A Review of Current Knowledge

SEWAGE SLUDGE: Operational and Environmental Issues

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Review of Current Knowledge

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SEWAGE SLUDGE
(also called wastewater biosolids)

Thermal hydrolysis pretreatment (149000 tDS/y) with mesophilic anaerobic digesters (17000 m^3) behind at Blue Plains Water Resource Recovery Facility, Washington DC, USA

Author: Dr T. D. Evans

Contents

1 Introduction

This ROCK is concerned primarily with “sludge” from urban and domestic wastewater treatment works, also called [after it has been treated] wastewater biosolids. As much as 50% of the dry matter in sludge can be surplus biomass grown in the course of treatment. Many of the principles will also apply to sludges from wastewaters from industrial processes and also to digestates from biogas plants. The main objective of treating these wastewaters has been to separate water and the other constituents so that the water is fit for release back to the environment, or for reuse (Figure 1). A second objective is to recover resources from the other constituents. This is being given increasing priority as we strive to move from being a disposal society to a recycling society; from a linear to a circular economy. It is important to keep in context the risks and benefits compared with “ambient” activities and with not recycling. To emphasise the point the Water Environment Federation uses the term “Water Resource Recovery Facilities” (WEF, 2014).

Figure 1 Sewage taken from the inlet and effluent (reclaimed water) from the outlet of Mogden WwTW

Sludge contains organic matter, nitrogen, phosphate, some potassium, magnesium, sulphur and the minor plant nutrients, which means that it is valuable as a soil improver for agriculture, land restoration, forestry, and other land-based activities. It also contains gold, silver, platinum and other metals and is a good substrate for biogas production. Westerhoff, et al. (2015) reported that, if they could all be recovered, the metals in sludge for a community of 1 million people would be worth about US$13 million annually but the questions for anybody considering this are whether there is a sufficient quantity of sludge and whether metals are present in concentrations and chemical forms that make recovery financially viable.

