptable in Australia. Environmental and waste policy in Europe is influenced by the Landfill Directive 99/31/EC, which amongst other targets, stipulates that the amount of biodegradable municipal solid waste (BMSW) disposed of in landfill will be reduced. 'Biodegradable waste' is defined as 'any waste that is capable of undergoing anaerobic or aerobic decomposition' (CEU, 1999 (Landfill Directive, Article 2)). Sludge partially fits the definition of biodegradable waste, as it contains organic matter that is capable of decomposition, therefore the disposal of sludge in landfill will continue to decline in Europe in the future.

Recycling to land for agricultural purposes, land restoration or, for example, use in forestry, is the only outlet where significant benefit can be derived from the nutrient resources and organic matter contained in sludge. Recycling of phosphorus (P) in biosolids is increasingly seen as an essential prerogative for sustainable development owing to the finite availability of this important mineral resource (Steen, 1998; Dawson, 2007; Green Alliance, 2007). There are also concerns about organic matter depletion in many regions of the world caused by intensive agricultural practices. The application of organic matter in secondary resources such as sewage sludge is considered essential to correct this decline in soil quality. Waste policies in many countries and in Europe also favour recycling of waste derived materials above their disposal (CEC, 1975). However, sewage sludge may contain residual levels of contaminants and infectious microorganisms, that may be excreted in faeces of individuals infected with enteric pathogens (see Table 1.1). Consequently, the practice is carefully regulated and controlled to prevent potential impacts on human health and the environment. In Europe, for example, the agricultural use of sludge is regulated by Directive 86/278/EEC (CEC, 1986).

In Victoria, sewage is treated by Urban Water Service Providers (UWSP) and the residual sludge has been accumulated in stockpiles on the treatment works. Currently, approximately 2 million t dry solids (DS) of sludge are either stored in lagoons or stockpiled; <5 % of annual sludge production (66,700 t DS) in Victoria is used beneficially (DNRE, 2002), equivalent to little more than 3000 t DS y^{-1}. Current Victorian State Guidelines prescribe digestion with a minimum storage period of three years as one method for producing Treatment Grade T1 material (EPA Victoria, 2004). The significance of a T1 grading is that material treated to this standard can be applied to land without restrictions related to microbiological quality.

Air-drying for three years is listed as a T1 process (EPA Victoria, 2004), there are no recommendations in the Guidelines for air-drying and storage for restricted grade

products (Treatment Grades T2 and T3). However, T1 biosolids are commonly used for purposes designated for the T2 grade. These grades represent the main operational outlets for biosolids in all other countries where recycling to agricultural land is a well developed and accepted practice. They are coupled with land use restrictions to allow the natural attenuation of any residual pathogenic organisms that may be present in the sludge after treatment, based on the well established multi-barrier approach to protect human health from infectious enteric disease when sewage sludge is recycled to farmland (WHO, 1981; US EPA, 2003). Although EPA Victoria has provided some site specific approvals for biosolids air-dried for less than 3 years to be land applied as a T3 product, the lack of clear guidance is a significant barrier to the expansion of beneficial reuse programmes for biosolids in Victoria.

The majority of the sludge produced in Victoria is treated by air-drying and storage (as outlined in Section 2), in accordance with the Victorian T1 storage process requirements – digested and dewatered to at least 10% w/w solids and stored for a minimum period of 3 years. The Biosolids Land Application Guidelines (EPA Victoria, 2004) indicate the need for further research to assess the treatment grade classifications associated with lagoon storage and drying beds. In Europe, Council Directive 86/287/EEC defines stabilised sludge as sludge that has undergone biological or chemical treatment, or long-term storage, but it does not define specific process conditions as these depend on local circumstances and are specified in the guidelines and legislation stipulated in individual Member States. For example, the UK Code of Practice for Agricultural Use of Sewage Sludge (DoE, 1989) describes liquid storage for a minimum period of 3 months as an effective treatment process for sludge. The main approach to sludge treatment in Victoria (anaerobic digestion followed by lagoon drying and storage) is considerably more rigorous than the DoE (1989) process description for the effective removal of pathogens by mesophilic anaerobic digestion. The UK Code of Practice recommends a mean retention time of ≥12 days primary digestion in a temperature range 35 ^{o}C +/- 3 ^{o}C followed by a secondary stage which provides a mean retention period of at least 14 days (DoE 1989, see Section 4). This process has been verified (Horan *et al*., 2004) as compliant with the requirements of the microbiological quality standards stipulated in the UK Safe Sludge Matrix (ADAS, 2001) for conventionally treated sludge for agricultural use (2 $\log_{10}$ removal and ≤5 $\log_{10}$ g^{-1} DS *Escherichia coli* – see Appendix 1) and the risks to health resulting from its use in agriculture are negligible (Carrington *et al*., 1998; Mara and Horan, 2002; Gale, 2003; 2005). The lagooning and air-drying phases for liquid digested sludge currently operating in Victoria are significantly longer than the 14 day storage requirement stipulated in the UK DoE Code of Practice. As there is no further admixture of sludge when the lagoon is finally filled for air-drying, the lagooning, air-drying and storage phases of the treatment process would be expected to have a very significant impact on the destruction of enteric organisms in sludge.

Without clear guidance and supporting information on the effect of weather conditions in Victoria on the pathogen removal efficiency of air-drying and storage, it is difficult to:

- demonstrate due diligence in the use of biosolids from air-drying and storage;
- have certainty in planning for regulatory approvals; and
- have robust systems to ensure reliable production of a specified product quality.

The situation is becoming critical, however, because some of the treatment plant operating within the State of Victoria no longer have space to continue the stockpiling

of sludge indefinitely (DNRE, 2002). Furthermore, some smaller lagoon treatment plants have never been desludged and it is expected that they will require desludging in the next 10 years (DNRE, 2002). This contrasts with other states in Australia, such as New South Wales and Western Australia, that have well developed land application programmes and where almost all of the sludge produced (approximately 95 %) is recycled to land, mainly agriculture (Gale, http:// www.bvsde.paho.org/bvsaar/cdlodos/pdf/theaustralasian109.pdf).

Another issue of importance is the effect of storage and air-drying on sludge nutrient value. Storage reduces the content of ammoniacal nitrogen (N) through volatilization and enables the slow mineralisation of organic N to take place potentially significantly reducing its fertilizer and agronomic value. Thus, the nutrient value of sludge is likely to be inversely proportional to the storage length. Therefore, further research is necessary to determine the optimal storage period, where risk from pathogens is sufficiently reduced and the final product still has adequate fertilising value.

This report critically reviews and summarises the published scientific literature concerning the efficiency of storage and air-drying sewage sludge at ambient temperatures at pathogen destruction and also the effects on nutrient and agronomic value of sludge. The underlying rationale developed in the report is that, even if technologically feasible, producing virtually sterile sludge may not be justified in terms of microbiological risk management if this cannot be supported by reasons of public health protection. Consequently, emphasis is placed on restricting the numbers of pathogens in sludge to within specified levels that do not pose a health or environmental hazard when sludge is used in agriculture and to recommend appropriate management and monitoring practices that ensure the required degree of hygienisation is routinely achieved (Hall, 1995; Gale, 2005).

1.2 Project aims and objectives

The overall aim of the project is to determine to what extent air-drying/storage treatment of sewage sludge is capable of pathogen elimination and whether a storage period for 3 years is necessary to reduce the pathogen numbers to acceptable levels where sludge can be used safely in agriculture.

Specifically, the objectives of the study are to:

- Identify the main pathogens of concern;
- Outline sludge classification systems with regard to pathogen levels;
- Determine the source-pathway-receptor linkage for exposure to pathogens;
- Overview sludge storage and air-drying management practices and engineering techniques;
- Determine the efficiency of storage/air-drying at pathogen reduction;
- Review the effects of storage/air-drying on the nutrient content and availability in sludge.
- Determine if there is scope to relax the T1 microbiological criteria for air-drying and storage, whilst maintaining adequate levels of health protection and safety when biosolids are used without restriction.
- Establish the potential of storage and air-drying biosolids to meet T2 and T3 type microbiological criteria for application to agricultural land with associated end-use restrictions.

1.3 Methodology

The literature study is based on:

- Research results published in scientific journals and conference materials;
- Scientific reports;
- On-line information acquistion using 'Aqualine' and 'Web of knowledge' abstracting databases
- Analysis of pathogen monitoring in two case studies carried out by Wannon Water, a water and sewerage service provider in Victoria, and reported by the Cairo Sludge Disposal Study (Hall *et al*., 1999).

Table 1.1 Examples of pathogens potentially excreted in faeces and present in sewage sludge, and related disease symptoms (adapted from: Gerba and Smith, 2005; Pepper *et al*., 2006; WHO, 2006)

Group	Pathogen	Disease and symptoms
Bacteria	*Aeromonas* spp.	Enteritis
	Campylobacter jejuni/coli	Campylobacteriosis – diarrhoea, cramps, abdominal pains, fever, nausea, arthritis; Guillain-Barré syndrome
	Escherichia coli (EIEC, EPEC, ETEC, EHEC)(1)	Enteritis
	Plesiomonas shigelloides	Enteritis
	Salmonella typhi/paratyphi	Typhoid/paratyphoid fever – headache, fever, malaise, anorexia, bradycardia, splenomegaly, cough
	Salmonella spp.	Salmonellosis – diarrhoea, fever, abdominal cramps
	Shigella spp.	Shigellosis – dysentery, vomiting, cramps, fever; Reiter's syndrome
	Vibrio cholerae	Cholera – watery diarrhoea
	Yersinia spp.	Yersiniosis – fever, abdominal pain diarrhoea, joint pains, rash
Viruses	Enteric adenovirus 40 and 41	Enteritis
	Astrovirus	Enteritis
	Calicivirus (including norovirus)	Enteritis
	Coxsackievirus	Various: respiratory illness; enteritis; viral meningitis
	Echovirus	Aseptic meningitis; encephalitis; often asymptomatic
	Enteroviruses types 68-71	Meninggitis; encephalitis; paralysis
	Hepatitis A virus	Hepatitis – fever, malaise, anorexia, nausea, abdominal discomfort, jaundice
	Hepatitis E virus	Hepatitis
	Poliovirus	Poliomyelitis – often asymptomatic, fever, nausea, vomiting, headache, paralysis
	Rotavirus	Enteritis
	Reovirus	Respiratory infections, gastroenteritis
Parasitic protozoa	*Cryptosporidium parvum*	Cryptosporidiosis – watery diarrhoea, abdominal cramps and pain
	Cyclospora cayetanensis	Often asymptomatic – diarrhea, abdominal pain
	Entamoeba histolytica	Amoebiasis – often asymptomatic; dysentery, abdominal discomfort, fever, chills
	Giardia intestinalis (also known as *lamblia*)	Giardiasis – diarrhoea, abdominal cramps, malaise, weight loss
	Balantidium coli	Diarrhoea, dysentery
	Toxoplasma gondii	Toxoplasmosis
Helminths	*Ascaris lumbricoides* (roundworm)	Ascariasis – generally no or few symptoms; wheezing, coughing, fever, enteritis, pulmonary eosinophilia
	Taenia solium/saginata (tapeworm)	Taeniasis
	Trichuris trichiura (whipworm)	Trichuriasis – unapparent through vague digestive tract distress to emaciation with dry skin and diarrhoea
	Ancylostoma duodenale/Necator americanus (Hookworm)	Itch, rash, cough, anaemia, protein deficiency
	Toxocara canis	Fever, abdominal pain discomfort, muscle aches
	Hymenolepis nana (dwarf tapeworm)	Taeniasis
	Schistosoma spp. (blood fluke)	Schistosomiasis, bilharzia

(1) EHEC – enterohaemorrhagic *E. coli*, EIEC – enteroinvasive *E. coli*
EPEC – enteropathogenic *E. coli,* ETEC – enterotoxigenic *E. coli*

Note to Table 1.1: illness related to occupational exposure to airborne endotoxin, a proinflammatory molecule produced from bacterial degradation, has been reported amongst sewage treatment plant operators (Ayres *et al.*, 2007). However, health effects for populations non-occupationally exposed are low. Direct handling of soil or other organic manures and materials is likely to pose similar risks of exposure to endotoxins as are biosolids. As biosolids are unlikely to increase the risk of exposure to endotoxins above that for other commonly used organic materials containing degraded bacteria, endotoxins have not been considered specifically in the review. Nevertheless, published data on non-occupational exposure is limited. In contrast to endotoxins, however, the potential risks to health of infectious pathogens and parasites in sludge is well documented and is therefore the main focus of the review.

2. SLUDGE MANAGEMENT IN VICTORIA

2.1 General aspects of sludge production in Victoria

Australasia is a source of approximately 360,000 t dry solids (DS) of biosolids per year (Gale, http://www.bvsde.paho.org/bvsaar/cdlodos/pdf/theaustralasian109.pdf). Data obtained from 1997 and 2001 surveys show that there are approximately 66,700 t DS of sludge produced each year in Victoria, from 175 wastewater treatment plants (Table 2.1; DNRE, 2002). Around 60% of these are major metropolitan plants (EPA Victoria, 2004)). The treatment plants managed by Melbourne Water treat approximately 60% of Victorian sewage (Figure 2.1) and is owned by the Victorian government, and there are 18 other Urban Water Service Providers (UWSP) – listed in Figure 2.2.

Two major treatment plants managed by Melbourne Water, are:

- Western Treatment Plant;
- Eastern Treatment Plant.

Other major WwTP in the State of Victoria are listed in Table 2.2.

Table 2.1 Sludge production in Victoria (Van Oorschot *et al*., 2000)

Biosolids Quantities in Victoria (dry tonnes)

Source of Biosolids	Fresh (Annual Production)	Sludge in Lagoons[1]	Stockpiles – Other[2]	Number of Plants
Rest of Victoria	27,000	157,520	96,720	173
Melbourne Water3	39,700	173,200	1,742,900	2
Total Victoria	66,700	330,720	1,839,620	175

Notes: 1) Biosolids stockpiled in lagoons could be either liquid biosolids or dewatered cake. Also includes solids in liquid treatment lagoons.
2) "Other" stockpiles are dewatered biosolids or air-dried biosolids.
3) Eastern and Western Treatment Plants.

Of the 175 treatment plants in Victoria, 57% are lagoon based, followed by activated sludge plants and trickling filter plants, with or without oxidation lagoons.

2.2 Sludge generation by Melbourne Water

Approximately 40% of Melbourne sewage, consisting mainly of domestic (91%) and partially industrial and commercial waste, is directed to the Eastern Treatment Plant, at Bangholme. The plant occupies a 1,100 ha site and treats sewage up to a secondary stage (data from 2005), using the activated sludge process (Figure 2.3).

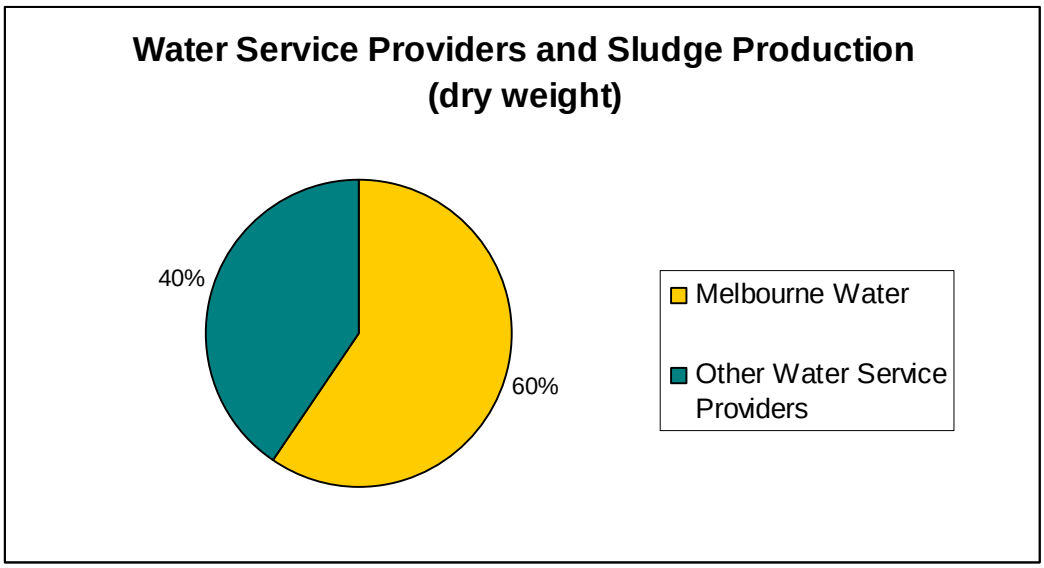

Figure 2.1 **Sludge production by Melbourne Water and other Water Service Providers (DNRE, 2002)**

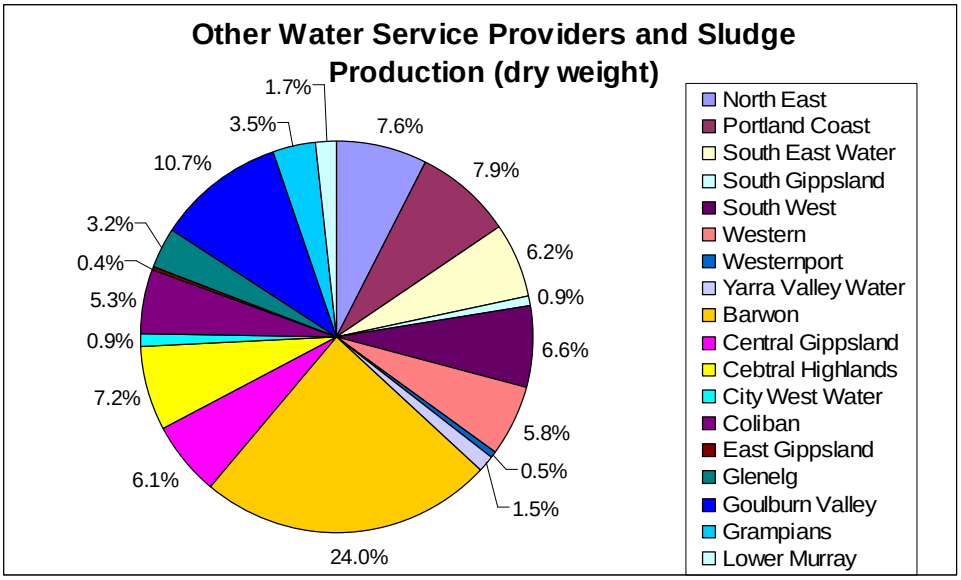

Figure 2.2 **Sludge production by other Water Service Providers (DNRE, 2002)**

Table 2.2 Other major treatment plants in the State of Victoria (Van Oorschot *et al*., 2000)

Wastewater Treatment Plant	Type of plant	Design Capacity ep(flow based)	Biosolids Generation dry t/yr[1]
Black Rock	IDEA	210,000	4,200
Dutson Downs	Lagoons	170,000	750[2]
Ballarat South	AS/TF BNR	145,000	1,650
Shepparton	Lagoons	130,000	600[2]
Bendigo	AS BNR	120,000	2,000
Warrnambool	IDEA	50,000	1,000
Mornington	AS	50,000	560
Brushy Creek	AS	43,000	450[2]
Altona	TF/lagoon	42,000	325[2]
Rosebud	AS	37,500	400[2]

IDEA – intermittent decanted extended aeration process
AS – activated sludge
TF – trickling filter
BNR – biological nutrient removal (phosphorus and nitrogen)
[1] Current generation rate based on data from EPA.
[2] Indicates an estimate as there was no data available.
[3] Excludes the two major treatment plants in Melbourne

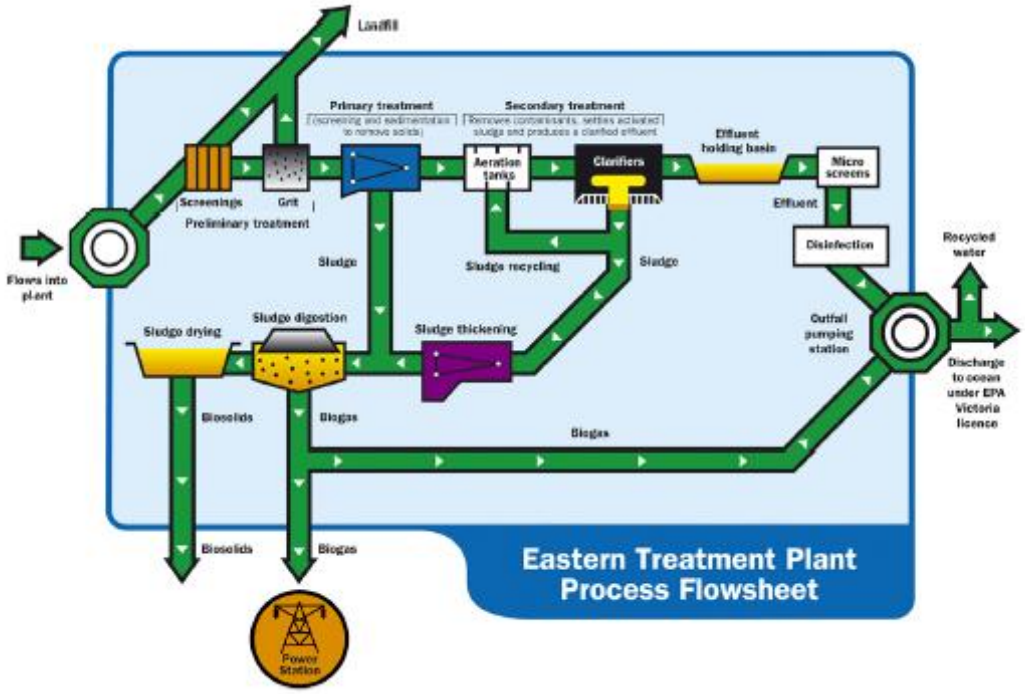

Figure 2.3 Sewage treatment at the Eastern Treatment Plant (Melbourne Water, 2005)

Secondary sludge is thickened using centrifuges and dissolved air flotation. Both primary and secondary sludges are treated by mesophilic anaerobic digestion and are pre-heated to 36°C. Digested sludge is dried in drying pans and lifted to be stored into stockpiles during the summer. Storage is for a minimum of 3 years, as required by the State Guidelines (EPA Victoria, 2004; Melbourne Water, 2005), although in practice very little of the sludge is used and is kept on site in long-term stockpiles.

The Western Treatment Plant is located at Werribee and occupies an area of 11,000 ha, and is therefore the most extensive sewage plant in Australia. It treats approximately 52% of Melbourne sewage from domestic, industrial and commercial sources (Melbourne Water, 2006a). Since 2005, all the influent wastewater is treated in lagoon systems. Before January 2005, however, land or grass filtration was still practised. The first pond in the series is an anaerobic lagoon, which is a covered for methane gas collection. Sedimentation of a large part of the suspended solids also occurs here. The effluent passes through several ponds of the lagoon system. Some of the ponds are also aerated and the wastewater is treated biologically by the activated sludge process to remove nitrogen before passing further in the pond chain (Melbourne Water, 2006b)

2.3 Sludge generation by other Water Service Providers in Victoria

The range of treatment methods operated by other USWPs in the State of Victoria is shown in Figure 2.4 in relation to volumes of wastewater treated. (Van Oorschot *et al.*, 2000). The distribution of sludge generation by other UWSPs by the different treatment options is presented in Figure 2.5. This shows that 72% of the production is from activated sludge systems (IDEA and BNR plants). The remainder is from trickling filter systems (humus sludge) and lagoons.

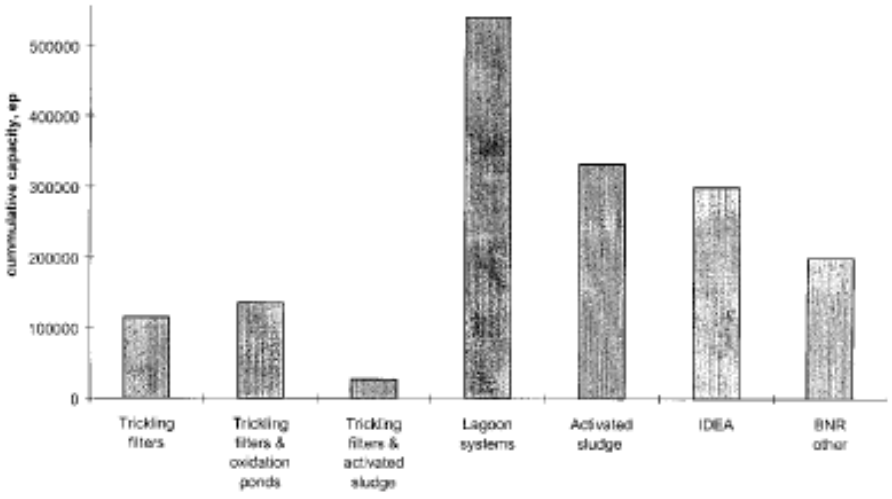

Figure 2.4 Wastewater treatment by different methods operated by other Water Service Providers (Van Oorschot *et al*., 2000)

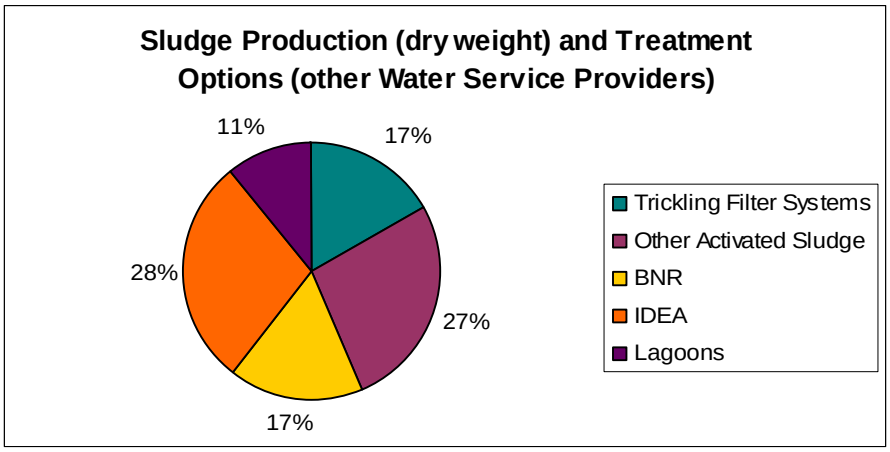

Figure 2.5 Sludge production by different treatment methods by other Water Service Providers (DNRE, 2002)

2.4 End-uses of sewage sludge in Victoria

Annual beneficial uses of biosolids is very limited and amounts to less than 5% of the total production and the outlets have included (DNRE, 2002):

- Composting;
- Mine site rehabilitation;
- Brick manufacture;
- Silviculture;
- Agriculture;
- Potting mixes.

This has developed into a chronic situation and the absence of suitable guidance on beneficial use has been partly blamed for the practice of accumulating sludge in lagoons and stockpiling indefinitely within the curtilage of treatment works (Van Oorschot *et al.*, 2000). Victoria has traditionally pursued air drying and storage of sludge, taking advantage of the suitable climate and access to adequate areas of land at treatment facilities. In recent years, however, pressures to reduce treatment plant footprint, intergenerational equity, waste management hierarchy and regarding treatment plant residuals as a resource rather than a waste have combined to result in the water industry seeking beneficial uses for biosolids and means of reducing stockpiles. Indeed, Victoria is the only State in Australia that has depended on long-term stockpiling of sludge (Figure 2.6). It is currently estimated that the amounts of biosolids remaining in lagoons or stockpiled in Victoria exceeds 2 M t DS (Table 2.1). The majority of the stockpiles (95 %) belong to Melbourne Water and the majority of these are located at the Western Treatment Plant.

The sludge from the treatment works operated by Melbourne Water has not been considered suitable for land application due to contaminant levels and low nutrient value (DNRE, 2002). However, the Corporation is strongly recommended to review the current chemical quality of the sludge as contaminant concentrations have fallen markedly in the past decades.

A number of specific uses of recently produced sludge include (DNRE, 2002):

- Blended soil improvement products;
- Landscaping;
- Land rehabilitation.

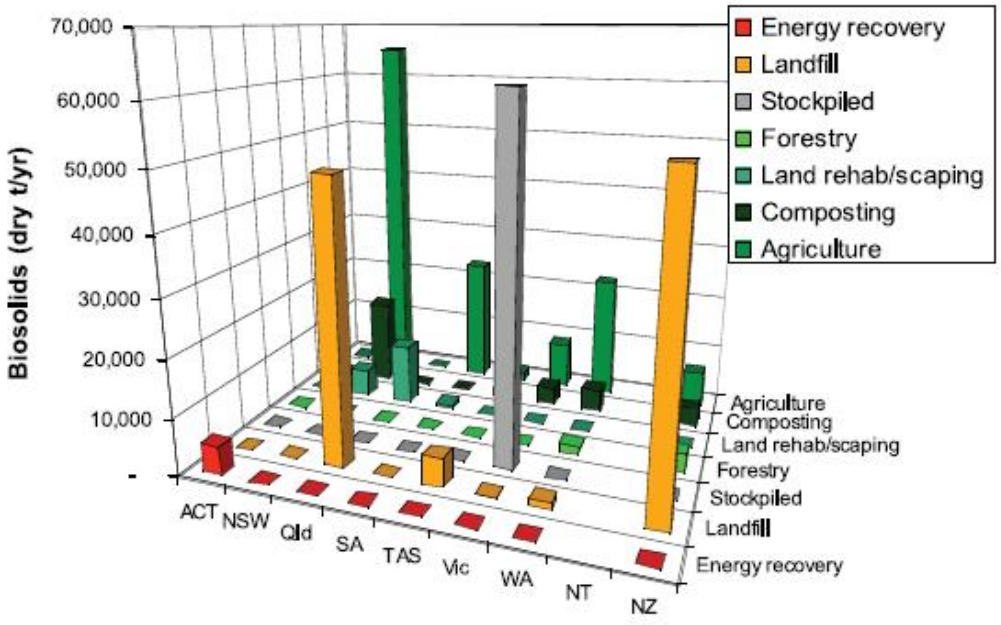

Figure 2.6 Biosolids end uses in Australia and New Zealand (Gale, http:// www.bvsde.paho.org/bvsaar/cdlodos/pdf/theaustralasian109.pdf**)**

The Water Industry in Victoria is developing further strategies for beneficial use of biosolids for consideration by regulators, stakeholders and the community. The costs of transferring the stockpiled biosolids to beneficial uses have been estimated at AU$ 7-20 M and the cost of beneficially using the current production is estimated to be AU$ 8-11 M (DNRE, 2002).

3. SLUDGE TREATMENT BY STORAGE AND AIR-DRYING

3.1 General description

Sewage sludge may be accumulated and stored for short or long periods of time. With regard to its duration, storage is categorised into (US EPA, 1979):

- Equalisation storage - up to 3-4 days;
- Short-term storage - up to 3-4 weeks;
- Long-term storage - longer than 1 month.

The focus of this report is on long-term storage, the types of which are listed in Table 3.1 below.

Table 3.1 Methods for the long-term storage of sludge (US EPA, 1979)

Long-term storage type	Method	Comments
Storage within wastewater treatment processes		
Imhoff tanks	Two-phase concentration	Lightly loaded systems can store for over 6 months. Most systems will require solids removal every 4 to 6 weeks.
Community septic tanks	Two-phase concentration	Sludge from many septic tanks is removed only once in several years.
Wastewater stabilisation ponds	Single and Two-phase concentration	Aerated ponds operate like aeration reactors. Other ponds use two-phase concentration and can store solids for many years.
Storage within sludge treatment processes		
Composting	Two-phase concentration and displacement	Evaporation with process accomplishes two-phase concentration. Processed solids not removable for 3 to 4 weeks.
Drying beds	Two-phase concentration and displacement	Initial settling accomplishes two-phase concentration. Processed solids not normally removable for 3 to 4 weeks.
Facilities provided primarily for storage of liquid sludge		
Facultative sludge lagoons	Two-phase concentration	Time required for initial settling limits storage to short or long term. Mechanics of sludge removal makes short-term storage very expensive. Odour-free operation requires anaerobically digested solids. Organic loadings must be restricted and surface agitation provided. Odour mitigation required when surface area exceeds 30 to 40 acres.
Anaerobic liquid sludge lagoons	Two-phase concentration	Time required for initial settling limits storage to short- or long-term. Mechanics of sludge removal makes short-term storage very expensive. Odour minimisation requires anaerobically digested solids. Usually operated without organic loading restriction. No surface agitation provided. Potential odour risk high, although no quantifying data available.
Facilities provided primarily for storage of dewatered sludge		
Sludge drying lagoons	Two-phase concentration	Initial settling accomplishes two-phase concentration. Processed solids not normally removable for 1 to 2 months. Odour minimisation requires anaerobically digested solids. Can be odourous if aerobically stabilised surface layers begin to decompose anaerobically when rewetted.
Unconfined stockpiles	Two-phase concentration	Requires stabilised dry (greater than 30 to 40% solids) sludge. Stockpiles are usually covered in very wet climates. Natural freeze drying is possible.

The types of storage prevailing in Victoria are lagoons with liquid sludge or dewatered cake. Some of the dewatered or air-dried sludge is also stored in stockpiles (DNRE, 2002).

Storage can be regarded as a permanent or temporary disposal route and/or as a treatment method. The main aim of storage as a treatment is sludge stabilisation, dewatering and odour removal (Pike, 1983).

3.2 Storage in lagoons and stockpiles

3.2.1 General description of lagoon construction

Lagoons are described as excavated cavities without a cover (Jiménez and Wang, 1979) and can provide storage for both liquid and dewatered sludge as a temporary or permanent measure. Pike (1983) describes a lagoon as constituting a relatively shallow tank with banks covered with earth or concrete. Lagoons better suit wastes with low solids content, which generally varies between 2-5% DS (Powers, 1976; Jiménez and Wang, 1979). Sites below ground level are termed 'lagoons' (Figure 3.1), whereas reservoirs with borders are commonly referred to as 'ponds' (Jiménez and Wang, 1979).

Figure 3.1 A lined lagoon (US EPA/USDA, 2000)

The recommended depth for lagoons used for dewatering by air-drying are typically 0.75 – 1.2 m deep, which compares to 1.5 – 2.0 m for activated sludge treatment tanks (EA, 2003). Drying lagoons are open to the air and operate at ambient temperature. The breakdown of organic matter occurs slowly under anaerobic conditions. As the process usually does not involve any horizontal mixing, the mineralisation stages do not develop in a uniform manner and it is difficult to determine the actual sludge retention time. The final stage of methane generation from sludge that has not been previously stabilised by anaerobic digestion, for instance, is often delayed (Pike, 1983).

The main lagoon types are (EA, 2003):

- Thickening, storage and digestion lagoons;
- Drying lagoons;
- Permanent lagoons.

Digestion lagoons may be used as substitutes for conventional invessel digesters, for example, when the latter have become overloaded. In a similar manner, sludge can be stored in drying lagoons in place of drying beds. Sludge can be directed to permanent lagooning as a low cost disposal option, with supernatant decanting to increase the storage capacity (EA, 2003). Lagoon design parameters and stabilisation variables depend on: available space, climate, subsoil permeability, lagoon depth and surface loading, as well as sludge properties (EA, 2003). Open-air digestion or storage of liquid digested sludge is increasingly likely to be considered as undesirable practice due to the emission of methane to the atmosphere, which is an important greenhouse gas. Typically, long-term storage treatment facilities for liquid sludge feature anaerobic sludge lagoons, facultative sludge lagoons, and drying lagoons.

3.2.2 Anaerobic liquid sludge lagoons

Organic matter decomposes in anaerobic conditions, there is usually no loading restriction and the supernatant is decanted and treated separately (Table 3.1).

3.2.3 Facultative sludge lagoons

Sludge stored in facultative lagoons (Figure 3.2) usually undergoes further anaerobic stabilisation (US EPA, 1979). The supplied sludge should be pre-treated in an anaerobic digester to avoid odour problems. The surface layer of this type of lagoon is maintained aerobic by providing organic matter at or below a critical area loading rate and agitating the layer with surface mixers. The aerobic layer contains algae that contribute to the available oxygen supply. Colloidal and soluble parts of the anaerobically digested sludge fed to the lagoon are broken down in the aerobic process at the surface, whereas the solid fraction settles to the bottom of the tank to be further anaerobically digested. The supernatant is returned for separate treatment (US EPA, 1979). Some of the nutrients and carbon dioxide produced in the aerobic and anaerobic decomposition are utilised by the algae. The pH of the surface layer is stabilised at 7.5-8.5, which prevents the production of hydrogen sulphide and therefore controls potential odour generation (US EPA, 1979).

3.2.4 Drying sludge lagoons

Drying lagoons principally rely on evaporation for dewatering sludge. Typically, drying sludge lagoons are filled with digested sludge, after settlement of solids the supernatant layer is decanted followed by a further application of digested sludge. The process is repeated until the required depth of thickened sludge is obtained and then air drying is commenced. They should be supplied with anaerobically digested material to avoid odour generation (US EPA, 1979). Therefore, air-drying can also be considered in association with storage and not as a separate process in this case.

Sludge dewatering practices in Victoria are predominantly based on lagoon drying systems where these are also referred to as ‘drying pans’, although this is not a term

that is generally or widely used outside of Australia to describe lagoon drying systems.

Dewatering sludge facilities store:

- Wet solids (with 15-60% DS) – usually stored in drying sludge lagoons
- Dry solids (with > 60% DS) – usually stored in stockpiles

3.2.5 Unconfined stockpiles

Unconfined stockpiles are used for storing air-dried or mechanically dewatered aerobically/anaerobically treated sludge. These may be covered, especially in the areas of intensive rainfall (US EPA, 1979).

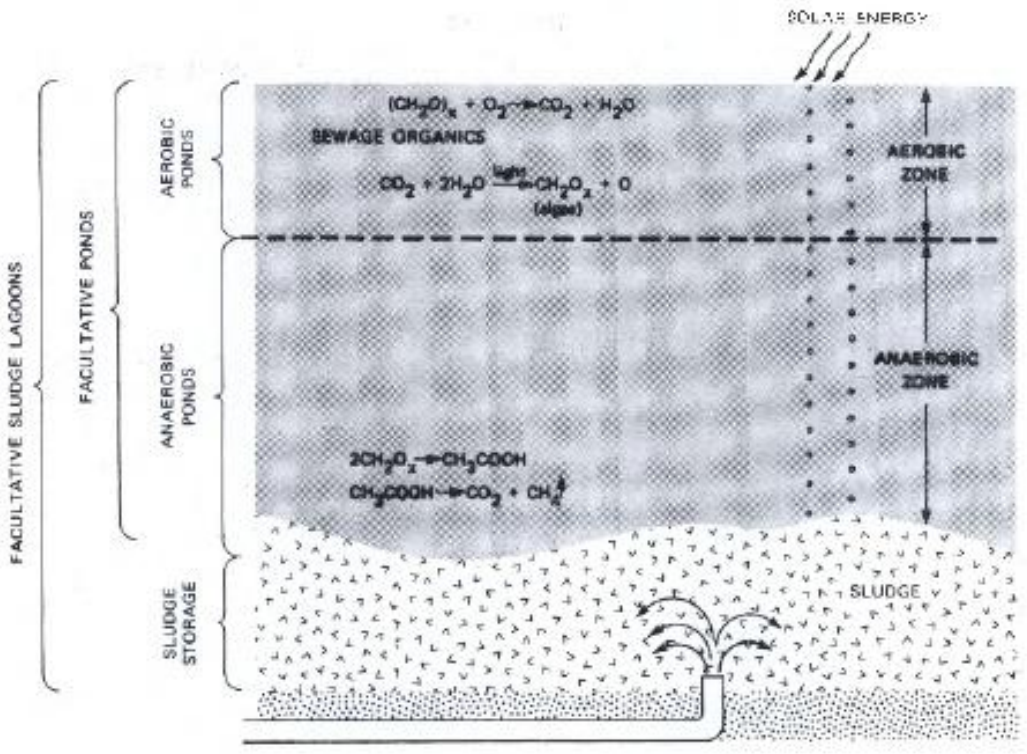

Figure 3.2 Facultative sludge lagoon with aerobic and anaerobic phases (US EPA, 1979)

3.3 Dewatering processes

Sludge dewatering can be achieved by air-drying or by mechanical systems (US EPA, 1999). As an alternative to lagoon-based air-drying, liquid sludge may be placed on beds containing a drainage media, such as sand, and allowed to dry through evaporation and drainage, which can increase the DS content to 45-90% (US EPA, 1999). Though simple in its mechanism, sand beds require large land areas and long periods of time. Paved drying beds are an alternative approach to drying using sand beds. The key difference between these methods and sludge

drying lagoons is that dewatering is assisted by also collecting underdrainage from drying bed systems.

Mechanical dewatering is practiced by larger wastewater treatment plants and has replaced air-drying in many countries throughout Europe. Dewatering is exclusively performed by mechanical methods in the UK. Mechanical dewatering is performed by a variety of methods, for example, vacuum filters (producing sludge with 12-22 % solids content), plate-and-frame filter presses (the most expensive; can dewater sludge to 35-45 % solids content), centrifuges (sludge with 25-35 % solids content), and belt filter presses (20-32% solids content) (US EPA, 1999).

3.4 Storage after mesophilic anaerobic digestion

Pathogen reduction in mesophilic anaerobic digestion is usually modest – eg up to 2 $\log_{10}$ removal of *E. coli* (Feachem *et al*., 1983; Gantzer *et al*., 2001). This is largely because the treatment temperature conditions are not particularly challenging to enteric pathogen survival, and also due to the mode of operation, which is typically on a feed-draw basis, so the process is potentially susceptible to by-pass flow of untreated sludge or only partially treated material in the removed sludge. Therefore, a period of secondary storage is recommended for sludge digestion; operating this stage on a batch basis is most effective at reducing pathogen numbers. For example, the UK Code of Practice for Agricultural Use of Sewage Sludge (DoE, 1989) requires a mean retention time of ≥12 days during primary digestion in a temperature range 35 ^{o}C +/- 3 ^{o}C followed by a secondary stage which provides a mean retention period of at least 14 days (DoE 1989). This process has been verified (Horan *et al*., 2004) as compliant with the requirements of the microbiological quality standards stipulated in the UK Safe Sludge Matrix (ADAS, 2001) for conventionally treated sludge for agricultural use (2 $\log_{10}$ removal and ≤5 $\log_{10}$ g^{-1} DS *Escherichia coli* – see Section 4 and Appendix 1). The Victoria Guidelines (EPA Victoria, 2004) also specify microbiological criteria for anaerobic digestion for different periods depending on digestion temperature (≥15 days at ≥35 ^{o}C or ≥60 days at ≥15 ^{o}C). The risks to health resulting from the agricultural use of sludge treated to this standard are negligible when the sludge is used under controlled conditions with associated land use restrictions (Carrington *et al*., 1998; Mara and Horan, 2002; Gale, 2005). Only when infections with the most environmentally persistent helminth parasites are prevalent in the human population (eg *Ascaris* spp.) and/or when the end-use is unrestricted would more extensive post-treatment be justified, such as by drying beds, thermophilic co-composting with an organic bulking material, or extended storage (WHO, 2006). These organisms would be a primary concern for specifying the conditions of treatment for sludge in developing countries where there may be a high prevalence of infections in the community (WHO, 2006). However, disease caused by helminth infection is usually rare in populations from industrialised countries operating advanced water treatment and sanitation practices and, consequently, the concentrations in sludge are small, or they are not-detectable (eg Table 3.2). Anecdotal evidence also suggests this is the case for the majority of the population in Australia, and helminths are not detected in Australian sludge (pers. com. D. Gardner, Wannon Water). Therefore, from a technical and risk management perspective, it is unnecessary to adopt more extensive treatment of sludge for general agricultural use under these circumstances as this does not contribute further to protecting the human population as the risks to health are already reduced to negligible levels (Godfree and Farrell, 2005; Gale, 2005; Lang *et al*., 2007).

Table 3.2 Numbers of enteric organisms in sewage sludge from Mexico and the US (Jiménez *et al.*, 2002)

	Parasite	Concentration (minimum and maximum)	
		Mexico	United States
Coliphages	*Escherichia coli* CN-13	$1.0 \times 10^6 - 1.9 \times 10^6$	1.3×10^5
PFU/gTS	*Escherichia coli* F+	$2.0 \times 10^3 - 3.2 \times 10^4$	1.3×10^3
Bacteria	fecal coliforms	$2.3 \times 10^7 - 9.3 \times 10^{10}$	2.0×10^7
MPN/gTS	*Salmonella typhi*	$9.5 \times 10^6 - 1.4 \times 10^8$	2.8×10^3
	Pseudomonas aeruginoss	$2.4 \times 10^5 - 4.6 \times 10^7$	2.8×10^3
Protozoa	*Giardia lamblia*	$1.3 \times 10^2 - 4.2 \times 10^4$	2.1×10^2
Cysts/gTS	*Entamoeba* spp.	$2.6 \times 10^2 - 3.8 \times 10^3$	Not reported
Helminth	*Ascaris* spp	66 – 136	1.4 – 9.7
Ova HO	*Trichuris* sp.	3 – 17	<0.01 – 1.4
viable/gTS	*Hymenolepis* spp.	3 – 10	0.02
	Toxocara sp.	1 – 5	0.3 – 1.2
	Enterobius sp.	0 – 4	0.02
	Trichosomoides sp.	0 – 3	Not reported
	Taenia sp.	0 – 2	0.41

4. CONTROLS ON STORAGE AND AIR-DRYING SEWAGE SLUDGE FOR USE IN AGRICULTURE

Examples of effective sludge treatment processes involving storage to reduce fermentability and the health hazards associated with its use in agriculture are described in the UK Department of the Environment *Code of Practice for Agricultural use of Sewage Sludge* (DoE, 1989) and are presented in Table 4.1. These processes were originally designed to achieve ≥1 $\log_{10}$ removal of indicator and pathogenic species, but have been recently demonstrated to achieve ≥2 $\log_{10}$ removal of *E. coli* in accordance with the requirements of the UK Safe Sludge Matrix (ADAS, 2001; Carrington, 2001; Horan and Lowe, 2002). Sludge meeting these requirements is classified as 'conventionally treated' and is suitable for use on agricultural land for food crop production provided certain waiting periods and cropping/harvesting restrictions are followed. Certain end-use conditions are slightly more restrictive than the T2 uses specified by EPA Victoria (2004). Thus, in the UK, conventionally treated sludge cannot be used on fruit crops of any sort (EPA Victoria allows use on tree fruits ≥1 m above ground level) or on grazed pasture unless deep injected or ploughed down. However, in general, the broad categories of site restrictions for T2 and T3 biosolids are similar to those in the UK Safe Sludge Matrix and USEPA (1993) for the principal end-uses of sludge in agriculture permitting application to combinable (eg cereals) and animal feed crops.

Table 4.1 Effective sewage sludge treatment processes involving storage (DoE, 1989)

Process	Descriptions
Mesophilic anaerobic digestion	Mean retention period of at least 12 days primary digestion in temperature range 35 ^{o}C +/- 3 ^{o}C followed by a secondary stage which provides a mean retention period of at least 14 days.
Liquid storage	Storage of untreated liquid sludge for a minimum period of 3 months
Dewatering and storage of treated sludge	If sludge has been treated by mesophilic anaerobic digestion prior to conditioning and dewatering, storage is required for a minimum period of 14 days
Dewatering and storage of untreated sludge	Conditioning of untreated sludge followed by dewatering and storage of the cake for a minimum period of 3 months

US EPA (1993) provides three alternative options to meet Class B pathogen reduction for the agricultural use of sewage sludge. These include either: the monitoring of indicator organisms (see Appendix 1), use of prescribed Processes to Significantly Reduce Pathogens (PSRPs), or use of processes equivalent to PSRP. Storage is not specifically prescribed as one of the PSRPs. However, air-drying is a PSRP. In addition, vector attraction reduction must be demonstrated and one of a list of 10 options must be met. These include minimum DS contents for biosolids depending on the stabilisation treatment of the sludge. These requirements are described in Table 4.2. Class B biosolids are suitable for use on agricultural land with associated land use, cropping and harvesting restrictions. Class A biosolids reduction criteria require specific density limits on pathogens and indicators to be met (see Appendix 1) as well

as one of 6 alternative processing options. Sludge that achieves this level of pathogen removal can potentially be used without further restriction due to the elimination of pathogenic organisms. Airdrying and storage are not specified within these options, or the associated Processes to Further Reduce Pathogens (PFRPs). However, they could be evaluated as a process equivalent to one of the PFRPs, as determined by the permitting authority. A number of researchers have used the Class A pathogen removal criteria within the US EPA Part 503 rule (US EPA, 1993) to bench-mark and assess the effectiveness of air-drying/storage at disinfection for unrestricted use on land. In other words, if air-drying and storage can achieve this level of pathogen removal passively it can be regarded as treated to a sufficiently high standard to permit unrestricted use.

Table 4.2 Storage/drying conditions prescribed as a PSRP and for vector attraction reduction in the US for agricultural use of sewage sludge (US EPA, 1993)

Purpose	Process description
PSRP	Biosolids are dried on sand beds or an a paved or unpaved basins for a minimum of 3 months. During 2 of the 3 months, the ambient average daily temperature should be above 0 ^{o}C
Vector attraction reduction	Drying unstabilised biosolids to at least 90 % DS
Vector attraction reduction	Drying stablised biosolids to at least 75 % DS

PSRP, Process to significantly reduce pathogens

EPA Victoria (2004) prescribes microbiological criteria for 3 treatment grades of sludge (Appendix 1). In addition to microbiological criteria for routine process monitoring, limits are specified for verification of prescribed processes and validation of alternative processes not prescribed in the Guidelines, to achieve the various treatment grades and these are also shown in Appendix 1. Grade T3 is the least stringent for general agricultural use on processed food crops, and is essentially similar to US EPA Class B biosolids. T1 is the highest grade for unrestricted use. The use of Grade T2 biosolids is relatively unrestricted, except that application to human food crops consumed raw and in direct contact with the sludge is not permitted. The only prescribed treatment process involving long-term storage is for T1 product, where sludge is digested, dewatered to >10% w/w solids and stored for > 3 years. Product must be stored in a manner that ensures no recontamination and not generate offensive odours. Treated material from conventional digestion processes, which may also involve storage, is classified as T3 Grade and requires anaerobic digestion ≥15 days at ≥35°C or ≥60 days at ≥15°C or aerobic digestion ≥40 days at ≥20°C or ≥60 days at ≥15°C. Vector attraction reduction measures also apply to all specified process conditions. Those vector attraction reduction measures relevant to air-drying/storage include:

1	Biosolids treatment process reduces volatile solids by ≥38%	all biological anaerobic or aerobic processes
2	Biosolids containing stabilised solids only, dried to ≥75% solids content	Fully stabilised by anaerobic or aerobic process
3	Biosolids containing unstabilised solids, dried to ≥90% solids content	Heat dried biosolids

5. TIME-TEMPERATURE DEPENDENT INACTIVATION OF ENTERIC ORGANISMS

The principal factors influencing pathogen inactivation during high-rate sewage sludge treatment processes (eg anaerobic digestion and composting) are temperature and time, and desiccation is important in the case of passive air-drying of sludge. Temperature is the most influential factor affecting pathogen destruction and the treatment time required for their reduction or elimination (Sorber and Moore, 1987; Hall, 1995) (Figure 5.1). At high temperatures above 45°C protein denaturation takes place and causes the death of most microorganisms (Pike and Carrington, 1986; Hall *et al*., 1995). Ambient temperature conditions are also important and the rates of pathogen die-off increase proportionally to the rise in temperature (Kaneshiro and Stern, 1985; Hall *et al*., 1995). The other factor, time is also important, because, with the exception of bacteria, enteric pathogens are unable to reproduce outside the host organism and eventually loose viability when released in the environment. Whilst enteric bacteria may potentially reproduce and grow in the external environment under favourable conditions of moisture and substrate supply and in the absence of predation and competition from other environmental microorganisms, they are not well adapted to survival outside the host and are also generally highly vulnerable to decay with time (Figure 5.1). The time-temperature decay profiles illustrated in Figure 5.1 are widely followed to define the conditions necessary for the complete elimination of pathogens in sludge indicated by the 'safety zone'.

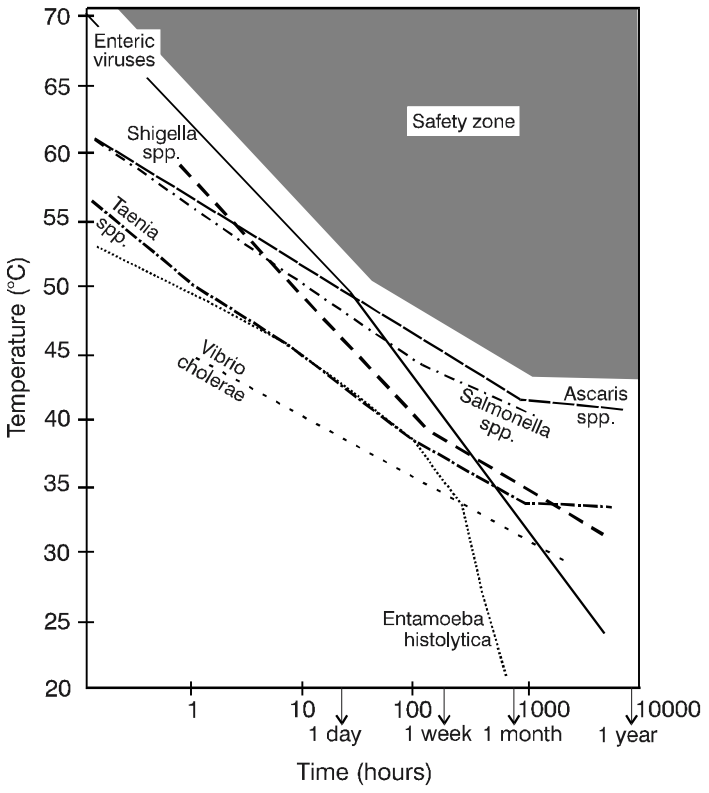

Figure 5.1 Time-temperature requirements for pathogen inactivation (Strauch, 1991; Carrington, 2001)

Pathogen survival at ambient temperatures is influenced by the pathogen type and physico-chemical conditions of the environment. The climate of Victoria (see Appendix 2) features different climate zones; it is hot and dry in the Mallee region and relatively cold in the Victorian Alps area, although temperatures usually only fall below 0°C at the highest altitudes. Melbourne and other large cities are located in the temperate climate; average annual maximum temperature in Melbourne reaching 19.8°C. The range of average annual minimum temperatures across Victoria is between 6-9°C and 0-3°C in the mountain area. Average maximum annual temperatures are between 15-18 °C in the central region (21°C in the north and 9-12°C in the mountains). The annual rainfall can be estimated at 500-800mm (by comparison, the average annual rainfall in the UK is 625-750mm in the south east region of England, 750-2500mm in the west, Wales and Scotland (SWA, 2005)). The Mallee region is the driest receiving 200-400 mm year of rainfall typically and the mountainous area has the most rain, 800-2400 mm. It can be assumed that sludge is treated in the central and north area, excluding the mountains. Under these conditions, it would take one month to inactivate *Entamoeba histolytica*, whereas *Ascaris* ova would persist much longer.

However, pathogen inactivation depends on many factors during sludge treatment and, in colder temperatures in anerobically digesting sludge, is particularly related to the inhibiting effect of fatty acids produced during digestion and the occurrence of other micro-organisms (Carrington, 2001).

Figure 5.2 presents the time-temperature relationship for the inactivation of *Taenia saginata* (human-beef tapeworm) eggs and *Ascaris* spp. ova to indicate treatment efficiency of thermophilic and pasteurisation treatment processes for sludge (Bruce *et al.*, 1990). These parasites are very resistant to adverse conditions and their elimination can therefore be taken to indicate the removal of other parasitic and pathogenic organisms (Feachem *et al*., 1983). Thus, at 50°C, both *Taenia* and *Ascaris* are reduced by ≥90 % (1 $\log_{10}$) in approximately 10 h. At 40°C, a longer time period is necessary and ≥90 % removal of *Taenia* occurs in approximately 3.5 days, for *Ascaris* the time period is 50 days.

Whilst the above relationships apply more strictly to active treatment methods involving some form of heating sludge, temperature and time of storage are also critical under ambient conditions. For example, O'Donnell (1984) measured the destruction rates of parasite eggs in stored liquid sludges to understand the fate of these agents of enteric diseases in sludge lagoons. Eggs from the roundworms, *Ascaris* spp., *Toxocara* spp., *Trichuris* spp., and the tapeworm, *Hymenolepis* spp., were treated with domestic sludges by aerobic or anaerobic processes. Sludge samples seeded with eggs were stored at 4 or 25°C or in a container inserted into the ground to simulate lagoon conditions. The number of eggs of all the species recovered from the samples decreased with storage time. The viability and infectivity of eggs recovered were related to the storage temperature and eggs stored at 4°C remained viable for longer than those stored at 25°C. After 25 months at 4°C, the *Toxocara* eggs and some *Ascaris* eggs remained both viable and infective, whereas most of these eggs stored at 25°C were rendered nonviable after 10 to 16 months of storage in sludge. Although storage temperature was found to be the most important factor affecting the destruction and viability of these eggs, other factors, such as the type of sludge digestion, whether or not the eggs were digested along with the sludge or added later, storage in the soil versus sludge, pH, and egg species also exhibited some minor effects. These controlled laboratory studies suggested that lagooning of sludge can be an effective method for the elimination of parasite eggs, particularly in warmer geographical locations. However, survival for more than three years was possible at the cooler temperature examined (4 ^{o}C).

The kinetics of pathogen destruction during storage of dewatered anaerobically digested biosolids (containing 33-52 % DS) were determined by Ahmed and Sorensen (1995) and the effects of temperature and duration of the storage period were quantified. Biosolids, seeded with *Salmonella typhimurium*, *Yersinia enteroeoliliea*, *Campylobacter jejuni,* bacteriophage f2, poliovirus, and *Ascaris suum* eggs were incubated at 5°,22°, 38°, and 49.5°C, under both aerobic and anaerobic conditions for up to 62 days. Destruction of pathogens in stored biosolids occurred at all temperatures examined and increased with increasing temperature. There was no significant difference between the destruction of pathogens under aerobic or anaerobic conditions at all temperatures studied. At 20°C, the decay rates of S. *typhimurium, Y. enterocolitica*, bacteriophage f2, poliovirus, and *A.* suum eggs were estimated to be approaximately 0.16, 0.13, 0.14, 0.08, and 0.01 $\log_{10}$ reductions per day, respectively (Table 5.1). Thus, Ahmed and Sorensen (1995) concluded that long-term storage of dewatered biosolids can be effective in reducing the risk of infection from the use of sludge on land. Storage was most effective at reducing numbers of enteric organisms when the storage period included a summer season when average ambient temperatures are ≥20 ^{o}C, which would be the case under ambient conditions in Victoria.

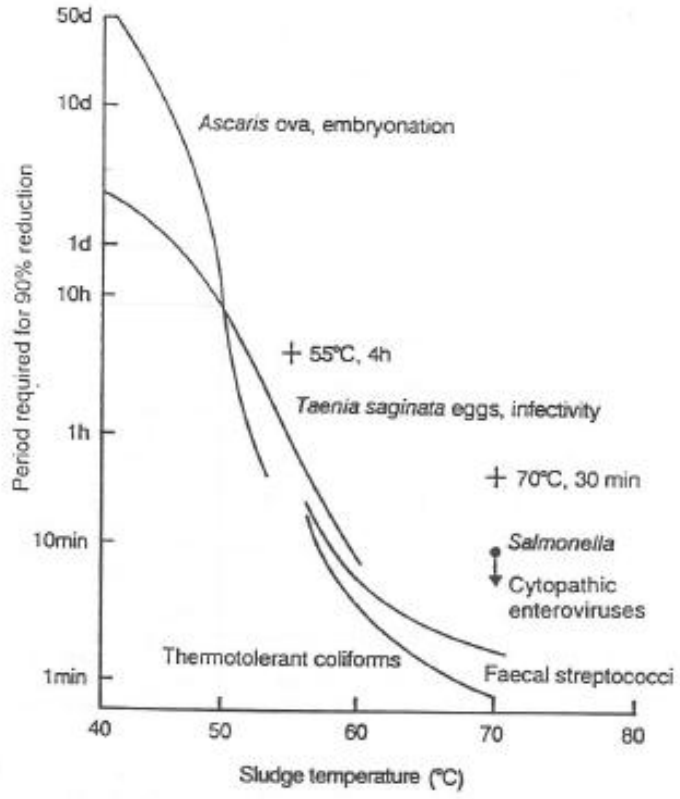

Figure 5.2 Time-temperature requirements for 90% pathogen inactivation. Crosses relate to temperature/time conditions specified in the UK Code of Practice (Bruce *et al*., 1990)

Table 5.1 Mean decay rates of enteric pathogens, parasites and indicators in dewatered anaerobically digested sewage sludge (Ahmed and Sorensen, 1995)

Organism	Decay rate (k) in log_{10} reductions day^{-1} at different temperatures (^oC)			
	50	35	20	5
Salmonella typhimurium	1.133	0.443	0.157	0.050
Yersinia enterocolitica	1.101	0.398	0.129	0.037
Bacteriophage f2	1.543	0.490	0.138	0.034
Poliovirus	0.813	0.276	0.084	0.022
***Ascaris suum* eggs**	0.211	0.043	0.008	0.001

Data for decay of salmonellas in digesting sludge stored at constant temperatures between 16 ^oC and 37 ^oC (Figure 5.3) show that decay increases with temperature (Pike, 1983). Over the range typical summer ambient temperatures:16-24 ^oC, the decimal reduction time, T_{90} was halved, or, in other words, the specific decay rate was doubled for a temperature increase of 4.5 ^oC (Figure 5.3). Rapid decay of *Salmonella* to below the detection limit was reported within one month by Jepsen *et al*. (1997) for dewatered anaerobic and aerobic stabilised sludges (containing 28 and 20 % DS, respectively) during warmer summer temperatures (20 – 30 ^oC) in Denmark (Figure 5.4). At winter temperatures (0 – 10 ^oC), however, the rate of decay was considerably slower and *Salmonella* were present after six months at the detection limit of 1 *Salmonella* 100 g^{-1}. However, the reductions achieved were also influenced by the initial concentrations of *Salmonella* in the sludge. Thus, before storage, sludge contained 100 *Salmonella* g^{-1} in the winter sample, but only 3 g^{-1} in the summer sample. The decay profiles measured in digested sludge were consistent with the rate values reported by Ahmed and Sorensen (1995) at 5 ^oC and 20 ^oC for the winter and summer temperature conditions, respectively. Jepsen *et al*. (1997), therefore concluded that storage had a very significant effect on the hygienic properties of sludge, especially on *Salmonella* reductions at temperatures ≥20 ^oC, although at temperatures <10 ^oC the effects of storage were relatively minor. Feacal streptococci were also monitored, but these showed not systematic reduction during storage. Therefore, Jepsen *et al*. (1997) considered them to be an unsuitable indicator of the hygienic properties of sludge during storage.

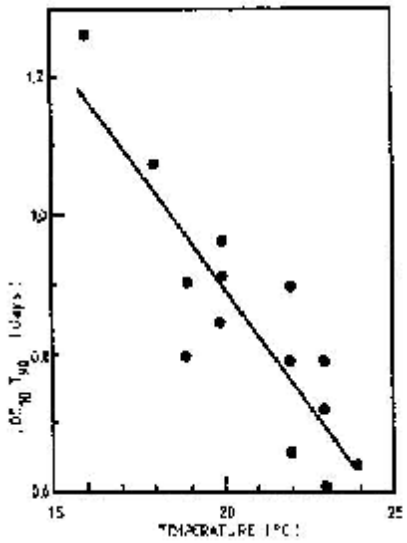

Figure 5.3 Effect of storage temperature on the decimal reduction time, T_{90}, of salmonellas in stored digesting sludge (Pike, 1983)

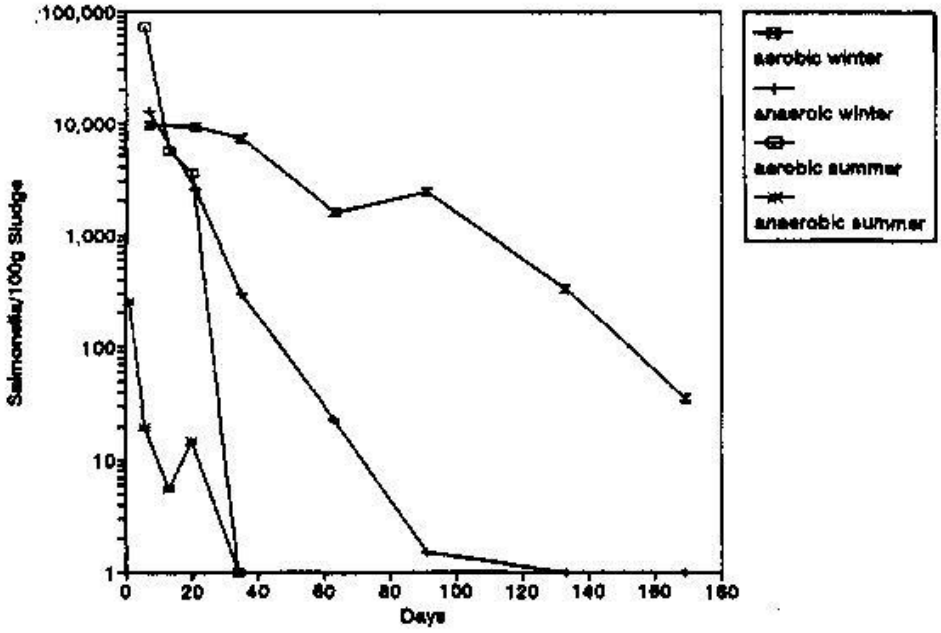

Figure 5.4 *Salmonella* decay during storage of aerobic and anaerobic sewage sludge during winter and summer seasons in Denmark (Jepsen *et al*., 1997)

6. STORAGE IMPACT ON PATHOGENS

6.1 Overview of effects of storage on inactivation of enteric organisms

Pike (1983) reviewed the impacts of long-term storage of sewage sludge on microbial pathogen survival. During the storage of sewage sludge, the viability and infectivity of most pathogens, except those that have long-lived and resistant resting stages (eg *Ascaris*), will decline. However, long-term storage is not a certain method for disinfecting sludge completely and this is not normally the principal aim, however, with heightening concern about environmental sources of enteric disease, and the associated adoption of increasingly stringent pathogen limits on sludge for recycling to land, the importance of pathogen reduction efficiency has increased. Storage may be used as a treatment for the stabilisation or further stabilisation of sludge (for example, lagoon or tank storage is used to achieve secondary digestion of sludge after primary mesophilic digestion - DoE, 1989), and this also reduces its dry matter content and its potentially odorous nature. Treatment in drying beds is also a form of storage used for dewatering sludge, which involves detention for several months. Storage is also a common feature of normal sludge management and recycling operations, in which sludge is held in lagoons or stockpiles until it can be transported and applied to land. Thus it provides a buffer between the production of sludge at the treatment works, and the fluctuations inherent in the availability of outlets or land for applying sludge.

Active disinfection involves destruction of the integrity of the microbial cell, its structures or of the mechanism of replication. These are involved with such measures as heat treatment and chemical disinfection. By contrast, storage may be regarded as a form of passive disinfection. It does not directly damage the cells as occurs with ‘active disinfection’, but it reduces the viability of pathogens, which die out mostly due to starvation and as a result of competition from other micro-organisms. At ambient environmental temperatures, enteric microorganisms adapted to life in the intestinal tract of warm-blooded animals, will rapidly be overgrown by other microoragnisms, although their presence in small numbers may be detected over long periods (Pike, 1983). Where conditions are wholly unfavourable, viability declines as endogenous metabolism of the cell utilises internal reserves of substrates. Dessication and damage by exposure to ultra-violet irradiation in daylight will also occur, but only at the surface of sludge (Pike, 1983).

In summary, the main inactivating effects of storage are achieved by (Pike, 1983):

- the reduction in water content;
- the mechanism of anaerobic digestion (microbial antagonism may inhibit enteric bacteria during digestion);
- starvation;
- microbial competition.

In the case of ova or other distributive stages of enteric parasites, Pike (1983) considered that their infectivity towards the host animal or man ingesting them would also decline with time. The ova of tapeworms (Cestoda) progressively decline in infectivity and largely become non-viable after 6 months from release from the mature proglottids. In the case of the Nematoda, eg *Ascaris lumbricoides*, the ova are fertilized internally and shed into faeces. At this stage the eggs usually contain two or four cells only and cellular division takes place under moist aerobic conditions in the environment (eg soil) to produce, after a few weeks, larval worms in the ova, able to infect after ingestion. Development to the infective stage is delayed by cold conditions

and is inhibited under anaerobic conditions in sludge. Although the ova of *Ascaris* can remain viable and infective for several years under moist conditions and are extremely resisitant, they are rendered non-viable by drying and exposure to UV radiation in daylight, as well as by heat treatment >55 ^{o}C.

Nicholson *et al*. (2004) reported that the maximum survival times of enteric pathogens in untreated livestock slurry was up to 3 months under UK temperate conditions, although pathogen survival times are longer in winter than in summer because of lower ambient temperatures – the average winter temperature in the UK is 5.6 ^{o}C and in summer is 14.1 ^{o}C. Solid manure storage for >1 month was reported to be sufficient to eliminate most pathogens, provided that auto-heating by composting activity occurred and temperatures reached >55 ^{o}C in the main body of the heap. This is possible with minimal management of bulky manure due to the combination of animal waste with bedding materials that favour composting activity to take place. This is more difficult with dewatered sludge cake, however, due to the high density and minimal porosity of sludge. In the case of livestock manure storage, however, periods exceeding 3 months were necessary to reduce pathogens to acceptable levels when autoheating did not occur (Nicholson *et al*., 2004). The UK Food Standards Agency (2005) therefore recommends the batch storage of solid manures and slurries for at least 6 months without additions of fresh manure to the store during this period in its draft *Guidelines for Growers to Reduce the Risks of Microbiological Contamination of Ready to Eat Crops: Managing Farm Manures For Food Safety.*

Jiménez and Nelson (2000) reported the effect of storage time on pathogen removal for raw sludge accumulated in a stabilisation pond in Mexico (Figure 6.1 and Table 6.1). This demonstrated significant reductions occurred in faecal coliforms and helminth ova counts. The inactivation was related to depth layer, which was linked to the age of the sludge (Jiménez and Nelson, 2000). It was assumed that sludge accumulated in vertical layers and the age of the sludge layers was inferred from this. Unfortunately, pathogen death rates could not be calculated because the initial concentrations of the pathogens were not known. Nevertheless, the analysis of the water/sludge interface showed 10^{7} MPN g^{-1} DS of faecal coliforms and the deepest layer of sludge contained $3.7x10^{3}$ MPN g^{-1} DS indicating approximately a 3.3 $\log_{10}$ reduction in the indicator organism. This would meet the 'Alternative 1' pathogen reduction criteria for biosolids treated US EPA Class B status for agricultural use (Appendix 1).

With regard to helminth ova, 85% constituted of *Ascaris* spp., and other species included: *Trichuris*, *Toxocara* and *Hymenolepis*. In Mexico, infections with enteric parasites are relatively common. Helminth ova remain a principal concern for the reuse of sewage sludge in the developing world, especially in rural areas (Jiménez *et al*., 2007). Therefore, under these conditions when helminth infections are prevalent in the human population and concentrations of viable eggs in sludge are high, it is essential that sludge treatment practices ensure the removal of these organisms if the sludge is to be used in agriculture. In the study in Mexico by Jiménez and Nelson (2000), the total concentrations of helminth ova decreased with depth (age), from an average value of approximately 50 eggs l^{-1} in the surface sludge to 14 eggs l^{-1} in the deepest layer. These results could be interpreted that the number of eggs in the sewage increased with time so that the deepest sludge shows less concentrations than the more shallow layers. However, the assumption that helminth eggs are destroyed with time is supported by the observation that the proportion of viable eggs increased with time. Consequently, it is plausible that there were initially more eggs present in the sludge, but that once they lost viability they were degraded and that only the viable eggs survived. The apparent presence of viable eggs in the deepest layer, which was estimated to be over eight years old, emphasised their potential longevity (Jiménez

and Nelson, 2000). However, it is possible that some mixing of the layers of sludge took place, so it is uncertain whether this work provides a realistic estimate of *Ascaris* survival in sludge storage lagoons. Most other studies performed on lagoons sampled without further sludge admixture show that *Ascaris* and other helminth parasites lose viability in much shorter periods of time than those recorded by Jiménez and Nelson (2000).

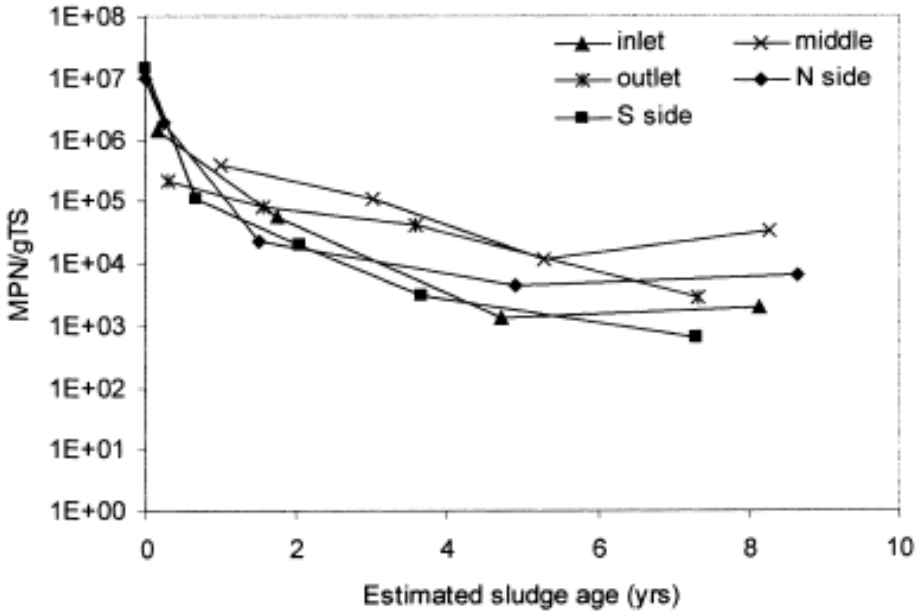

Figure 6.1 Faecal coliform concentrations as a function of age in a raw sludge stabilisation pond, Mexico (Jiménez and Nelson, 2000)

Table 6.1 Helminth ova concentrations as a function of depth in a raw sludge stabilisation pond, Mexico (Jiménez and Nelson, 2000)

		Sample location				
Estimated average sludge age (yrs)	Inlet	N side	Middle	S side	Outlet	Average
		Viable eggs per g TS/total eggs per g TS (percent viable)				
1.05	169/273 (62)	15/31 (48)	6.1/21 (29)	36/132 (27)	24/53 (46)	50/102 (42)
3.36	60/102 (59)	17/31 (55)	12/20 (59)	6.2/66 (9)	2.9/7.7 (38)	20/45 (44)
6.05	46/57 (81)	9.7/11 (85)	7.5/11 (67)	7.4/30 (24)	2.7/5.4 (50)	15/23 (61)
8.75	46/58 (79)	2.9/5.6 (52)	0.2/0.2 (100)	21/55 (38)	2.0/2.8 (74)	14/24 (68)

Pendersen (1981) reported the effect of sludge storage conditions (time and temperature) on pathogen removal and estimated the storage times necessary to achieve a 90 % reduction in pathogen content (Table 6.2). Based on these data, Pike (1983) predicted that bacteria and viruses would by reduced by 1 $\log_{10}$ within 8 months at ambient temperatures ≤20 ^{o}C , but, as would be expected, much longer storage was required to remove more persistent parasites.

Tests carried out in India on waste from an Oxfam toilet (Carrington, 1980), at ambient temperatures, showed reductions of above 95% in pathogen levels after 3 months of storage (Table 6.3), but presumably conditions would be relatively warm in that region. Although dates of the tests were not indicated, average temperatures in India vary between 16-24°C in January and 24-32°C in July (SWA, 2005), therefore it may be assumed that the temperature was probably above 20°C.

Table 6.2 Inactivation of pathogens by sludge storage (Pike, 1983)

Reduction of 90%, ≥ 20°C		Reduction of 90%, ≤ 20°C
Bacteria	- 1 month retention	Over 6 months retention
Viruses	- over 2 months retention	Over 8 months retention
Parasite ova	- 6 months retention	At least 3 years retention

Table 6.3 Inactivation of pathogens by anaerobic digestion (at ambient temperature) (Carrington, 1980)

Pathogen	Tank with liquid waste retained anaerobically for 8 days	Tank with solid waste retained anaerobically for 3 months
Cholera vibrios	98.95 % reduction	99.87 % reduction
Salmonella	87.7 % reduction	98.7 % reduction
E. coli	Similar to *Salmonella* reductions	Similar to *Salmonella* reductions
Nematodes ova	96.27 % reduction (caused by sedimentation)	97.82 % reduction (caused by sedimentation)

Overall, the consensus of opinion amongst researchers is that the efficiency of liquid sludge storage (Note: primary liquid digested sewage sludge typically contains 2 – 5 % DS) at pathogen removal is generally considered to be moderate to good (Table 6.4 and 6.5), although the published data are not entirely consistent. Most of the scientific evidence indicates storage typically achieves ≥90% inactivation of bacteria and viruses (Toze, 1997). No health impacts have been reported (RCEP, 1996) from the use of sludge treated to this standard under circumstances when the general population is free from helminth infections and consequently sludge does not contain significant concentrations of helminth eggs or ova (ie ≥1 g^{-1} DS; WHO 2006). Processes that can ensure at least 90% destruction of main pathogen types have been described as an 'effective' treatment (Bruce *et al*., 1990; Hall *et al*., 1995), therefore, long-term storage of liquid sludge may also be considered as an effective treatment method (DoE, 1989).

However, other work has qualitatively classified the efficiency of pathogen removal by long-term lagoon storage of liquid sludge, certainly for bacteria and viruses which are usually the main enteric organisms of concern in industrialised societies, as 'good' (Table 6.6) (Farrell and Stern, 1975; Carrington, 1978) and capable of almost total pathogen destruction (Godfree and Farrell, 2005). The efficiency of destruction is increased by batch operation and avoiding admixture of raw sludge to the treated material.

Estimated survival times and decimal reduction values of pathogens during storage of sewage sludge or faeces at 20 – 30 ^{o}C are listed in Table 6.7 and 6.8 (WHO, 2006). With the exception of resistant helminths, maximum survival times are generally <100 days and are usually much shorter than this.

Table 6.4 Efficiency of treatment by storage as compared to other methods (Van Oorschot, 2000)

Process	Stabilisation	Pathogen reduction	Reduction of water content
Alkaline stabilisation:			
• Custom processes	►►	►►	►
• N-VIROTM Soil	►►►	►►►	►
• RDP Envessel pasteurisation	►►►	►►►	►
Anaerobic digestion	►►	►►	►
Autothermal thermophilic aerobic digestion ATAD	►►►	►►►	►
Aerobic digestion	►►	►	►
Incineration	►►►	►►►	►►►
Composting	►►►	►►►	►
Sludge lagoon	►►	►►	►►
Wet air oxidation/Vertech process	►►►	►►►	►
Thermal drying	►►►	►►►	►►►
Oil from sludge technology OFS	►►►	►►►	►►►
Active Sludge Pasteurisation ASP	►►►	►►►	►►►
Filter presses	►►	►►	►►
Drying pans	►►	►►	►►►
Drying beds	►►	►►	►►►

►►►=Good
►►=Medium
►=Poor

Table 6.5 Efficiency of treatment by storage in relation to main types of pathogens (Carrington, 1980)

Process	Poor	Moderate	Good
Raw Sludge Storage	*Ascaris* ova *Taenia* ova	Viruses Bacteria	-

Table 6.6 Efficiency of treatment by long-term lagoon storage of sewage sludge for pathogen removal as compared to other treatment methods (Farrell and Stern, 1975; Carrington, 1978)

Process	Evaluation
Anaerobic digestion	Fair
Aerobic digestion	Fair
Lime treatment	Good
Pasteurisation (70°C)	Excellent
Irradiation	Excellent
Heat treatment (195°C)	Excellent
Composting (60°C)	Good
Lagooning (long-term)	Good

Table 6.7 Survival times of enteric organisms and time needed for 90 % reduction (T_{90}) during storage of sewage sludge at 20 – 30 °C (WHO, 2006)

Organism	Survival (days)	T_{90} (days)
Bacteria		
Thermotolerant coliforms	<90 usually <50	15 - 35
Salmonella	<60 usually <30	10 - 50
Viruses	<100 usually <20	Rotavirus: 20 – 100 Hepatitis A: 20 – 50
Protozoa (*Entamoeba*)	<30 usually <15	*Giardia*: 5 – 50 *Cryptosporidium*: 20 – 120
Helminth (eggs)	Several months	*Ascaris*: 50 - 200

Table 6.8 Decimal reduction times (T_{90}) for enteric organisms during storage of sewage sludge or faeces (WHO, 2006)

	T_{90} faeces (days, mean ± standard deviation)
Salmonella	30 ± 8
EHEC	20 ± 4
Rotavirus	60 ± 16
Hepatitis A virus	55 ± 18
Giardia	27.5 ± 9
Cryptosporidium	70 ± 20
Ascaris	125 ± 30

A summary of the effects of ambient temperature storage of dry excreta and faecal sludge, which has not been previously treated by a stabilisation process, such as anaerobic digestion, is shown in Table 6.9 (WHO, 2006). For dry excreta and faecal sludge, which has not received any previous treatment, WHO (2006) recommend storage for 1.5-2 years when ambient temperatures are in the range 2-20 ^{o}C and >1 year when the ambient temperature is >20-35 ^{o}C.

6.2 Bacteria inactivation

In contrast to certain helminth ova, long-term lagoon storage of liquid digested sludge provides very effective removal of salmonellae, however it does not ensure complete inactivation (Hall *et al*., 1995).

Table 6.9 Recommendations for storage treatment of dry excreta and faecal sludge before use (WHO, 2006)

Treatment	Criteria	Comment
Storage; ambient temperature 2–20 °C	1.5–2 years	Will eliminate bacterial pathogens; regrowth of *E. coli* and *Salmonella* may be considered if rewetted; will reduce viruses and parasitic protozoa below risk levels. Some soil-borne ova may persist in low numbers.
Storage; ambient temperature >20–35 °C	>1 year	Substantial to total inactivation of viruses, bacteria and protozoa; inactivation of schistosome eggs (<1 month); inactivation of nematode (roundworm) eggs, e.g. hookworm (*Ancylostoma/Necator*) and whipworm (*Trichuris*); survival of a certain percentage (10–30%) of *Ascaris* eggs (≥4 months), while a more or less complete inactivation of *Ascaris* eggs will occur within 1 year (Strauss, 1985).
Alkaline treatment	pH >9 during >6 months	If temperature >35 °C and moisture <25%, lower pH and/or wetter material will prolong the time for absolute elimination.

Table 6.10 shows the geometric mean counts of *Salmonella*, pre- and post-lagooning sludge, at 5 WwTP by Pike (1983) in the UK. The tests demonstrated pathogen reductions of 91.4-99.2% (between 1- and 2-$\log_{10}$). The lowest mean numbers of *Salmonella* were measured during the summer period and highest in winter (Pike, 1983).

Significant reductions in *Salmonella* counts were achieved after 6 months of storage and were consistent with other reported data (eg Jones, 1975). However, numbers of *Salmonella dublin* did not decline after storing cattle slurry for 36 days (Jones, 1975). In contrast, *Salmonella* was inactivated after 60 days storage of dehydrated sludge (Gantzer *et al*., 2001). However, Gibbs *et al*. (1995) did not detect any change in *Salmonella* numbers after 6 months storage. Other tests for *Salmonella* in sludge carried out by Thames Water Authority in the UK were inconclusive about the effects of storage on removal (Table 6.11), but in this case only presence/absence of the bacteria was determined and it is not possible from these results to elucidate the effect of storage on the decay in numbers of the pathogen. Surampalli *et al*. (1993) reported a 1 $\log_{10}$ reduction in indicator bacteria (faecal coliforms and faecal *Streptococcus*) and *Salmonella* after storing aerobically and anaerobically digested sludges for 30 and 42 days at 20 ^{o}C, respectively.

Table 6.10 Inactivation of *Salmonella* by lagooning sewage sludge (Pike, 1983)

Works and features	Period of sampling	*Salmonella* per 100 ml (no. of samples)		Fraction remaining
		Input	Output	
Mixed primary and activated sludge, mainly domestic. Retention up to 1 year; sludge mostly removed in late spring and summer	over 12 months	770 (87)	23 (87)	0.03
Primary sludge, mainly domestic, retention up to 6 months	April - September	140 (17)	12 (14)	0.086
Domestic; 5 lagoons in series retention up to 1 year	-	827 (4)	26 (4)	0.031
Domestic sludge, mesophilically digested 10-15 d, lagooned 6-8 weeks	-	325 (4)	2.6 (4)	0.0080
Mixed domestic and industrial sludge; circulated between two lagoons, retention up to 6 months	-	89 (4)	9.0 (4)	0.010

Table 6.11 Inactivation of *Salmonella* by lagooning (Pike, 1983)

Works G	9/20 (45%) samples positive	Lagooned for less than 2 years
Works F	5/41 (12%) samples positive	25% of samples came from sludge treated less than 2 years; 4% of samples from sludge treated more than 2 years

No *Salmonella* or faecal coliforms were detected by Gibbs *et al*. (1995) in dewatered digested sludge after 34 weeks storage with mean weekly minimum and maximum sludge temperatures of 13.5 to 21.4 ^{o}C, respectively. However, both organisms were detected at week 52. This was unrelated to changes in the moisture content or temperature of the sludge that could encourage regrowth, as both these parameters were decreasing at this time. It appeared that the occurrence of the enteric organisms was explained by recolonisation (Zaleski *et al*., 2005) due to contamination from animal faeces, which was possibly washed through surface cracks into the sludge pile. Faecal streptococci declined to approximately 1000 g^{-1} wet weight by week 24, but concentrations increased to more than 5 $\log_{10}$ g^{-1} wet weight with no obvious change in conditions to explain the increase. Jepsen *et al*. (1997) have considered that Faecal streptococci were unsuitable as an indicator of the microbiological quality of stored biosolids.

Salmonella survival during storage is influenced by ambient temperature conditions. Thus, *Salmonella typhi* were found after 80 days of storage of activated sludge at 10-16°C but were not detected after 13 days storage at 20-21°C (Ruchhoft, 1934; Carrington, 1978). The effect of temperature, however, decreases over time. The reduction rates of *Salmonella Typhimurium* were 1.2 ± 1.0, 1.8 ± 0.3 and 3.8 ± 0.5 log MPN g^{-1} DS of sludge at 7°C, 13°C and 21°C, respectively, but declined over time in

the case of 13 and 21°C (Berggren *et al*., 2004), whereas the reduction rate remained constant at 7°C. Consequently, factors other than temperature became more important in controlling decay at the later stages. After 214 days (7 months) storage, *Salmonella* was completely eliminated at all 3 storage temperatures (Figure 6.2) (Berggren *et al*., 2004). Haible (1989) showed that *Salmonella* spp. were eliminated from aerobically and anaerobically stabilised sewage sludge after 5 months storage, regardless of storage conditions. After one year, faecal *Streptococcus* spp. were reduced to 105 g^{-1} DS and Enterobacteriaceae were ≤104 g^{-1} DS in uncovered sludge. The results showed that anaerobically digested sludge may be stored uncovered regardless of when storage begins, but aerobically digested sludge should be covered if storage begins in winter, to avoid potential recolonisation.

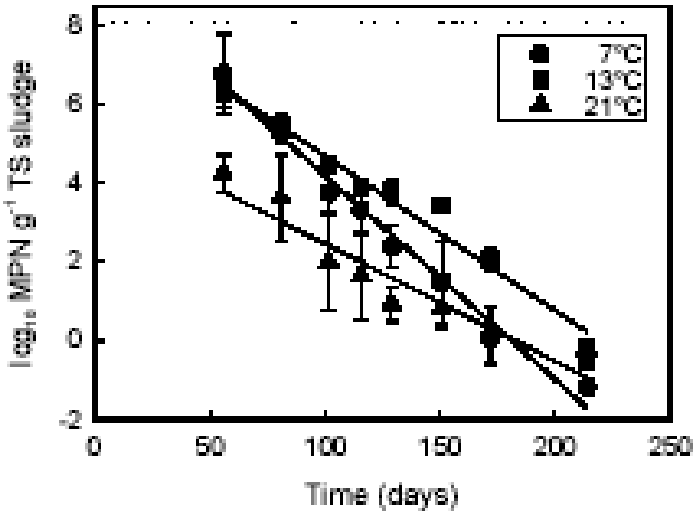

Figure 6.2 Effect of storage at different temperatures on the survival of *Salmonella Typhimurium* (Berggren *et al*., 2004)

In the UK, storage of unstablised sludge for at least 3 months was required for use in agriculture to ensure effective treatment (DoE, 1989). This is no longer practiced, however, as it generated major odour niusance and active management and treatment to stabilise sludge eg by anaerobic digstion before secondary storage is the preferred approach. However, a national survey of the operational performance of treatment facilities at reducing numbers of the indicator bacteria, *E. coli*, is sludge confirmed that lagooning achieved a 2 $\log_{10}$ reduction in *E. coli* (Table 6.12) (UKWIR, 1999; EA, 2003). Specifically, the mean reduction shown was 2.65 $\log_{10}$ and the mean numbers of organisms that survived the treatment was 5.93 $\log_{10}$ 100 g^{-1} DS (approximately 10^6 organisms per 100 g^{-1} DS, equivalent to 10^4 g^{-1} DS). In the UK, average mean temperatures the south in January are 4-6°C and 16°C in during the summer period in July. Consequently, lagooned sludge complies with the pathogen reduction requirements for conventionally treated and Class A biosolids in the UK Safe Sludge Matrix and US EPA Final Part 503 Rue (US EPA, 1993). However, reductions as high as 5 $\log_{10}$ were observed for lagooned sludge at particular WwTP (Godfree and Farrell, 2005). The effect of air-drying sludge on indicator bacteria, and pathogen numbers, is variable and may range from 0.5 to greater than 4 $\log_{10}$ (Table 6.13).

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Table 6.12 Reduction in *E. coli* counts achieved by different sludge treatment methods (UKWIR, 1999; EA, 2003)

Sludge treatment	Number of sites	Number of samples	Mean log-transformed Reduced count before and after treatment of *E.coli* per 100 g of sample (based on dry weight)	Mean log-transformed count of *E.coli* per 100 g of sample after treatment (based on dry weight)
Lagooning	2	36	2.65	5.93
MAD, liquid *	14	208	1.39	7.41
MAD, cake	5	93	2.29	6.65
Vermiculture	1	14	5.12	4.50
Composting	2	31	6.71	2.43
Lime addition	3	32	7.10	1.45
Thermal drying	4	70	7.14	1.67

* After primary digestion

Table 6.13 Pathogen and indicator removal by air-drying sludge relative to other treatment processes (Godfree and Farrell, 2005)

	Log reduction		
Treatment	**Coliform bacteria**	**Enteric viruses**	**Parasites**
Mesophilic anaerobic digestion	**0.5 to 4**	**0.5 to 2**	**0**
Aerobic digestion	**0.5 to 4**	**0.5 to 2**	**0**
Composting	**2 to >4**	**2 to >4**	**2 to >4**
Air-drying	**0.5 to 4**	**0.5 to >4**	**0.5 to >4**
Lime stabilization	**2 to >4**	**>4**	**0**

In contrast to the storage of liquid sludge, tests on *E. coli* removal during the storage of mechanically dewatered sludge showed that the treatment did not significantly reduce *E. coli* counts (Figure 6.3; Gantzer *et al.*., 2001). Storage periods of up to 120 days are typically practised in the UK for primary digested sludge that is immediately dewatered mechanically by centrifugation, without a period of secondary liquid storage, to comply with the pathogen reduction requirements specified in the Safe Sludge Matrix. Reactivation and regrowth of *E. coli* have been observed under these circumstances (Cheung *et al*., 2003; Qi *et al*., 2004), but this is not a phenomena observed with other mechanical dewatering techniques (Cooper *et al*., 2005) or sludge that is treated to stabilise the organic matter by anaerobic digestion followed by lagooning, air-drying and storage. Regrowth would be possible for instance if air-dried and stored raw sludge were to become rewetted (Zaleski *et al*., 2005; WHO, 2006). Similar patterns of reduction and regrowth were observed in trials in Victoria at Warrnambool (see Section 9) and this may be linked to rainy periods or warm weather (Edmonds, 1976; Gantzer *et al.*, 2001), or recolonisation with enteric bacteria due to contamination form faeces of wild animals and birds (Gibbs *et al*., 1995; Zaleski *et al*., 2005). Yeager and Ward (1981) observed the regrowth of enteric bacterial species inoculated into sterile raw sludge at 37 ^{o}C containing ≤75 % DS, but no growth was observed in samples containing ≥85 % DS. Furthermore, the presence of a community of indigenous microorganisms in sludge significantly reduced the extent of regrowth of *Salmonella typhimurium* seeded into sludge compared to inoculation of sterile samples. The

numbers also declined to below detectable limits within a few days in sludges containing viable indigenous microorganisms, whereas little decrease occurred with salmonellae grown in previously sterilised sludges (Yeager and Ward, 1981). Sidhu *et al*. (2001) also showed that the indigenous microflora play a significant role in suppression of *Salmonella* regrowth in composted biosolids.

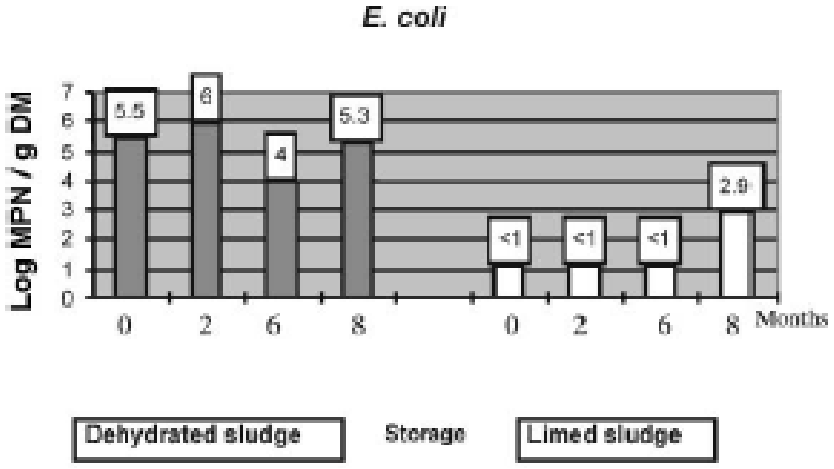

Figure 6.3 Effect of storage time on *E. coli* numbers in mechanically dewatered and lime-amended sewage sludge (Gantzer *et al*., 2001)

Garrec *et al.* (2003) reported *Listeria* spp. and *L. monocytogenes* were found respectively in 87 % and 73 % of different dewatered sludge types and in 96 % and 80 % of sludges stored in tanks. Numbers of *L. monocytogenes* were in the range 0.15-20 MPN g^{-1}DS in dewatered sludge and 1-240 MPN g^{-1} DS in stored sludge, but did not show seasonal trends. However, added *Listeria* decay relatively rapidly in the soil environment. *Listeria* are also found to be ubiquitous in the native soil microbial community and, after incorporation of sludge into soil, there would be no net contribution to the numbers naturally present in the soil environment (Rogers *et al*., 2008).

The effects of long-term storage with occasional mixing of biosolids on survival of different pathogenic bacteria species including *Salmonella typhimurium, Yersinia enterocolitica* and *Campylobacter jejuni*) was investigated by Ahmed and Sorensen (1997). These field investigations were performed at 5 WwTP in Utah with dewatered digested and air-dried sludge seeded with the pathogens. Pathogenic organisms were reduced to below detection limits in all the sludge piles within a year, irrespective of whether the piles were turned or if autoheating (which can achieve temperatures of 50-57 ^{o}C) occurred.

6.3 Virus inactivation

Haible (1989) reported that aerobic and anaerobic sludge samples were free of enteroviruses after storage for 1 year. Baron *et al*. (1989) measured more rapid die-off of faecal indicator organisms than enteroviruses and parasitic ova, except for *Clostridium* spp in biological sludges stored for 4 months under temperate conditions. By contrast concentrations of enteroviruses paralleled changes in the numbers of faecal coliforms in the microbiological assessment of lagooned sludge by Farrah *et al*. (1981). Enteroviruses dropped to low or undetectable values when the addition of digested sludge to the lagoon was suspended, and also when the sludge was applied

to soil. Poliovirus serotypes accounted for <90 % of all viruses identified initially, but these are evidently sensitive to decay as they declined to <40% of viral isolates, and echoviruses and coxsackieviruses were the most common enteroviruses identified. Decay of indigenous enteric viruses during of storage of settled primary and mixed-liquor activated sludges is reported by Hurst and Goyke (1986). Virus survival was statistically dependent upon storage temperature, but not sludge type or DS content. Based upon the observed rates of inactivation, the average times required for 90 % inactivation were 26 days at 23 ^{o}C, 180 days at 2 ^{o}C, and 163 days at -70 ^{o}C, although the rates of inactivation were not statistically significant for the two coler temperature regimes. Brewster *et al*. (2005) found that reovirus was more resistant to increased temperature and persisted for longer during storage than poliovirus, but was not detected in sludge after storage for one year under ambient conditions. Decay rates of enteric viruses during storage of digested sludge are likely to be faster than for undigested sludge types due to the virucidal effects of ammonia in the sludge (Ward and Ashley, 1977a)

6.4 Parasites inactivation

Infections by intestinal parasites are usually rare in most developed countries. However, giardiasis, caused by the enteric protozoa *Giardia lamblia* was the most common cause of enteric disease in Western Australia in the early 1990s and, consequently, large concentrations of *Giardia* cysts were detected in anaerobically digested sewage sludge from WwTP in Perth (Hu *et al*., 1996). The concentration of cysts in digested sludge was reported as 4000 g^{-1} DS, which is considerably higher (10x) than typically reported for contemporary sewage sludge (Soares *et al*., 1994; Chauret *et al*., 1999). The population declined to 1000 cysts g^{-1} DS after 3 months storage of 40 m^3 batch of dewatered cake at 20 – 30 % DS, and subsequently remained at this concentration for the duration of the monitoring period of 60 weeks (Hu *et al*., 1996). In a second storage trial no consistent trend in cyst destruction was observed and concentrations varied from 1000 to 8000 cysts g^{-1} DS during a 24 week monitoring period, which could be explained due to variability in the sampling procedures. In a related experiment by the same group, Gibbs *et al*. (1995) also reported that average *Giardia* concentrations remained stable at over 1000 cysts g^{-1} wet weight (sludge DS started at 12 % and increased to 30 % by the end of the study). The average weekly minimum and maximum sludge temperatures recorded at a depth of 20-40 cm in this study were 13.5 – 22.1 ^{o}C. However, the enumeration methodology did not distinguish between viable and non-viable cysts and also the sludge was stored in a wet condition whereas storage combined with drying sludge is reported as highly effective at parasite destruction. Indeed, *Giardia* concentrations declined rapidly when sludge was incorporated into soils and were generally not detected after two weeks, which may been due to the low moisture content of the soil (<5 %) (Hu *et al*., 1996).

Sludge storage for 6 weeks at >20 ^{o}C is expected to destroy the viability of *Giardia* cysts (Feachem *et al*., 1983).

Ascaris is highly resistant to adverse physical and chemical conditions and its destruction is indicative of the removal of all other pathogenic oprganisms as well (Feachem *et al*., 1983). .*Ascaris* ova develop into the infective stage in the soil under favourable conditions – temperature range of 23-33°C, adequate moisture and oxygen supply. Provided that the conditions remain favourable, the ova remain infective for several years (Pike, 1983; Hall *et al*., 1995). They are also very resistant to chemical disinfection. They are also destroyed by heating. Thus, dry and warm climates provide better conditions for the elimination of the parasite, with rapid die-off rates at sludge moisture contents of 5% (Hall *et al*., 1995).

The development of nematode ova into the infective stage is delayed by cold temperature and inhibited under anaerobic conditions (Pike, 1983). *Ascaris* ova survive sludge digestion at 30°C for 3 months, whereas hookworm ova were inactivated after 64 days at 20°C and 41 days at 30°C (Carrington, 1980), and early studies suggested both species survive air-drying (Rodulfs *et al*., 1950; Carrington, 1978). Temperatures of 7 and 13°C had no effect on the viability of *Ascaris suum* ova during 214 days (7 month) storage (Berggren *et al*., 2004). It was concluded that inactivation required higher temperatures and/or longer storage to eliminate the eggs. Storage at 21°C for the same duration reduced the viability of the ova between 81-99%. The pH value also declined reduced during treatment to 2.0 (7°C), 2.7 (13°C) and 1.5 (21°C) and this may also have been another factor affecting ova survival (Berggren *et al*., 2004).

Cherubini *et al*. (2002) examined the effects of combining drying followed by solarisation to heat sludge (maximum temperature was 37 ^{o}C) and *vice versa* over a period of 60 days on the inactivation of helminth eggs in anaerobically digested sludge in Brazil. *Ascaris* was the most prevalent helminth and by day 60, drying followed by exposure to solar radiation reduced the number of viable eggs by 30 %. Monitoring pathogen destruction during storage of seeded dewatered digested and air-dried biosolids at 5 WwTP in Utah, USA, Ahmed and Sorensen (1997) showed that *Ascaris suum* eggs were not detectable within 1 year irrespective of turning regime or whether there was evidence of autoheating. They concluded that storage time was the most important factor in the destruction of *A. suum* eggs. Haible (1989) reported the viability of the eggs of *Ascaris suum* decreased from 100 to 14 % after 11 months' storage of aerobically and anaerobically digested sludges, and, based on the overall reductions of enteric bacteria, viruses and *Ascaris* that recommended a minimum storage period for digested sludge of 1 year for complete hygienisation of the sludge. Time was also the most important factor reducing viability of eggs of *Ascaris suum* during storage and drying of sludge at Slovakian WwTP (Plachy and Juris, 1995). At one WwTP there was a rapid reduction in viable eggs from October to December from 80.4 % at the beginning of the experiment to 19.8 % in December. The rate of inactivation subsequently decreased and after 240 days only 5 % of the eggs remained viable. Temperature also had a significant impact on destructions rates. For example, at another plant that experienced cooler ambient temperatures, the rate of inactivation was slower and 36 % of eggs were viable after 320 days of drying and storage. However, at both sites, the moisture content of the sludges remained relatively high and only increased from approximately 2 – 4 % to 14 – 19 %, which is unlikely to significantly impact the survival of the parasite (see Section 7.4).

Apart from *Ascaris* spp., other persistent types of helminths are *Trichuris* and *Taenia*. Storage improves helminth ova destruction when accompanied by air-drying. Nevertheless, the time required may be as long as several months (Hall *et al*., 1995).

Baron *et al*. (1989) found that storage of biological sludges for four months under temperate conditions had little effect on coccidium and amoeba cysts removal, whereas the numbers of *Ancylostoma* eggs were reduced. Chevrier *et al*. (1988) stored domestic and abattoir sewage sludge for 4 months and also showed that the number of protozoal cysts was unaltered whereas helminth eggs declined significantly with increasing duration of storage. Numbers of parasite ova measured in lagooned sludge in Greater Chicago in 1976-77 were, *Ascaris* = 203 per 100 g DS (the most abundant), *Toxocara* = 173 per 100 g DS, *Toxascaris leonine* = 48 per 100 g DS and *Trichuris* = 36 per 100 g DS. Embryonation rates of ova from freshly digested sludge

were 64, 53, 63 and 20 %, respectively, and corresponding values for lagooned sludge were reduced to 24, 10, 43 and 6 %.

A summary of helminth removal efficiencies of different sewage sludge treatment processes provided by WHO (2006) is listed in Table 6.14. This indicates that a 3 log_{10} removal may occur in 4 months in sludge settling ponds, which is similar to the level of removal possible with advanced thermophilic treatment processes over a 1 – 5 day period, and drying for approximately 2 weeks may achieve approximately a 0.5 log_{10} removal (WHO, 2006).

Table 6.14 Helminth removal in different sewage sludge treatment processes (WHO, 2006)

Treatment option or process	Helminth egg log reduction	Duration
Low-cost		
Faecal sludge settling ponds	3	4 months
Faecal sludge reed drying beds (constructed wetlands)	1.5	12 months
Drying beds for dewatering (pretreatment)	0.5	0.3–0.6 months
Composting (windrow thermophilic)	1.5–2.0	3 months
pH elevation >9	3	6 months
Anaerobic (mesophilic)	0.5	0.5–1.0 month
High-cost		
pH elevation >12	3	
Thermophilic, in-vessel (aerobic/anaerobic)	3	1–5 days

Gantzer *et al*. (2001) measured the concentrations of nematodes after dehydrating sludge and in limed sludge storage in France (Table 6.15). The nematode eggs identified included:

- *Ascaris* - 34.8%;
- *Trichuris* - 34.8%;
- *Toxocara* - 13.7%;
- *Capillaria* – 13.8%.

The initial numbers of eggs in raw sludge were variable: 2-53 eggs 10 g^{-1} DS (total eggs) and 2-45 eggs 10 g^{-1} DS (viable eggs). Storage of limed sludge consistently reduced both total and viable ova counts (this could also be possibly explained by the

physical dilution with lime addition). In case of dewatered sludge, storage reduced the number of viable eggs, but not sufficiently to meet US EPA Class A pathogen requirements of <1 4 g^{-1} DS for *Biosolids Treated in Other Processes* and *Biosolids Treated in Unknown Processes* (Appendix 1).

Table 6.15 Reductions in nematode eggs by storage(1) of dehydrated and lime-amended sewage sludge (Gantzer *et al*., 2001)

Sludge type	Duration	Total nematode eggs (mean 10 g^{-1} DS)	Total viable nematode eggs (mean 10 g^{-1} DS)
Storage of dehydrated sludge	0 d	23	6
	60 d (2 months)	12	1
	180 d (6 months)	7	2
	240 d (8 months)	7	3
Storage of limed sludge (slaked lime 62%), pH=11.2	0 d	29	13
	60 d (2 months)	16	5
	180 d (6 months)	8	<1
	240 d (8 months)	8	<1

(1)Sludge stored in the open-air but sheltered from rain

Cysticercosis due to *Taenia saginata* is one of the major risks to cattle when sewage sludge is used to fertilise grassland grazed by cattle. Outbreaks of the disease in cattle are usually related to poor human hygiene and faecal waste disposal practices, or the accidental overflooding of municipal wastewaters onto pastures (Cabaret *et al*., 2002). Indeed, Cabaret *et al*. (2002) considered that the normal controlled application of treated sewage sludge on grassland represented a low risk of causing cysticercosis. *Taenia* ova do not represent a risk when applied to cultivated agricultural land due to the rapid incorporation of sludge into the soil (Barbier *et al*., 1989).

The ova of Cestodes (eg *T. saginata*) become non-viable after around 6 months in the outside environment (Pike, 1983)**.** *Taenia* ova are eliminated after 6 months of storage in tropical climates and the process can be hastened if the moisture content of sludge falls below 10% during storage (Hall *et al*., 1995).

An epidemiological study by Pike (1986) demonstrated that accelerated cold digestion at 3°C (performed in 2 tanks, each retaining sludge for 50d) is one of the most effective processes that ensure at least 90% reduction of the infectivity of *T. saginata* ova in calves. Other processes that showed the similar efficiency were: thermophilic aerobic digestion at 50°C for 6 days; lime treatment for 1-2 days with initial pH of 12; pasteurisation at 52°C for 3 h combined with anaerobic digestion at 35°C and retention for at least 24 hours and pasteurisation at 55-60°C for 3 hours.

Lagooning sludge at 7°C for 29 days reduced the infectivity of *T. saginata* ova in calves by at least 99% Other treatments capable of achieving similar activation rates were anaerobic digestion at 35°C for 30 days followed by lagooning at 7°C for 15 days and pasteurisation at 55-60°C for 3 hours combined with anaerobic digestion at 35°C for 30 days (Figure 6.4; Pike, 1986).

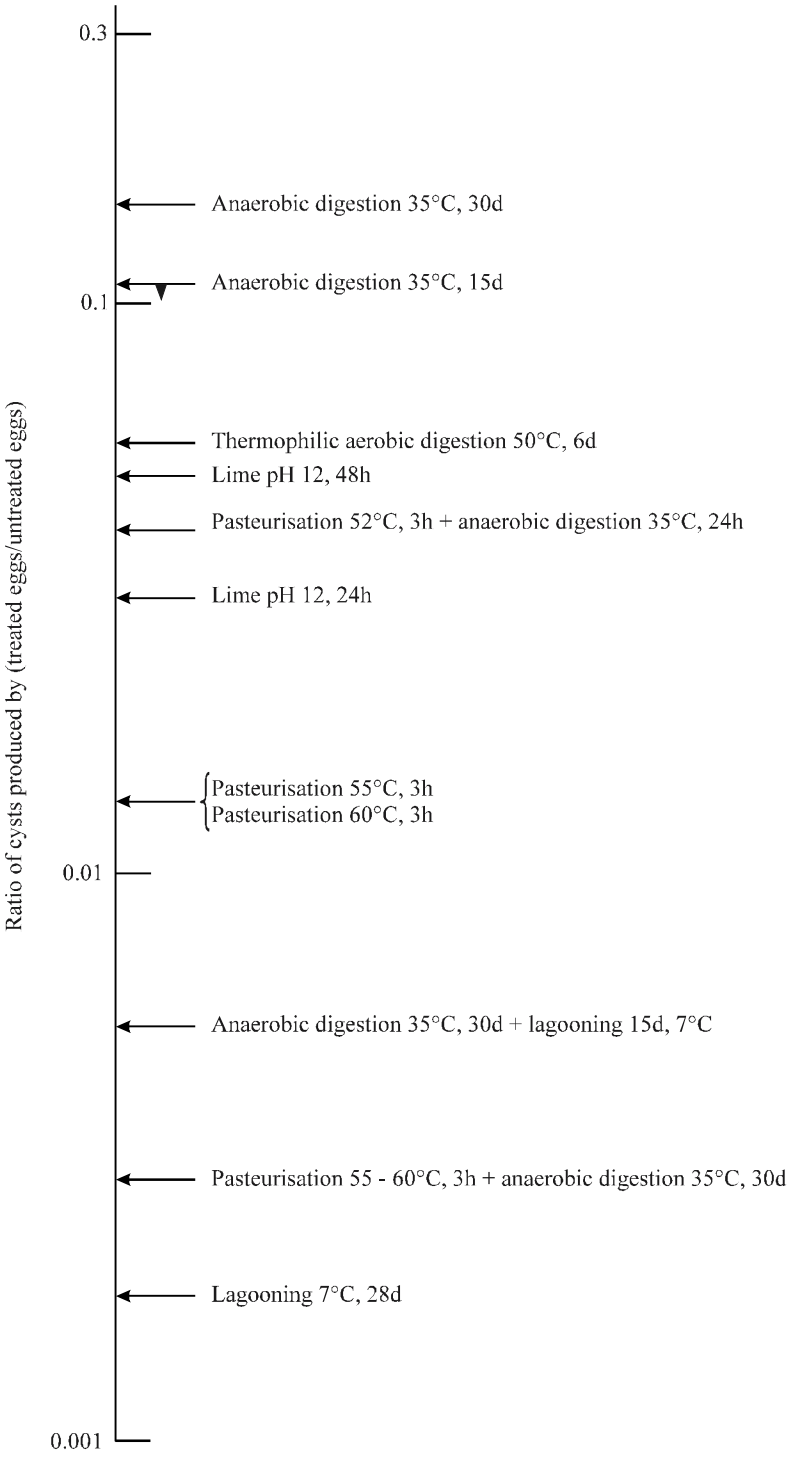

Figure 6.4 Efficiency of various sludge treatment processes to reduce the infectivity of *Taenia saginata* in calves (Pike, 1986)

This work represented a seminal study of the effects of sludge treatment processes on the inactivation of a relatively resistant, economically important parasite and is unique amongst the reported research as the viability of treated ova and infectivity in the second host was measured directly. The results indicate lagooning liquid sludge is an aggressive environment to pathogen survival and the majority of helminths and other parasites are significantly reduced by this process. A critical issue for efficient treatment is to operate the process in batches or as a plug-flow process because systems involving mixing and continuous or daily feeding are not efficient in reducing infectivity (Pike, 1986). Reimers *et al*. (1986) also confirmed in spiking experiments the effectiveness of lagoon-storage in the inactivation of parasites, which were eliminated after one year.

Murray (1960) observed the natural heating and rise in temperature of sludge maturation/storage heaps sufficient to inactivate *Ascaris* ova associated with airdrying sludge to a moisture content in the range 45-60% (Table 6.16). In this study in Pretoria, 98% of the *Ascaris* ova present in the untreated sludge were removed from the effluent and could be found in the sludge. Raw sludge was subjected to digestion and drying, which inactivated approximately 30 % of the ova, before the sludge was formed into heaps. Samples taken from the heaps of partly dried digested sludge contained 1 potentially infective ovum g^{-1} DS in the interior and 14 ova g^{-1} DS in the exterior layer – as compared with 140 present in the raw sludge. The temperature rise caused by microbial activity in the stockpiled sludge was responsible for inactivating the ova. Subsequently, digested sludge was used to build a 30.6 m^3 heap. Sludge initially contained 2,000 potentially infective ova g^{-1} DS. The heap base and outer layer was formed from matured sludge (sludge that matured inside other heaps). The temperature in parts of the heap reached 57°C. Samples taken after 2 months from the bottom and outer layers contained no viable ova. However, the inside of the heap was found to have 75 potentially infective ova g^{-1} DS, and this was possibly explained due to the uneven heating of the heap. Thus, the efficiency of ova destruction during storage of air-dried sludge was 96 % inside of the heap and 100% at the bottom and outer layers.

Another phase of sampling involved a larger sludge heap of approximately 76.5 m^3 with a base and outer layer formed of matured sludge, which contained a very low count of potentially infective ova (Murray, 1960). The heap heated up quickly and the highest temperature measured was 73 °C. The interior (samples from at least 30.5 cm-deep) did not contain *Ascaris* ova after 2 weeks. However, 80 ova g^{-1} DS were detected at the 15 cm base layer after 2 months. The average of all the heap samples after 4 months was 6 viable ova g^{-1} DS. One sample contained as much as 600 viable ova g^{-1} DS presumably due to uneven heat development within the heap. On the basis that fresh sludge contained 2,000 potentially infective ova g^{-1} DS and that the dried sludge had 6 viable ova g^{-1} DS, the overall average efficiency of the process 99.7% , equivalent to almost 3 $\log_{10}$.

A final set of tests were carried out on heap sizes over 76.5 m^3, but in this case they were not insulated with matured sludge. The raw sludge contained approximately 2000 potentially infective ova g^{-1} DS and after treatment numbers were reduced by 85 – 100 %. Other researchers also demonstrate that any form of sludge management that increases the temperature of the biosolids (eg self heating through compost autoheating, solar radiation or natural high ambient temperature; Ahmed and Sorensen, 1995; Hall *et al*., 1999; Al-Hmoud *et al*., 2006) will shorten the time required for the destruction of pathogens and further improve the sanitary quality of sludge.

Table 6.16 Reduction in *Ascaris* ova in operational sludge heaps (Murray, 1960)

Average samples					Special samples			
Heap number	Approx. age months	Moisture percent.	*Ascaris* ova per gm.d.m.		Description of sample	Moisture percent.	*Ascaris* ova per gm.d.m.	
			Total	Potentially infective			Total	Potentially infective
11 I	4	49	600	30	Outside 2" layer	53	1850	185
11 I	4	63	750	45	Inner zone at 2 months	44	840	90
12	3	61	2400	100	Dry mouldy layer	12·5	210	0
12	3	55	1400	120	Longitudinal section	55	1100	0
13	8	57	1100	0	Outside 0—2" layer	43	470	15
13	8	—	—	—	Layer on ground 0—1"	60	1400	0
14	2	46	900	20	Upper brown friable layer	45	330	0
14	2	—	—	—	Lower anaerobic black layer	63	750	5
14	5	48	500	5	Layer on ground 0—3", 2 months	69	2800	0
15	3	39	300	3	Outside 0—3" layer under grass	47	1300	250
15	4	35	450	40	Outside 0—3" layer under grass	36	120	80
15	4	—	—	—	Dry patches inside heap	7	7	0
19	3	44	1200	250	—	—	—	—
19	3	40	2400	310	—	—	—	—
20	3	44	440	0	—	—	—	—
20	3	—	—	—	Dry patches inside heap	9	230	0
21	2	43	640	0	—	—	—	—
21	2	39	480	0	—	—	—	—

VIABLE OVA: Ova that under laboratory conditions (cultured in 2% formalin at c.20-25°C) begin to develop within a month. Generally c. 90% of the total ova number (in undried digested sludge) is capable of such development

POTENTIALLY INFECTIVE OVA: Ova that under the conditions specified above, cultured for over 1 month, reach the infective worm stage. Generally, it is 60-70% of the total ova number that reaches this stage

7. AIR-DRYING IMPACT ON PATHOGENS

7.1 Overview of effects of air-drying on inactivation of enteric organisms

Conventional sludge drying beds used for dewatering and drying of faecal sludge and anaerobic digester residue will reduce the sludge volume by 50 – 80 %. Sludge drying can reduce the water content to below 20-30 %, which results in partial pathogen removal (WHO, 2006). Dried sludge still may contain pathogens – the main concern being the potential presence of helminth eggs if infections with these organisms are prevalent in the population (WHO 2006). Under these conditions it is recommended that dried sludge should therefore receive further treatment, eg, by composting or prolonged storage) to eliminate these organisms. If they are not present, however, additional treatment is unlikely to be necessary and the material will be suitable for use directly as an agricultural soil improver.

Great majority and possibly all bacteria viruses and protozoa cysts are destroyed at temperatures of above 20°C by drying sludge in open beds for 2-3 months (Feacham *et al.*, 1983; Hall *et al*., 1995). In general it is reported that moisture contents in sludge of <50 % can be detrimental to the survival of microorganisms (Yeager and Ward, 1981; Ward *et al*., 1981; Al-Azawi, 1986). Yeager and Ward (1981) showed that populations of six types of faecal bacteria were stable for over 90 days at 21 ^{o}C when inoculated into sterile liquid sludge (5 % DS). However, inactivation rates were proportional to the moisture loss by evaporation from the sludge. However, inactivation occurred up to a maximum DS content of 90 % and bacterial numbers generally remained stable as the DS increased further.

7.2 Bacteria inactivation

Bacteria are relatively sensitive to the effects of drying sludge on survival times. For example, air-drying inactivates *Salmonella typhi* in a few minutes, but anaerobic digestion for 12 days at 20°C and 10 days at 30°C is required to destroy the pathogen (Carrington, 1980). In other research, *Salmonella* was detected in 1 out of 27 samples after 10 weeks of drying sludge (Hales, 1974; Carrington, 1978).

However, early research suggest there is an inconsistent effect of air-drying of survival. Thus, *Salmonella paratyphi* was isolated for up to 41 days on a drying bed and *Salmonella typhi* was detected after 180 days in sludge dried to a moisture content of 14% (Stokes, 1945; Carrington, 1978). Some early studies (eg Grunnet, 1975; Carrington,1980) indicated that there was no difference in *Salmonella* counts between freshly digested sludge and sludge that had been dried for 6-12 months.

7.3 Virus inactivation

Temperature is the most influential factor affecting the survival of viruses in the environment, and the inactivation threshold is above 50°C (Bitton, 1978; Gray, 2004). However, water activity is also important and dewatering significantly reduces viral numbers.

In general, it is estimated that air-drying can achieve 1-3 $\log_{10}$ reduction in enterovirus concentrations (Table 7.1; Gerba *et al*., 2002).

Table 7.1 Inactivation of enteroviruses by different sewage sludge treatment processes (Gerba *et al*., 2002)

Treatment	Reduction (log10)
Anaerobic digestion (mesophilic)	1
Aerobic	1
Composting	2–3
Air drying	1–3
Lime stabilization	3

Only 8 PFU g^{-1} of Echovirus 7 were detected in sludge air-dried for 13 d in Florida (Wellings *et al*., 1976; Carrington, 1980). Evaporation is the most cost-effective method of dewatering (if space and climatic conditions permit). The effects of this treatment process on viral inactivation were studied by Ward and Ashley (1977b). Layers of raw sludge (1 cm thick), seeded with virus, were placed in a tray in the laboratory and air-dried at 21°C. Samples were taken at various degrees of dryness and stored in sealed bottles to prevent further drying, although this was not precisely controlled in relation to time. All of the samples with different DS contents were tested together for poliovirus type 1, coxsackievirus B1 and reovirus type 3 after 4 days and again after a further 7 days of incubation at 21 ^{o}C, ie giving a total incubation period of 11 days after evaporation was initiated (Table 7.2 and 7.3). The samples were incubated for the extended period (ie day 4 – 11) in sealed bottles to prevent further drying by evaporation.

The experiment demonstrated that air-drying can reduce the virus content by more than 4-5 $\log_{10}$ (Table 7.4). The reduction rate in poliovirus was the fastest at two stages: when the solids content increased to 65% (total reduction of poliovirus PFU at that point was 83% after 4-days evaporation) and 83%, where inactivation reached 4-log after 4 days and above 5-log 11 days after evaporation was initiated (Table 7.5). These two values represent breakpoints in the virus stability and demonstrate that further increases in the solid content (above 83%) is not necessary. Other pathogens tested, coxsackievirus and reovirus, showed similar trends in reduction rates, therefore Ward and Ashley (1977b) considered that this behaviour may be applicable to many enteric viruses.

Viral inactivation may at least partially be linked to increased exposure of virions to liquid-air interfaces (Ward and Ashley, 1977b). These results were also supported by Moore *et al*. (1976), who showed the rapid inactivation of poliovirus occurred in soils containing <10% water.

7.4 Parasites inactivation

Parasites can be inactivated by drying and exposure to UV radiation (Pike, 1983). However, some aspects of the effects of air-drying combined with storage on pathogen survival in sewage sludge cannot be directly attributed to either one or other of these stages specifically and are a consequence of both approaches interacting to influence pathogen decay. Thus, as sludge moisture content decreases by airdrying to 30-50%, storage in heaps can increase the temperature of the sludge due to spontaneous composting activity (Hall *et al.*, 1995). This process may be important and contribute to the effects of airdrying and storage on the destruction of helminth ova. For example,

inactivation of the ova requires a temperature of 55°C for 2 hours (Murray, 1960), or 1 hour at 60°C and 30 min at 65°C during aerobic composting (Hall *et al*., 1995).

Table 7.2 Recovery of poliovirus in raw sludge after air-drying to different solids contents (Ward and Ashley, 1977b)

Sludge solids (final %)	Recovery of PFU/ml	
	4 days	11 days
5	1.8×10^7	6.5×10^6
12	1.7×10^7	4.5×10^6
20	9.5×10^6	4.0×10^6
30	6.4×10^6	3.8×10^6
58	5.5×10^6	3.2×10^6
65	4.0×10^6	3.2×10^6
83	2.5×10^3	$<2.5 \times 10^2$
91	1.0×10^3	$<2.5 \times 10^2$

Table 7.3 Recovery of coxsackievirus and reovirus in raw sludge after air-drying to different solids contents (Ward and Ashley, 1977b)

Sludge solids (final %)	Recovery of PFU/ml	
	4 days	11 days
Coxsackievirus B1		
5	1.5×10^7	1.3×10^7
33	1.1×10^7	3×10^6
93	1×10^3	$<2 \times 10^2$
Reovirus		
5	2.1×10^6	1.2×10^6
20	1.8×10^6	8.6×10^5
40	1.2×10^6	7.0×10^5
60	7.1×10^5	2.3×10^5
73	4.5×10^5	2.0×10^4
94	$<2 \times 10^2$	$<2 \times 10^2$

Table 7.4 Efficiency of evaporation at reducing enteric viruses in air-dried sewage sludge – note the number of days refers to the time period after evaporation was initiated (Ward and Ashley, 1977b)

Percentage of virus reduction					
	Original titer (control sample)	**5% solids, 4 days**	**5% solids, 11 days**	**91% solids, 4 days**	**91% solids, 11 days**
Poliovirus 1	$2.4x10^7$ PFU/ml	25%	72.9%	99.996% (5-log)	>99.999% (above 5-log)
	Original titer (control sample)	**5% solids, 4 days**	**5% solids, 11 days**	**Sample: 93% solids, 4 days**	**Sample: 93% solids, 11 days**
Coxsackievirus B1	$1.7x10^7$ PFU/ml	16.7%	23.5%	99.994 (4-log)	>99.999% (above 5-log)
	Original titer (control sample)	**Sample: 5% solids, 4 days**	**Sample: 5% solids, 11 days**	**Sample: 94% solids, 4 days**	**Sample: 94% solids, 11 days**
Reovirus 3	$2.3x10^6$ PFU/ml	8.7%	47.8%	>99.99% (above 4-log)	>99.99% (above 4-log)

Table 7.5 Critical dry solids concentrations linked to rapid phases of poliovirus 1 inactivation in air-dried sewage sludge – note the number of days refers to the time period after evaporation was initiated (Ward and Ashley, 1977b)

Percentage of virus reduction					
	Original titer (control sample)	**Sample: 65% solids, 4 days**	**Sample: 65% solids, 11 days**	**Sample: 83% solids, 4 days**	**Sample: 83% solids, 11 days**
Poliovirus 1	**$2.4x10^7$ PFU/ml**	**83%**	**86.7%**	**99.99% (4-log)**	**>99.999% (above 5-log)**

Conventional sludge stabilisation processes including aerobic and anaerobic digestion are relatively ineffectively against parasite eggs. However, reporting research completed in the US, Reimers *et al*. (1986) concluded that by contrast, drying beds were very effective at destroying parasites due to a combination of reduced moisture availability, solar radiation, temperature and time. Thus, the complete destruction of *Ascaris* and *Toxocara* eggs occurred when the DS content of sludge is 80 % and other reports showed that all *Ascaris* eggs were destroyed when the DS content was >95 %. Parasites were inactivated in sludges during the summer season in the Northern US by high temperatures in the sludge due to solar radiation.

8. CASE STUDY – IMPACTOF SOLAR/AIR-DRYING SLUDGE AND STORAGE IN EGYPT

8.1 Bacteriology

Extensive studies on the effectiveness of sludge treatment by storage and air-drying in Egypt were undertaken by Hall *et al.* (1995; 1999) as part of the Cairo Sludge Disposal Study. This programme of work examined the chemical and microbiological quality of sludge produced by the 6 main WwTP in the Greater Cairo region and its suitability and value for recycling to farmland.

Tables 8.1 – 8.3 compare bacteria counts in fresh and air-dried sludge. Several cycles of filling and air-drying sludge in sludge lagoons was completed and, after the last filling, sludge was dried for a period of up to 6 months depending on season (shorter in summer). Sludge was lifted from the lagoons and stored for a minumim period of 6 months. There was a significant amount of variation in counts between the sludges from different works. As would be expected, *E. coli* were detected in all the samples of raw sludge examined and in fresh digested sludge from the Zenien WwTP. Mean numbers of faecal coliform bacteria in raw sludge were equivalent to 8 $\log_{10}$ g^{-1} DS. However, no *Salmonella* or *Klebsiella* were detected in raw sludge from Abu Rawash or digested sludge from the Zenien WwTP, whereas 6 % of the samples examined from Berka WwTP contained these bacteria. The counts of faecal coliform bacteria were several orders of magnitude lower in air-dried sludge. For instance, faecal coliform numbers in sludge from Berka WwTP were reduced from $1x10^8$ MPN g^{-1} DS (mean value) to $1.3x10^6$MPN g^{-1} DS, equivalent to a 2-$\log_{10}$ reduction. At Abu Rawash air-drying and storage reduced faecal coliforms by 3-$\log_{10}$.

Salmonella were present in samples of air-dried sludge from all the treatment works, although the numbers of samples analysed were too few to determine whether this was significant and no enumeration was completed. Occurrence of the pathogen in the treated, air-dried sludge could be explained due to recontamination, for instance, due to the presence of vectors; regrowth due to rewetting is also a possibility albeit very unlikely under the climatic conditions in Egypt. The average concentration of *Salmonella* measured by Muhammad *et al*. (2007) in drying sludge from three WwTP in Saudi Arabia were in the range 22-127 g^{-1} DS, albeit only up to 14 days drying.

Faecal coliforms were significantly reduced, by several orders of magnitude (2 – 3 $\log_{10}$), in air-dried digested sludge compared to raw, air-dried material. Furthermore, the two samples of air-dried digested sludge tested negative for all of the specified types of parasites (*Eimeria* spp., *Fasciola* spp., *Ascaris, Trichostrongylides* also see Section 8.2). These results therefore support the practice of sludge digestion before air-drying and storage.

Table 8.1 Bacterial contents of fresh and air-dried unstabilised raw sludge, Abu Rawash WwTP, Cairo, Egypt (Hall *et al*., 1999)

Bacteria	Mean	90%ile	sd	n	Air-dried sludge (MPN g^{-1}) n=2
Total coliform bacteria (MPNx10^{10}/100ml)	38.5	148.0	69.1	27	
Faecal coliform bacteria (MPNx10^{8}/100ml)	23.0 (4.6 g^{-1} DS)*	89.8	45.3	43	5.3x10^{5}
E. coli (percent of samples tested positive)	100			21	
Salmonella (percent of samples tested positive)	0				50%
Klebsiella (percent of samples tested positive)	0				
Remarks	Reduction in faecal coliform bacteria (raw sludge mean compared to air-dried sludge samples): 99.88% (3-log) Reduction in Salmonella: inconclusive results				

* Based on the assumption that samples contained 5% DS

Table 8.2 Bacterial contents of fresh and air-dried unstabilised raw sludge, Berka WwTP, Cairo, Egypt (Hall *et al*., 1999)

Bacteria	Mean	90%ile	sd	n	Air-dried sludge (MPN g^{-1}) n=3
Total coliform bacteria (MPNx10^{10}/100ml)	28.5	28.0	70.4	15	
Faecal coliform bacteria (MPNx10^{8}/100ml)	5.0 (1 g^{-1} DS)*	16.0	7.15	21	1.3x10^{6}
E. coli (percent of samples tested positive)	100			17	
Salmonella (percent of samples tested positive)	6				100%
Klebsiella (percent of samples tested positive)	6				
Remarks	Reduction in faecal coliform bacteria (raw sludge mean compared to air-dried sludge samples): 98.7% (2-log) Reduction in Salmonella: inconclusive results				

* Based on the assumption that samples contained 5% DS

Table 8.3 Bacterial contents of fresh and air-dried digested sludge, Zenein WwTP, Cairo, Egypt (Hall *et al*., 1999)

Bacteria	Mean	90%ile	sd	n	Air-dried digested sludge (MPN g^{-1}) n=2
Total coliform bacteria (MPNx10^{10}/100ml)	228.6 (45.72 g^{-1} DS)*	314	51.0	14	
Faecal coliform bacteria	Not determined				2.2x10^3
E. coli (percent of samples tested positive)	100			17	
Salmonella (percent of samples tested positive)	0				50%
Klebsiella (percent of samples tested positive)	0				
Remarks	Reduction in Salmonella: inconclusive results				

* Based on the assumption that samples contained 5% DS.

Other microbial analyses were carried out on a series of drying tests with raw liquid sludge on a drying bed in the summer and winter seasons to reflect different ambient climatic conditions. The bed was refilled (4 times) with sludge (each layer allowed to dry out first) to a depth of approximately 30 cm. Pathogen reductions achieved are shown in Table 8.4. Samples examined in the course of drying contained high numbers of total coliform bacteria initially (in the range of 10^6 – 10^7 MPN 100 ml^{-1}, equivalent to 2x10^5-2x10^6 MPN g^{-1} DS), with occasional detection of *Salmonella* and *Klebsiella*. In trial Winter 1 (1996/97), reductions in total coliforms ranged from 99% (2-log_{10}) to above 99.99% (4-log_{10}), and therefore approached 100 %. Removal to less than the limit of detection occurred after 4.5 months.

Later, however, indicator numbers increased, which may be explained by regrowth or recontamination of the unstabilised sludge (total coliforms are widely used as a faecal indicator, but they may also originate form other environmental sources). Removals of 2 to 4-log_{10} of total coliforms were also observed in trial Winter 2 (1996/97) and during the summer season (1997). The only parasite detected after drying was *Eimeria* (in just 3 samples). *Salmonella*, detected at the early stages, was not found after 5-month drying. Temperature is noted as having a significant influence on survival times, which decline in warmer conditions (eg O'Donnell *et al*., 1984; Ahmed and Sorensen, 1995). Under Egyptian conditions, Hall *et al*. (1999) reported average mean temperatures in summer were 28°C and in winter were 13°C.

Table 8.4 Pathogen content of air-dried raw sludge during drying trials (Hall *et al*., 1999)

Sludge drying trials				
Drying trial	**Period after sludge removed/dry (months)**	**Parasite eggs g^{-1}**	**Salmonella (% of samples (number of samples))**	**Total coliforms (MPN g^{-1} DS)**
Winter 1 (1996/97)	0 0.5 4.5 5 6 6.5	Eimeria (50 g^{-1}) Eimeria (2 g^{-1}) Not detected Not detected Not detected Not detected	0 (1) 50 (2) 100 (1) 0 (1) 0 (1) 0 (10)	10^5 10^5 <0 <10 <10 <10 - 10^3
Winter 2 (1996/97)	2 6	Not detected Eimeria (10 g^{-1})	0 (3) 0 (3)	10^4 <10 – 10^2
Summer 1997	0 0.5 1	Not detected Not detected Not detected	100 (1) 70 (10) 20 (10)	<10 – 10^4 <10 - 10^3 <10

Another recent study in Egypt (Khalil and Mafouz, 2000) showed that solar drying sludge reduced microbial counts of *Salmonella*, *Shigella* and faecal coliforms by 81.8 – 99.8 % in the winter season, and 91.6 – 99.5 % in the summer season. In some cases, however, numbers increased during the summer period. This is surprising as most authors consistently report significantly reduced survival in warm and dry conditions. It is possible therefore that summer samples were contamination from an external source such as the faeces of wild birds and animals attracted to stockpiles of sludge, possibly due to the presence of insect larvae, during the summer. Hall *et al*. (1999) also noted that high numbers of faecal bacteria measured in dry sludge in drying lagoons were probably from this source.

Indeed, other investigations on the effects of solar drying on the densities of enteric bacterial pathogens and indicators in sewage sludge were recently reported by Al-Hmoud *et al*. (2006) in Jordan and confirm the earlier findings of the Egyptian study by Hall *et al*. (1995) regarding the effectiveness of drying at disinfecting sludge. Average faecal coliform inactivation rates (kd) during the warm dry seasons were 0.18 - 0.19 day^{-1} when US EPA Class A criteria (US EPA, 1993) were met in approximately 20 days (<1000 g^{-1} DS) . During the winter season, however, the inactivation rate was reduced to 0.04 day^{-1}. Numbers of *Salmonella* spp.dropped below the Class A levels (ie < 3 per 4 g DS) within 20 days during warm spring and summer periods. However, during the winter period, cooler temperatures, higher relative humidities and rainfall, prevented the biosolids from achieving Class A bacterial levels. Al-Hamoud *et al*. (2006) concluded that, in semi-arid regions, disinfecting biosolids for reuse by solar drying is an economically viable and technically feasible method during warm dry periods. However, it would not achieve Class A disinfection standards during the cold and wet winter season.

8.2 Parasitology

Hall *et al*. (1999) reported parasite numbers in air-dried and stored sludge in Egypt - Tables 8.5-8.8.7 contain the numbers of parasitic ova found in fresh raw sludge from the Abu-Rawash and Berka WwTP and freshly digested sludge from Zenein WwTP in

the Greater Cairo region, and in air-dried (raw and digested) sludge. Sludge was air-dried in lagoons and after the last filling was dried for a period of up to 6 months, depending on season, and was stored after lifting for a period of at least 6 months. A selection of important human and animal parasites were measured. *Eimeria* is a genus of Apicomplexan protozoan parasite that includes various species responsible for the poultry disease coccidiosis. No human infections with this parasite have been reported, however, infections of the closely related *Cyclospora cayetanensis* have been reported (Robben and Sibley, 2004). *C. cayetanensis* was described as a new protozoan organism approximately 10 years ago, and has been increasingly recognized as a human pathogen. In both immunocompetent and immunocompromised humans, it causes a watery diarrhoea that can be protracted (2–3 weeks in duration), and currently it has no known animal reservoir. *C. cayetanensis* is more commonly isolated from patients in tropical and subtropical regions, but outbreaks in the United States, Canada, and Germany linked to contaminated fruits or vegetables imported from other countries have occurred. *Heterophys* is a parasite of fish that transfers to humans. *Trichostrongylus* species are small gut nematodes that infect the small intestine of herbivores and also infect humans. *Trichostrongylides* are a group of nematode species that infect ruminants and humans. *Fasciola* is the common liver fluke and is a parasitic flatworm of the class Trematoda that causes fasioliasis, which is an infection of the bile duct in several mammals and which is especially important in sheep and cattle although it is rare in humans (Feachem *et al.* 1983).

The data indicated that anaerobic digestion followed by air-drying sludge increased the removal of parasites compared to drying of untreated, raw sludge. Thus, 5-25 *Eimeria* ova were counted in 1g of fresh sludge and 1-25 ova/g of air-dried sludge from Abu Rawash (Table 8.5). Greater removal of ova of this parasite was observed at Berka WwTP; here initial concentrations of *Eimeria* ova were in the range 5-50 ova/g in fresh sludge and were reduced to 1-25 *Eimeria* ova/g in air-dried sludge. Approximately 50% of samples tested positive for the presence of the pathogen, in both cases (Table 8.6). Digestion followed by air-drying was much more effective in destruction of parasitic ova and out of 4 parasites tested, none were found in the air-dried digested sludge from Zenein WwTP (Table 8.7).

Table 8.5 Parasite ova in fresh and airdried, raw sludge from Abu Rawash WwTP, Cairo, Egypt (Hall *et al*., 1999)

Parasite	Percent of samples tested positive for parasite eggs (range of numbers of eggs/g of fresh sludge[(1)]) n=21	Air-dried sludge Percent of samples tested positive for parasite eggs (range of numbers of eggs/g of air-dried sludge) n=2
Eimeria	24 % (5-25)	33 % (1-25)
Heterophys	5 % (5)	n.d.
Trichostrongylus	14 % (5)	n.d.
Trichostrongylides	n.d.	0 %
Ascaris	5 % (1)	50 % (1-25)
Fasciola	5 % (50)	0 %

[(1)]Refers to fresh weight of sludge as collected

Table 8.6 Parasite ova in fresh and airdried, raw sludge from Berka WwTP, Cairo, Egypt (Hall *et al*., 1999)

Parasite	Percent of samples tested positive for parasite eggs (range of numbers of eggs/g of fresh sludge[(1)]) n=17	Air-dried sludge Percent of samples tested positive for parasite eggs (range of numbers of eggs/g of air-dried sludge) n=6
Eimeria	47 % (5-50)	50 % (1-25)
Heterophys	0 %	n.d.
Trichostrongylus	29 % (1-10)	n.d.
Trichostrongylides	n.d.	0%
Ascaris	12 % (10)	33 % (1-25)
Fasciola	18 % (5-25)	0%

[(1)]Refers to fresh weight of sludge as collected

Table 8.7 Parasite ova in fresh digested and air-dried digested sludge, Zenein WwTP, Cairo, Egypt (Hall *et al*., 1999)

Parasite	Percent of samples tested positive for parasite eggs (range of numbers of eggs/g of fresh sludge[(1)]) n=41	Air-dried sludge Percent of samples tested positive for parasite eggs (range of numbers of eggs/g of air-dried digested sludge) n=2
Eimeria	29 (5-50)	0 %
Heterophys	2 (25)	n.d.
Trichostrongylus	17 (5-50)	n.d.
Trichostrongylides	n.d.	0 %
Ascaris	5 (5-25)	0 %
Fasciola	2 (25)	0 %

[(1)]Refers to fresh weight of sludge as collected

Surveys were also carried out on abandoned drying beds and in sludge storage lagoons in the Western Desert (Tables 8.8 and 8.9). Sludge from abandoned drying beds, subjected to high levels of solar radiation and desiccation and assumed to be 3 years old was found to contain total coliforms in the range of 10^3 – 10^5 MPN g^{-1}. This number was higher than expected and was attributed to the large number of birds at the site (Hall *et al.*, 1999). Importantly, however, no parasitic ova were detected in the samples except one, which contained 1 ova of *Trichostrongylus* g^{-1} (complete results shown in Table 8.8).

Practically no parasitic ova were detected in abandoned drying beds nor in the Western Desert Lagoons sludge (Tables 8.8 and 8.9). Parasite ova were frequently detected in sludge used in drying trial tests, often in high numbers of up to 100 ova g^{-1}, but all parasitic eggs (apart from *Eimeria*, found in just 3 samples) were eliminated within 6 months during drying trial tests on a drying bed (see Section 8.1, Table 8.4; a summary of the results is also presented in Table 8.10) (Hall *et al*., 1999). The coliform numbers remained at the level of 10^5 MPN g^{-1} in sludge in the Desert Lagoons, probably due to inputs from wild birds. However, the parasitic ova of *Fasciola* and

Trichostrongylus were only detected in semi-dried sludge (Table 8.9 and 8.11). One sample contained 1 *Ascaris* ova g^{-1} of sludge. It must be noted that tests were carried out immediately after the sludge dried after rewetting, so the recent addition of moisture may have increased the apparent survival of enteric organisms (Hall *et al*., 1999).

Table 8.8 Pathogen content of 3 year old air-dried sludge, Cairo (Hall *et al*., 1999)

Abu Rawash old WWTP drying beds (fresh sludge basis[(1)])				
Location	**Sludge state**	**Parasites**	**Bacteria**	**Total coliforms (MPN/g)**
Old sludge	Dry since 1994	No eggs found	*E. coli*	$4.2x10^4$
Old sludge	Dry since 1994	No eggs found	*E. coli*	$1.2x10^5$
Old sludge	Dry since 1994	No eggs found	*E. coli*	$9.0x10^5$
Old sludge	Dry since 1994	No eggs found	*E. coli*	$8.0x10^4$
Old sludge	Dry since 1994	No eggs found	*E. coli*	$1.7x10^5$
Old sludge	Dry since 1994	No eggs found	*E. coli*	$7.0x10^3$
Old sludge + 2.5% CaO	Dry since 1994	No eggs found	*E. coli*	$2.2x10^5$
Old sludge + 2.5% CaO	Dry since 1994	No eggs found	*E. coli*	$2.1x10^4$

[(1)]Refers to fresh weight of sludge as collected

Table 8.9 Pathogen content of sludge in Western Desert Lagoons (Hall *et al*., 1999)

Location	**Sludge state**	**Parasites**	**Total coliforms (MPN g^{-1})**
Lagoon 3	Semi-dry	*Fasciola* 25/g *Trichostrongylus* 50/g	$2.8x10^5$
Lagoon 1	Dry	No eggs found	$1.2x10^5$
Lagoon 1	Dry	*Eimeria* 1/g	$2.9x10^5$
Lagoon 2	Dry	No eggs found	$2.8x10^5$
Lagoon 5	Dry	No eggs found	$3.2x10^5$
Lagoon 8	Dry	*Ascaris lumbricoides* 1/g	$1.1x10^4$
Old sludge + 2.5% CaO	Dry since 1994	No eggs found	$2.1x10^4$

Table 8.10 Summary of pathogen reductions during raw sludge drying trials, Cairo (Hall *et al*., 1999)

Pathogens reductions after treatment				
Drying trial	**Duration of drying**	**Total Coliforms**	**Salmonella**	**Parasite eggs/g**
Winter 1(1996/97)	6.5 months	Reductions from 99% (2-log) to above 99.99% (4-log). Total reduction occurred after 4.5 months. Later, however, the number of pathogens increased, which may be due to regrowth or recontamination.	Not detected	Not detected
Winter 2(1997/98)	6 months	Reductions from 99% (2-log) to above 99.99% (4-log).	No detected	*Eimeria*: 10 ova/g
Summer 1997	1 month	Reductions from 99% (1-log) to above 99.99% (4-log).	Detected in 20% samples (2 out of 10)	Not detected

Table 8.11 Summary of pathogen content of drying and dry sludge in Western Desert Lagoons (Hall *et al*., 1999)

Western Desert Lagoons (fresh sludge basis[(1)])				
Location	**Sludge state**	**Parasites**	**Bacteria**	**Total coliforms (MPN/g)**
Lagoon 3	Semi-dry	*Fasciola* 25/g *Trichostrongylus* 50/g	*E. coli* *Salmonella*	$2.8x10^5$
Lagoon 1	Dry	No eggs found	*E. coli* *Aerobacter*	$1.2x10^5$
Lagoon 1	Dry	*Eimeria* 1/g	*E. coli* *Proteus*	$2.9x10^5$
Lagoon 2	Dry	No eggs found	*E. coli* *Aerobacter*	$2.8x10^5$
Lagoon 5	Dry	No eggs found	*E. coli* *Aerobacter*	$3.2x10^5$
Lagoon 8	Dry	*Ascaris lumbricoides* 1/g	*E. coli* *Aerobacter*	$1.1x10^4$
Old sludge + 2.5% CaO	Dry since 1994	No eggs found	*E. coli* *Aerobacter*	$2.1x10^4$

[(1)]Refers to fresh weight of sludge as collected

8.3 Summary

The evidence from this Case Study demonstrated the effectiveness of storage and drying at bacterial pathogen and parasite removal, and that inactivation is enhanced by storing/drying of anaerobically digested sludge. Storage for 6 months after drying was therefore recommended to produce adequately sanitised sludge for use in agriculture under Egyptian conditions (Hall *et al*., 1999). These results were also confirmed recently by Ashmawy *et al*. (2005) from a comprehensive microbiological assessment of sludge from the 6th October WwTP, Giza, Egypt, which showed that helminth ova (*Ascaris*, *Trichuris*, *Trichostrongylus*, *Taenia* and *Hymenolepis*) and enteric protozoa, as well as enteroviruses, were eliminated after 6 months residence time in the drying beds. Faecal coliforms, *E. coli*, faecal Streptococci and coliphage were reduced to 1-2 $\log_{10} g^{-1}$ in the dried sludge.

9. CASE STUDY - AIR-DRYING INVESTIGATIONS BY WANNON WATER, VICTORIA

9.1 Utility profile

Wannon Water, a water and sewarage service provider in south-west Victoria, was formed in 2005 by merging Glenelg water, Portland Coast Water and South West Water. The wastewater and drinking water facilities operated by Wannon Water are shown in Figure 9.1.

Figure 9.1 Wastewater and drinking water facilities operated by Wannon Water (Wannon Water, 2006a)

The sludge storage and treatment facility is located in Camperdown and sludge is transported here from the Warrnambool reclamation plant on a daily basis and the Port Fairy reclamation plant on Monday, Wednesday and Friday (Wannon Water, 2006b). Statistics available from Wannon Water (http://www.wannonwater.com.au/index.php?option=com_content&task=view&id=302&Itemid=323) indicate biosolids production from Port Fairy is 610 t DS y^{-1} and Warrnambool generates 1653 t DS y^{-1}. The sludges are produced from biological wastewater treatment processes at both the sewage treatment works and are thickened by mechanical gravity belt thickener before transporting to Camperdown.

At Camperdown, thickened liquid sludge is stored in a holding lagoon during winter, whereas in the summer months it is spread and mechanically turned to allow for more efficient drying. Drying duration depends on the weather conditions, but generally takes several weeks. Dried sludge is stored in stockpiles. The annual sludge production from Camperdown is equivalent to approximately 2,500 t (Wannon Water, 2006a).

9.2 Microbiological quality testing 2000-2002

During the period 2000-02, Wannon Water conducted a series of monitoring trials to determine the pathogen reduction achieved by air-drying and storage of sewage sludge. Sludge from Warrnambool was enumerated for *E. coli* post dewatering at the point of loading into the hopper for transportation. The mean number (determined by an MPN method) of *E. coli* was $9.4x10^4$ g^{-1} and the geometric mean number was $5x10^4$ g^{-1} in samples from 2000-2002. These numbers fall within the range of conventionally treated sludge stipulated in the UK Safe Sludge Matrix for use on agricultural land (ADAS, 2001), and treatment grade T3 in EPA Victoria (2004).

Biosolids samples tested at Camperdown in August 2002 (Table 9.1) contained very low numbers of *E. coli* (<2000 g^{-1}) and as few as 0.2 g^{-1} in biosolids from Warrnambool. Salmonellae were not detected at the level of <1 per 25 g^{-1} in Warrnambool biosolids. Samples of the tested biosolids did not contain A*scaris* nor *Taenia* ova. Enteric viruses values were less than 1pfu $4g^{-1}$ in all of the samples examined.

Current EPA Victoria Guidelines (EPA Victoria, 2004) only specify long-term storage of sludge for >3 years to produce the highest quality Treatment Grade T1 sludge for use without restriction. However, Wannon biosolids are typically dried for several weeks and these results suggest that this approach provides an alternative treatment method for producing a treated material that complies with Treatment Grade T_2 microbiological criteria.

9.3 Effects of air-drying sludge on microbiological quality

9.3.1 Drying trials 2002 – *E. coli* and *Salmonella* – 3 weeks

Further designed trial tests were completed by Wannon Water to investigate the reductions in enteric organisms during the treatment process at Camperdown. Using *E. coli* and *Salmonella* as test organisms (helminths have not been detected in the raw sludge – pers. com. D. Gardner, Wannon Water). The effects of airdrying sludge for three weeks are shown in Tables 9.2 and 9.3, on these organisms, respectively. The numbers of *E. coli* declined by 0.5-2 $\log_{10}$ by air drying over this time period at an ambient temperature of approximately 15°C (BoM, 2007a). Mixing raw sludge with a proportion of dried sludge (at 60-70 % DS) could improve pathogen inactivation. *Salmonella* was detected in 25 g of sludge in all but one of the dried-sludge samples. As the bacteria was not enumerated it is not possible to draw any conclusions about the impact of drying on its removal. However, absence of *Salmonella* in that case could indicate drying was effective at inactivating the pathogen overall, since (a) *Salmonella* removal closely follows that of *E. coli*, (b) other research shows drying and storage to be effective at eliminating *Salmonella* (see Sections 6.2 and 7.2), and (c) extending the drying/storage period would be expected to further increase the extent of removal.

Table 9.1 Microbiological properties of biosolids sampled at Camperdown storage and treatment facility on 7 August 2002, Wannon Water, Victoria (pers com D. Gardner, Wannon Water)

Sample	Temp. (°C)	VS/TS	Sample Site	*E. coli* MPN g^{-1}	*Salmonella* $25g^{-1}$	Helminth ova/cysts $4g^{-1}$		Enteric viruses $4g^{-1}$		
						Taenia	*Ascaris*	Reovirus	Enterovirus	Andeovirus
Warrnambool Biosolids/1	14.6	0.21	Sth,bottom	<2000	<1	0	0	<1	<1	<1
Warrnambool Biosolids/2	53	0.21	Top	<2000	<1	0	0	<1	<1	<1
Warrnambool Biosolids/3	32.3	0.43	Nth, bottom	<2000	<1	0	0	<1	<1	<1
Camperdown Municipal	14.2	0.23	Top	<2000	<1	0	0	<1	<1	<1
Brown Bear Trial Plot C.	13.8	0.78		<2000	<1	0	0	<1	<1	<1
Werribee										
Warrnambool Biosolids, Lagoon 2	12	2.15	North	0.2	Not detected	0	0	<1	<1	<1
Warrnambool Biosolids, Lagoon 2	12	1.42	Centre	0.2	Not detected	0	0	<1	<1	<1
Warrnambool Biosolids, Lagoon 2	12	2.83	South	0.2	Not detected	0	0	<1	<1	<1

Table 9.2 Effect of air-drying sludge for 3 weeks on *E. coli* removal (pers com D. Gardner, Wannon Water)

E. coli MPN g^{-1} Drying start day: 23/04/2002					
Date	**100% Sludge (Pile B)**	**100% Sludge from WWTP (Pile E)****	**75% Wet sludge 25% Dry sludge* (Pile A)**	**50% Wet sludge 50% Dry sludge* (Pile C)**	**25% Wet sludge 75% dry sludge* (Pile D)**
26/04/2002	**27,000**	**-**	**-**	**27,000**	**17,000**
02/05/2002	**23,000**	**-**	**920,000**	**70,000**	**11,000**
09/05/2002	**22,000**	**-**	**27,000**	**17,000**	**2,000**
16/05/2002	**5,000**	**17,000**	**8,000**	**2,000**	**2,000**
Remarks	**Reduction of 81.48% (c. 0.5-log) Over 20 days**		**Reduction of 99.13% (c. 2-log) Over 20 days**	**Reduction of 92.59% (c. 1-log) Over 20 days**	**Reduction of 88.24% (c. 1-log) Over 20 days**

*Dry sludge = approx 60-70% dry solids
** Drying start day: 13/05/2002

Table 9.3 Effect of air-drying sewage sludge for 3 weeks on *Salmonella* removal (pers com D. Gardner, Wannon Water)

Salmonellae 25 g^{-1} DS Drying start day: 23/04/2002					
Date	**100% Sludge (Pile B)**	**100% Sludge from WWTP (Pile E) ****	**75% Wet sludge 25% Dry sludge* (Pile A)**	**50% Wet sludge 50% Dry sludge* (Pile C)**	**25% Wet sludge 75% Dry sludge* (Pile D)**
09/05/2002	**detected**	**-**	**detected**	**detected**	**detected**
16/05/2002	**not detected**	**detected**	**detected**	**detected**	**detected**
Remarks	The result may suggest that air-drying can reduce salmonellae in wet sludge without addition of dry solids	The reduction rate (if occurred) is not known			

*Dry sludge = approx 60-70% dry solids
** Drying start day: 13/05/2002

9.3.2 Drying trials 2003 - *E. coli* and *Salmonella* – 4 weeks

The effects of air-drying on the microbiological quality of sludge were also examined on Warrnambool sludge, which was dried for a period of approximately 4 weeks to approximately 76% DS, using different turning frequencies (pers. com. D. Gardner, Wannon Water). There were two replicate piles of sludge of 60 m^3 per turning regime.

A high VS/TS ratio (> 0.6) is indicative of high biodegradability of organic matter and the presence of undigested organic matter in sludge. In general, the VS/TS decreased during the drying processes to values <0.6, indicating that the organic matter was digesting during the process.

Greater reductions in *E. coli* were observed in these tests (Tables 9.4-9.6) compared to the work completed in 2002 (Section 9.3.1), which was probably explained by higher ambient temperatures measured in 2003. Thus the maximum average temperature measured during the monitoring period was 24.5°C (BoM, 2007b). However, *E. coli* numbers increased significantly after initial reductions in plots B, D and F. This may be linked to the rewetting of sludge on 28/02/2003, however, this effect was short-lived and numbers subsequently declined to low values towards the end of the monitoring period. Regrowth of enteric bacteria is possible when dried sludge, containing organic matter that is not fully microbiologically stabilised, is rewetted (Zaleski *et al*., 2005), but

these results suggest this effect is only transient and numbers are reduced after potential regrowth events by further air-drying and storage. *Salmonella* numbers did not change during the process, but were very low and ≤1 g^{-1}. Four weeks is a relatively short period and storage/air-drying sludge for a longer period of up to 6 months is recommended for removal of *Salmonella* (Berggren *et al*., 2004; Hall *et al*., 1999), although significant log removals would be achieved in a shorter period (eg 3 months; Carrington, 2001).

Table 9.4 Effect of air-drying for 4 weeks on *E. coli* and *Salmonella* numbers in sludge; turned 3 times per week (pers com D. Gardner, Wannon Water)

Plot A

Date	Ambient temp. (°C)	Sample temp.		% solids	VS/TS	Sample Site	*E. coli* MPN g^{-1}	*Salmonella* Org. g^{-1}
		Min	Max					
15/02/2003	15.5	16.8	20.7	14	0.25	n.d.	160,000	0.9
28/02/2003 4 mm rainfall up to 3pm	17.2	23.0	37.1	34	1.80	Side of pile	110,000	1
07/03/2003	27.7	24.1	25.8	40	0.82	n.d.	7,900	0.9
14/03/2003	18.2	20.9	25.9	61	0.75	Side of pile	3,100	0.9
18/03/2003	n.d.	n.d.	n.d.	n.d.	0.61	n.d.	99	1

Plot B

Date	Ambient temp. (°C)	Sample temp.		% solids	VS/TS	Sample Site	*E. coli* MPN/g	*Salmonella* Org./g
		Min	Max					
15/02/2003	15.5	20.0	22.9	15	5.39	n.d.	54,000	0.9
28/02/2003 4 mm rainfall up to 3pm	17.2	21.8	24.8	34	1.85	Top of pile	110,000	1
07/03/2003	27.7	23.7	27.1	40	1.32	n.d.	28,000	0.9
14/03/2003	18.2	22.1	23.7	58	0.76	Top of pile	94,000	0.9
19/03/2003	26.1	26.2	27.7	77	0.38	Top of file	99	0.9

Table 9.5 Effect of air-drying for 4 weeks on *E. coli* and *Salmonella* numbers in sludge; turned once per day (pers com D. Gardner, Wannon Water)

Plot C

Date	Ambient temp. (°C)	Sample temp.		% solids	VS/TS	Sample Site	*E. coli* MPN/g	*Salmonella* Org./g
		Min	Max					
15/02/2003	15.5	n.d.	n.d.	13	5.21	n.d.	160,000	0.9
28/02/2003 4 mm rainfall up to 3pm	17.2	21.7	34.4	39	1.14	n.d.	110,000	1
07/03/2003	27.7	25.4	31.3	56	0.58	n.d.	54,000	0.9
14/03/2003	18.2	21.5	29.5	70	0.49	Top of pile	2,000	0.9
18/03/2003	26.1	30.5	32.6	80	0.35	Side of pile	1,200	0.9

Plot D

Date	Ambient temp. (°C)	Sample temp.		% solids	VS/TS	Sample Site	*E. coli* MPN/g	*Salmonella* Org./g
		Min	Max					
15/02/2003	15.5	n.d.	n.d.	13	4.99	n.d.	92,000	0.9
28/02/2003 4 mm rainfall up to 3pm	17.2	21.5	25.6	28	0.71	Top of pile	110,000	1
07/03/2003	27.7	26.9	28.1	41	0.81	n.d.	160,000	1
14/03/2003	18.2	20.8	23.2	72	0.49	Side of pile	1,700	0.9
18/03/2003	32.2	29.1	32.4	83	0.43	Top of pile	1,500	0.9

Table 9.6 Effect of air-drying for 4 weeks on *E. coli* and *Salmonella* numbers in sludge; turned twice per day (pers com D. Gardner, Wannon Water)

Plot E

Date	Ambient temp. (°C)	Sample temp.		% solids	VS/TS	Sample Site	*E. coli* MPN/g	*Salmonella* Org./g
		Min	Max					
15/02/2003	15.5	n.d.	n.d.	13	5.64	n.d.	160,000	0.9
28/02/2003 4 mm rainfall up to 3pm	17.2	19.5	20.9	42	0.84	Side of pile	4,300	1
07/03/2003	27.7	24.3	26.3	60	0.43	n.d.	3,300	1
12/03/2003	32	30.0	32.0	79	0.49	Top of pile	1,100	0.9

Plot F

Date	Ambient temp. (°C)	Sample temp.		% solids	VS/TS	Sample Site	*E. coli* MPN/g	*Salmonella* Org./g
		Min	Max					
16/02/2003	n.d.	n.d.	n.d.	n.d.	4.22	n.d.	92,000	0.9
28/02/2003 4 mm rainfall up to 3pm	17.2	19.2	21.2	54	0.57	Top of pile	9,300	1
07/03/2003	27.7	23.2	31.1	65	0.40	n.d.	160,000	1
12/03/2003	32	27.2	35.4	74	0.37	Side of pile	630	0.9

An overall summary of the reductions in *E. coli* and *Salmonella* achieved by air-drying sludge for 4 weeks, and the corresponding %DS and VS/TS after drying is presented in Table 9.7. Increasing the frequency of turning increased the rate of drying, however, there was no overall difference in the extent of *E. coli* removal achieved between the different turning regimes, and the mean reduction after 4 weeks was generally >99 % in all cases. Final numbers of *E. coli* in air-dried product would also comply with the conventional treatment standard for agricultural use of sludge in the UK Safe Sludge Matrix (ADAS, 2001).

Table 9.7 Summary of reductions in pathogen numbers achieved by air-drying sludge and corresponding DS and VS/TS values

Plot	% DS	VS/TS	*E. coli* reduction	*Salmonella* reduction
Plot A	>61	0.61	99.94% (c. 3-log)	No change
Plot B	77	0.38	99.82% (c. 3-log)	No change
Plot C	80	0.35	99.25% (c. 2-log)	No change
Plot D	83	0.43	98.37% (c. 2-log)	No change
Plot E	79	0.49	99.31% (c. 2-log)	No change
Plot F	74	0.37	99.31% (c. 2-log)	No change
Mean	76	0.44	99.33% (c. 2-log)	No change

9.4 Summary

The results form the Wannon Water Case Study showed that helminth parasites and enteric viruses were not detectable in biosolids and the numbers of *Salmonella* are very small or not detectable**.** Air-drying for 3 - 4 weeks consistently achieved *E. coli* reduction requirements specified for T3 grade or conventionally treated biosolids (ADAS, 2001; EPA Victoria, 2004), and in some cases T2 and enhanced treatment grades (ADAS, 2001; EPA Victoria, 2004) could also be attained. The results suggest that extending the storage period further by a number of weeks would produce biosolids consistently within the *E. coli* requirements of these treatment grades and probably also to Treatment Grade T1.

10. NUTRIENT VALUE

10.1 Major nutrient concentrations in sewage sludge

Main nutrients required for plant growth are nitrogen (N), phosphorus (P) and potassium (K). Wastewater treatment elutriates soluble nutrients, such as K, from sludge, therefore the content of this element in biosolids is not agronomically significant and is typically 0.1 – 0.4 % DS (Hall, 1986) and should be provided for crop growth from other sources. Typical concentrations of N and P in different treated sludge types are reported in Table 10.1.

Table 10.1 Typical composition of sewage sludge treated by different processes (adapted from MAFF, 2000; pers. com. B. Chambers, ADAS, UK and unpublished data, Imperial College London)

Sludge type	DS (%)	Total N (% DS)	Mineral N (%TN)	Total P[(1)] (% DS)
Digested liquid	4	5	40	1.5 (3.5)
Digested cake	25	5	15	1.5 (3.5)
Lime stabilized	40	2	10	1
Thermally dried	95	4.3	5	2 (2.5)
Compost	60	2	5	1

[(1)]Chemical and biological P removal is increasingly practised at WwTP and where is practiced the amount of total P in sludge is expected to increase – indicated by values in brackets

Digested sludge typically contains 5 % of total N in the dry solids and raw sludge also contains similar amounts of total N (Hall, 1986). Nitrogen in sludge is present in both both mineral (predominantly as NH_4^+) and organic forms. Mineral N is readily available to plants, whereas the organic N fraction undergoes mineralisation by soil microorganisms before it can be utilised for crop growth (Torrey, 1979). Therefore, the amount of mineral-N in sludge, and the proportion of organic-N that is mineralisable in soil are important factors that govern the N fertiliser value of sludge. Dewatering and treatment process significantly affect both the amount of inorganic N that is in the sludge and the stability of the organic matter which influences its subsequent mineralisation in soil.

The available nitrogen content in liquid digested sludge has been estimated as (Hall and Williams, 1984):

(ammoniacal nitrogen) + 15% (organic nitrogen)

The overall availability of N in liquid digested sludge is typically reported as 60 % (Hall, 1986).

Sewage generally contains about 1.5 % DS of total P. However, P concentrations in sludge are generally increasing with the expanding practice of P removal at WwTP, which can raise the total P content by 3-5 times (Smith *et al*., 2002). Recent data for the UK suggest that total P concentrations in digested sludge are typically about 3.5 % DS (Table 10.1). The plant availability of P in sludge is reported as 50 % of mineral P fertiliser (MAFF, 2000). However, P availability is reduced by drying and also potentially by the chemical dosing with iron or aluminium for P removal during

wastewater treatment (de Haan, 1981; Smith *et al*., 2002; O'Connor *et al*., 2004). Biological P removal, on the other hand, may increase P availability from biosolids.

The nutrient concentrations reported in air-dried sludge in Egypt by Hall *et al*. (1999) are presented in Table 10.2. In liquid sludges, an appreciable proportion of the total N content occurs as ammonia and much of this may be expected to be lost by volatilisation during drying. Thus, mean N contents of dried sludges are usually less than liquid sludges. In general, the N content of liquid sludges in Egypt was about 2.5 % DS, whereas that of the dried sludges was about 1.5 % DS (Table 10.2).

10.2 Impact of treatment on nutrient value of sludge

Hall *et al*. (1999) describe a major programme of field trials investigating the agronomic value of air-dried sludge under Egyptian conditions. The trials involved an extensive range of arable and fruit crop production and the information was formulated into agronomic guidance for the use of sewage sludge as an agricultural fertiliser in Egypt. A summary of the first season (ie the crop grown immediately after sludge was applied) N value of sludge is shown in Table 10.3. The results indicated that air-dried sludge had a N value equivalent to 20 % of mineral fertiliser N on clay soil and 30 % of mineral N on desert soil. Therefore, between 20 - 30 % of the N contained in biosolids was available for uptake to the following crop. Mechanically dewatered digested sludge had a higher N value in the field experiments under Egyptian conditions, equivalent to 50 % of mineral N. Under UK temperate conditions, anaerobically digested sludge cake has a N value of 30 % in the first year relative to inorganic fertiliser (Morris *et al*., 2003). Approximately half the contribution is from the mineral N contained in the sludge and the remaining 50 % is due to mineralisation of the organic N fraction. The N availability of mechanically dewatered raw sludge is typically 20 % relative to mineral N with a range of 17 – 32 % (MAFF, 1994; Hall and Williams, 1984).

The ammoniacal N content of liquid digested sludge is typically about 45 % of the total N content, however, mineral N is reduced to 25% of the total N content by lagoon storage (Hall and Williams, 1984). The organic fraction also continues to mineralise during storage and this also reduces the amount of N that is mineralisable when the sludge is applied to the soil. Consequently, after storage, the nitrogen mineralisation rate of digested sludge is reduced to 9%, equivalent to about half of the rate for fresh liquid digested sludge. Thus, lagoon matured digested sludge has an overall N value of approximately 50 % compared to mineral N fertiliser (Hall and Williams, 1984).

The N content of undigested sludge is less sensitive to dewatering compared to digested sludge because, in this case, the N is mostly bound up with the organic matter, with only 5-10% present in solution in the ammoniacal form. However, the organic matter mineralises slowly under anaerobic conditions in storage and drying lagoons and the released ammonia will volatilise during drying reducing the total N content (Hall *et al*., 1999).

Table 10.2 Chemical properties (mean values and 95% confidence limit) of air-dried sludges[(1)] from different WWTP and of livestock manures from local sources in Cairo, Egypt (Units: bulk density) as t m^3; ds, VS, N, P, K and Fe as %, other elements as mg kg^{-1}; Hall *et al*., 1999)

WWTP	Bulk density	DS	VS	N	P	K
Abu Rawash	0.74	87.2 ±6.1	51.9 ±14.7	1.61 ±0.49	0.57 ±0.28	0.23 ±0.07
Berka	0.69 ±0.08	90.7 ±5.0	37.2 ±6.8	1.71 ±0.27	0.88 ±0.29	0.24 ±0.08
Helwan	0.82	93.3 ±4.5	27.0 ±5.9	0.85 ±0.13	0.61 ±0.45	0.19 ±0.04
Zenein	0.63 ±0.07	89.1 ±6.6	42.0 ±6.8	1.79 ±0.31	1.06 ±0.35	0.38 ±0.17
Alexandria	nd	88.5 ±10.0	25.2 ±14.8	1.63 ±0.52	1.09 ±0.39	0.38 ±0.18
FYM	0.63 ±0.23	90.9 ±5.3	23.8 ±9.3	0.85 ±0.27	0.69 ±0.28	0.70 ±0.17
Chicken manure	nd	79.2 ±29.5	53.1 ±33.1	2.53 ±1.41	1.35 ±2.07	0.75 ±0.86

[(1)]Raw air-dried, except for Zenien, which was mesophilically anaerobically digested and Alexandria which was composted

Table 10.3 Nitrogen value of air-dried raw and mechanically dewatered digested sewage sludge in two Egyptian soil types and relative to farmyard manure (FYM) (Hall *et al*., 1999)

Manure type	% of mineral fertiliser N	
	Clay soil	Desert soil
Air-dried raw	20	30
Mechanically dewatered digested	50	50
FYM[(1)]	55	60

[(1)]The relatively high effectiveness of FYM was also related to the supply of K in the manure

In an early study, Murray (1960) showed that storing air-dried, digested sludge, containing 40-55 % DS, in heaps reduced the total N content of the sludge by approximately 30 % after 4 months storage compared to dried sludge lifted directly from the drying beds, which contained 3.5 % of total N DS. However, no additional N loss was observed after a further 5 months storage period (9 months total storage time)., The mineralisation of organic N continues during storage of moist sludge and Murray (1960) indicated that N losses by ammonia volatilisation would be significant should the sludge be allowed to dry out before it is incorporated into the soil. Indeed, increasing the DS content to 90 % by air-drying the sludge after storage reduced the N content from 2.5 % DS to only 1 % DS. As would be expected, the amounts of other major nutrient elements in the sludge (P, K and Ca) were not affected by the storage or drying regime.

Microbial activity declines as the moisture content decreases and minimal mineralisation activity may be expected when the DS content of sludge is >90 %. Therefore, once dried, the N content of sludge is likely to be conserved with only minimal further loss. However, mineralisation of sludge organic matter during lagooning of sludge and the drying process (in pans and after lifting into piles), until the critical moisture content that inhibits microbial activity is reached, and the volatilisation of ammonia contained in liquid sludge and released by mineralisation during drying will significantly reduce the N content and fertiliser value of sludge, potentially by as much as 70-80 %. Volatilisation losses of mineral N will be raised by the practice of turning sludge to increase the rate of drying.

11. CONCLUSIONS AND RECOMMENDATIONS

11.1 Pathogen removal

- The main enteric organisms that have been examined to evaluate the efficiency of sludge storage and air-drying at pathogen removal include: faecal coliforms, *Escherichia coli*, *Salmonella* spp., enteric viruses, *Giardia* spp. and *Ascaris* spp.

- The rationale for the selection of pathogens or indicators for evaluation is that they demonstrate potentially:

  – high resistance to adverse conditions (eg *Ascaris*);
  – low or unknown infective doses (eg viruses and parasites);
  – high prevalence in waste-water, sludge and environment (eg faecal coliforms, *E. coli*, *Salmonella*).

- A major survey of UK sludge treatment practices showed that lagooning can reduce *E. coli* numbers by up to 5 $\log_{10}$, whereas air-drying is capable of reducing numbers by 4 $\log_{10}$. Reactivation and regrowth of *E. coli* have been observed in primary digested biosolids after dewatering by centrifugation to approximately 25 % DS, and cake storage periods of up to 120 days are practised in the UK to comply with the pathogen reduction requirements specified in the Safe Sludge Matrix. However, air-drying sludge increases the rate of pathogen inactivation, for example, up to 4 $\log_{10}$ reductions in *E. coli* were reported within 6 months during drying trials of sludge on a drying bed in a Case Study in Egypt.

- Faecal streptococcus did not follow the pattern of decay of enteric pathogenic bacteria (*Salmonella*) and may be unsuitable as an indicator of the hygienic quality of stored sewage sludge.

- Regrowth or recolonisation of enteric bacteria is possible in during sludge storage, particularly for unstabilised sludge, if the sludge is rewetted through ambient rainfall, or is contaminated with the faeces of wild animals and birds. However, numbers subsequently rapidly decay with continued drying and storage. The extent of regrowth is limited in sludge by the presence of viable indigenous organisms in sludge due to microbial competition and antagonism and, consequently, numbers rapidly decline under these conditions. As would be expected, there is no corresponding increase in parasitic ova during sludge storage since these organisms, and viruses, are highly specialised parasites and can only reproduce within an infected host.

- The information examined in this review of literature shows that storage can completely inactivate *Salmonella*, however the probability of complete inactivation is not 100%. Typically, 90-100% inactivation of *Salmonella* can be achieved after 6-months storage of dehydrated sludge. As with all enteric organisms, the rate of inactivation is increased by temperature.

- Temperature is one of the main environmental parameters influencing pathogen removal initially and rates of decay increase with increasing temperature. At later stages other factors are probably more important in terms of pathogen destruction.

- Viruses are inactivated by temperatures above 20°C and desiccation. Enteric viruses are destroyed after approximately 300 days at 25°C. Significant removals equivalent to 4-5 $\log_{10}$ are possible in much shorter time periods when sludge is dewatered to ≥83% DS.

- Sludge treatment by mesophilic anaerobic digestion followed by 14 days of storage (secondary digestion) as a batch process reduces *E. coli* numbers by ≥2 $\log_{10}$ to ≤5 $\log_{10}$ g^{-1} DS. Sludge treated to this standard is suitable for application to agricultural soil with associated land use restrictions (ADAS, 2001). These criteria are considered highly precautionary with regard to minimising the risk of infection from the agricultural use of sewage sludge (Gale, 2003. 2005; Mara and Horan, 2002). Thus the risk of infection from Salmonella is negligible, for example.

- Long-term sludge storage of air-dry sludge for ≥6 months can ensure 80-100% reduction in *Ascaris* ova. However, the data reviewed here demonstrates that *complete* elimination is highly related to temperature and/or pH and cannot be achieved readily. Under ambient weather conditions in Egypt, for example, *Ascaris* and other parasites were not detected after 6 months storage of sludge following air-drying.

- Storing air-dried sludge (40 – 55 % DS) in maturation heaps can achieve up to 100% removal of *Ascaris* ova due to microbial self- (auto-) heating of the piles through a composting action and possible microbial antagonism, although complete inactivation may not be achieved. Storage-maturation for 2 months achieved ≥90 % removal of *Ascaris* ova.

- Storage periods of up to 3 years for liquid and dewatered biosolids are recommended where *Ascaris* is a prevalent problem and the sludge is to be used without restriction (WHO, 2006).

- The potential high prevalence of *Ascaris* infections in the human population in many developing regions, the consequentially large concentrations of infective ova in sludge, and resistance of the ova to environmental stress and their long-term persistence in soil justify a highly precautionary approach to sludge management under these circumstances. Unless infected sludge can be treated by composting or other heat-based process, or the environment enables almost complete desiccation of sludge under high temperature ambient conditions, long-term storage for a period up to 3 years may be the only possible option available.

- Parasite infections in humans living in developed countries are usually very limited and helminth infections are exceptionally rare. Therefore, the microbiological quality of sludge under these circumstances reflects the health of the general population and the ova, cysts or oocysts of parasitic helminths in particular are very low or absent. Indeed, numbers of parasites in Victorian sludge are considered to be low.

- The potential presence of the most persistent parasitic organisms in sludge eg *Ascaris lumbricoides* is a critical factor in defining appropriate storage periods for air-dried sludge. However, as in other developed countries with high hygienic standards of potable water supply and wastewater treatment, parasitic organisms such as *Ascaris* are not routinely detected in Australian sludges. Therefore, a survey of public health information relating to enteric parasite infections in the Australian population and of other sources of parasites within wastewater collection catchments (eg abattoirs and animal production units) is

recommended. This would serve three purposes to: (a) demonstrate the potential transfer of parasites to sewage sludge during wastewater treatment, (b) identify organisms that may be of potential concern for further monitoring specif to Australian conditions and (c) to further clarify appropriate storage times for sludge prior to land application.

- The ova of tapeworms (Cestoda) progressively decline in infectivity and largely become non-viable after 6 months from release from the mature proglottids.

- Pathogens are inactivated by air-drying sludge as moisture decreases to <50 %. Inactivation of bacterial pathogens and indicators is proportional with the increase in moisture loss up to a sludge DS content of 90 %. Above this value bacterial populations may be less sensitive to further drying and may remain relatively stable.

- Greater decay occurs in warm ambient conditions, therefore inclusion of a summer cycle in the drying regime enhances pathogen destruction in temperate climates.

- Measure viability otherwise efficiency of inactivation cannot be thoroughly assessed.

- In summary, the main inactivating effects of storage are achieved by:

  – the reduction in water content;
  – the mechanism of anaerobic digestion;
  – starvation;
  – microbial competition.

- For the most important groups of enteric organisms in developed countries (ie bacteria and viruses), storage of stabilised, dewatered/air-dried biosolids for 6 months – 1 year period can meet a very high standard of microbiological quality equivalent to Class A or enhanced treatment status (US EPA, 1993; ADAS, 2001) and would be suitable for unrestricted use. This should achieve at least the *E. coli* standard for the T2 Treatment Grade for sludge in Victoria EPA (2004), which would be permitted for unrestricted use in other international regulations controlling the use of sewage sludge (US EPA, 1993).

- Storage/air-drying is capable of reductions in the range of 4-5-log, and often of total pathogen inactivation. To increase the efficiency of this type of treatment and improve consistent results, the following measures can be suggested:

  – pre-treatment by mesophilic anaerobic digestion;
  – liming;
  – drying in thin layers;
  – treatment in batches and not as a continuous or semi-continuous system to avoid by-pass flow and cross-contamination with untreated sludge and vector attraction;
  – Cover storage stockpiles to minimise rewetting and/or contamination with faeces of wild animals and birds which could lead to temporary recolonisation of the sludge with enteric bacteria.

11.2 Nutrient value

The long-term storage and air-drying of sewage sludge significantly reduces the availability of the two key nutrients contained in sludge with high potential agronomic value, N and also possibly P. Mesophilic anaerobic digestion of sludge releases N as NH_4^+ due to the microbial mineralisation of the organic N, which is highly volatile and is lost to the atmosphere during storage of liquid sludge. Further losses of N occur due to the continued mineralisation of organic N to NH_4-N during storage and initial stages of drying of liquid sludge, which is also lost to the atmosphere by volatilisation as NH_3. Drying sludge leads to further substantial gaseous loss of N and, consequently, the mineral N content of dry sludge (eg <90 % DS?) is small and typically <5% of the total N content and will decline with both storage time and the dry solids content. Thus, the principal methods of treating sludge after mesophilic anaerobic digestion of storage and air drying employed in Victoria would be expected to significantly reduce both the content and availability of N in sludge due to:

- High stability of the organic N due to continued mineralisation during the drying phase, which is equivalent to the storage of liquid sludge;
- Substantial gaseous loss of NH_3-N initially contained sludge, and released during the pan-drying phase, by air-drying and storage.

Phosphate, the other major agronomically important nutrient contained in sludge, undergoes complex inorganic transformations during the dehydration of sewage sludge to more recalicitrant, less soluble forms of Ca and Fe phosphate minerals (eg Ca-apatite. Consequently, liquid sludge has the highest P availability, and P release decreases with the extent of dewatering sludge.

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APPENDIX 1

Numerical indicator organism and pathogen reduction criteria

Victoria, Australia:

Specified pathogen limits for prescribed treatment processes in EPA Victoria Guidelines (EPA Victoria, 2004)

Treatment	T1	T2	T3
Faecal coliforms - *E. coli*	**<100 MPN/g d.w.**	**<1000 MPN/g d.w.**	**<2,000,000 MPN/g d.w.**
Salmonella	**< 1/50g d.w.**	**< 10/50g d.w.**	
Viruses - Enteric viruses	**≤ 1 PFU /100g**	**N/A**	**N/A**
Ascaris	**N/A**	**N/A**	**N/A**

Specified pathogen limits for 'alternative' treatment processes (EPA Victoria, 2004)

Treatment	T1	T2	T3
Faecal coliforms - *E. coli*	**<100 MPN/g d.w.**	**<1000 MPN/g d.w.**	**<2,000,000 MPN/g d.w.**
Salmonella	**< 1/50g d.w.**	**< 10/50g d.w.**	**1 log reduction (90% reduction)**
Viruses - Enteric viruses	**>3 log reduction (>99.9% reduction)**	**2 log reduction (99% reduction) Or < 2 PFU/10g in batch testing**	**1 log reduction (90% reduction)**
Ascaris* ova	**>2 log reduction (>99% reduction)**	**N/A**	**N/A**

*****as the *Ascaris* ova content in Victoria raw sludge is very low and it is therefore difficult to define further reductions caused by treatment, the guidelines allow for the use of a different indicator (potentially *E.coli* or *Salmonella*) as long as it has been approved by EPA Victoria (EPA Victoria, 2004).

United Kingdom:

Categories for treated sludge stipulated in the UK Safe Sludge Matrix (ADAS, 2001)

Sludge type	Definition	Microbiological criteria	Cropping interval
Conventional	Sludge that has undergone a treatment process to significantly reduce numbers of pathogens	≥2 $\log_{10}$ removal of *E. coli* ≤5 $\log_{10}$ *E. coli* g^{-1} DS in sludge	Vegetable crops: 12-month harvest interval Ready-to-eat salad crops: 30-month harvest interval Fruit or horticulture crops: not permitted
Enhanced	Sludge that has been subjected to a treatment process capable of virtually eliminating pathogens present in the original sludge	≥6 $\log_{10}$ removal of *E. coli* ≤10^3 $\log_{10}$ *E. coli* g^{-1} DS in sludge No *Salmonella* in 2 g DS	Fruit, salad, vegetable and horticulture crops: 10-month harvest interval

DS, dry solids

United States:

Specified pathogen limits in Class A and B biosolids (US EPA, 1993, 1994)

Treatment	All 6 class A pathogen alternatives	Alternatives 3 and 4* of class A pathogen alternatives	Alternative 1** of class B pathogen alternatives
Faecal coliforms	**<1000 MPN/g T.S. or meet *Salmonella* limit**	**<1000 MPN/g T.S. or meet *Salmonella* limit**	**Geometric mean of 7 samples: < 2,000,000 MPN/g T.S. Or < 2,000,000 CFU/g T.S.**
Salmonella	**< 3 MPN/4 g T.S. or meet Faecal coliforms limit**	**< 3 MPN/4 g T.S. or meet Faecal coliforms limit**	**N/A**
Viruses - Enteric viruses	**N/A**	**< 1 PFU / 4g T.S.**	**N/A**
Ascaris	**N/A**	**< 1 / 4g T.S.**	**N/A**

Notes:

*Alternative 3, class A of pathogen requirements: Biosolids Treated in Other Processes
Alternative 4, class A of pathogen requirements: Biosolids Treated in Unknown Processes

** Alternative 1, class B of pathogen requirements: The Monitoring of Indicator Organisms

World Health Organization

Microbiological guideline values for verification monitoring in large-scale treatment systems for sludge for use in agriculture (WHO, 2006)

Helminth eggs (number g^{-1} DS)	*E. coli* (number g^{-1} DS)
<1	<1000

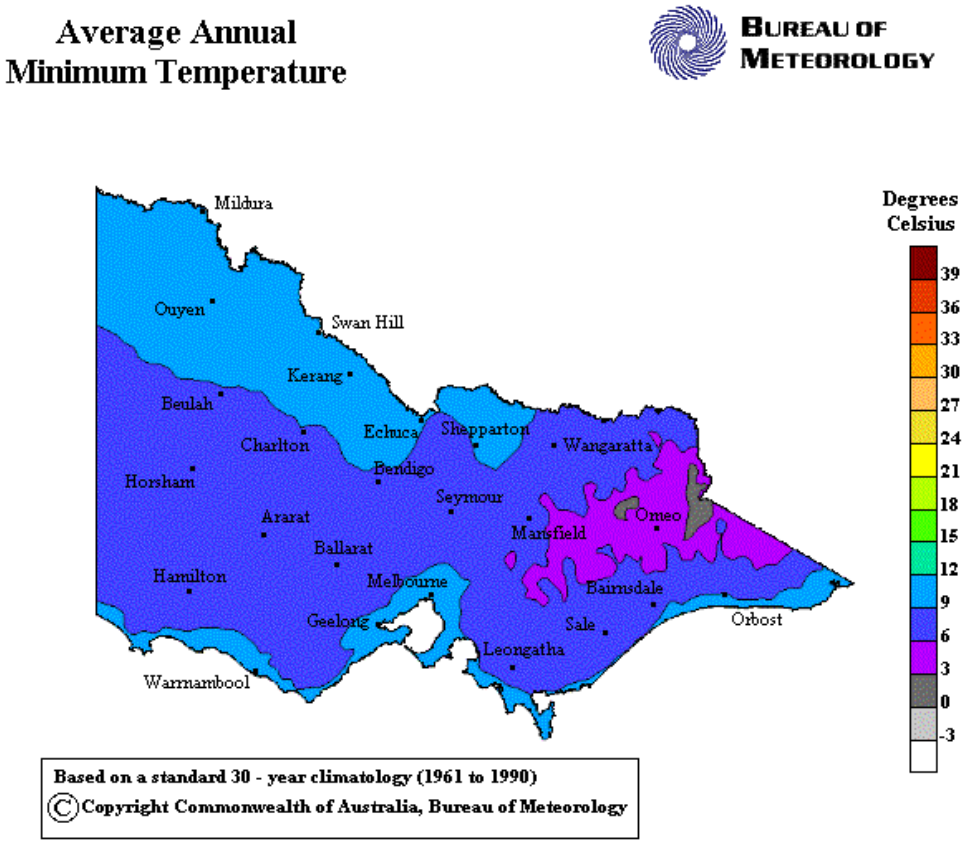
Microbiological criteria for sludge treatment grades for land application in Victoria, Australia (EPA Victoria, 2004)

Treatment Grade T1
Verification (of prescribed processes) < 1 Salmonella $50g^{-1}$ DS, <100 *E.coli* MPN g^{-1} DS and ≤1 enteric virus PFU $100g^{-1}$ DS. Verification of inhibition of pathogen regrowth is also required.
Routine monitoring (of prescribed processes) is based on <100 *E.coli* MPN g^{-1} (DS).
Alternative process microbiological verification described on case-by-case basis. Default performance criteria include: >3 log reduction in enteric viruses, >2 log reduction in *Ascaris* ova and achieving the *Salmonella* and *E. coli* criteria. Vector attraction reduction controls also required.
Treatment Grade T2
Routine monitoring (of prescribed processes) <10 Salmonella $50g^{-1}$ DS, <1000 *E. coli* MPN g^{-1} DS.
Alternative process Based on achieving *Salmonella* and *E. coli* criteria and demonstration of 2 log *Taenia saginata* and enteric virus removal or batch testing to demonstrate < 1 *Taenia* ova per 10g and < 2 enteric virus PFU per 10g. Vector attraction reduction controls also required.
Treatment Grade T3
Routine monitoring (of prescribed processes) <2,000,000 *E.coli* MPN g^{-1} DS.
Alternative process Based on *E. coli* criteria and 1 log reductions in Salmonella and enteric viruses. Vector attraction reduction controls also required.

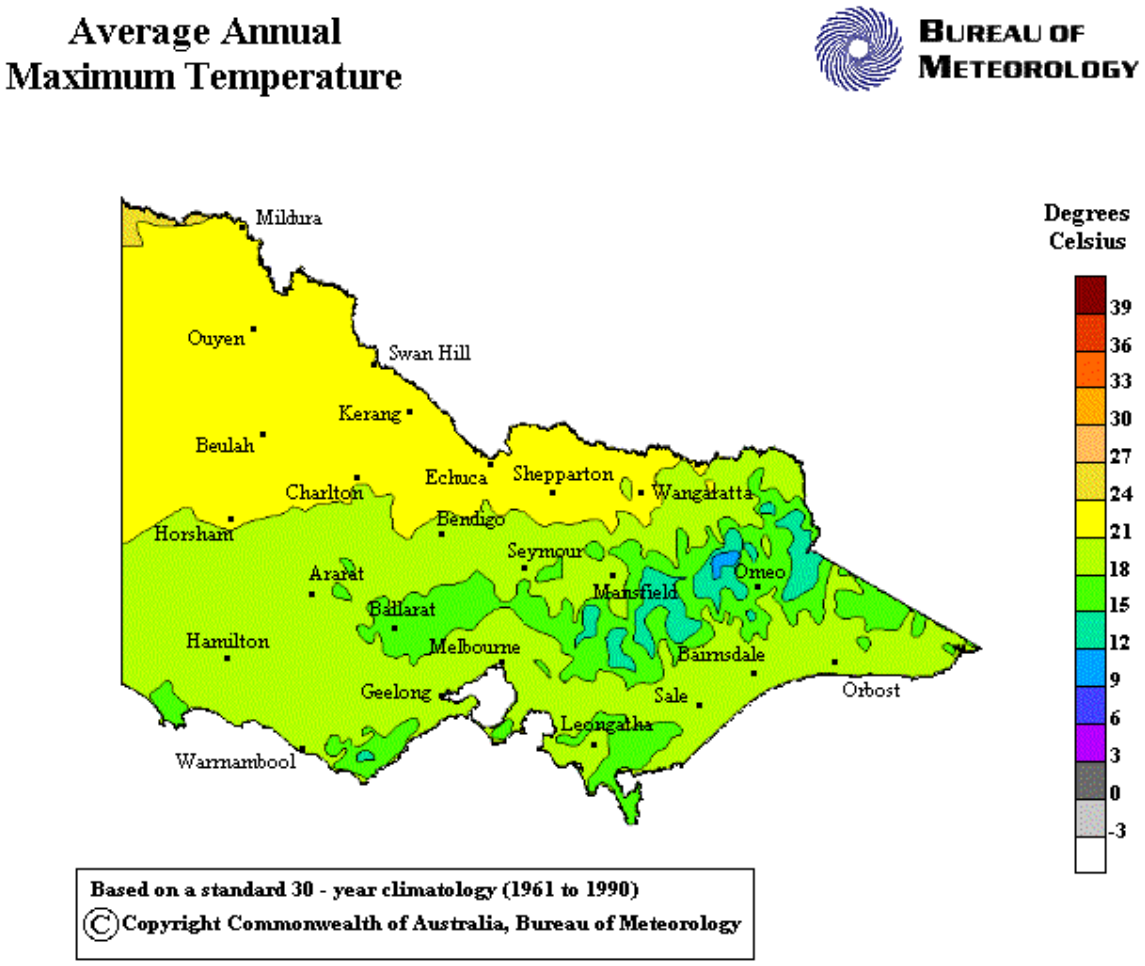
APPENDIX 2

Temperature and rainfall conditions in the State of Victoria

Average annual minimum temperature, Victoria (BOM, 2007a)



Average annual maximum temperature, Victoria (BOM, 2007a)



Average annual rainfall, Victoria (BOM, 2007a)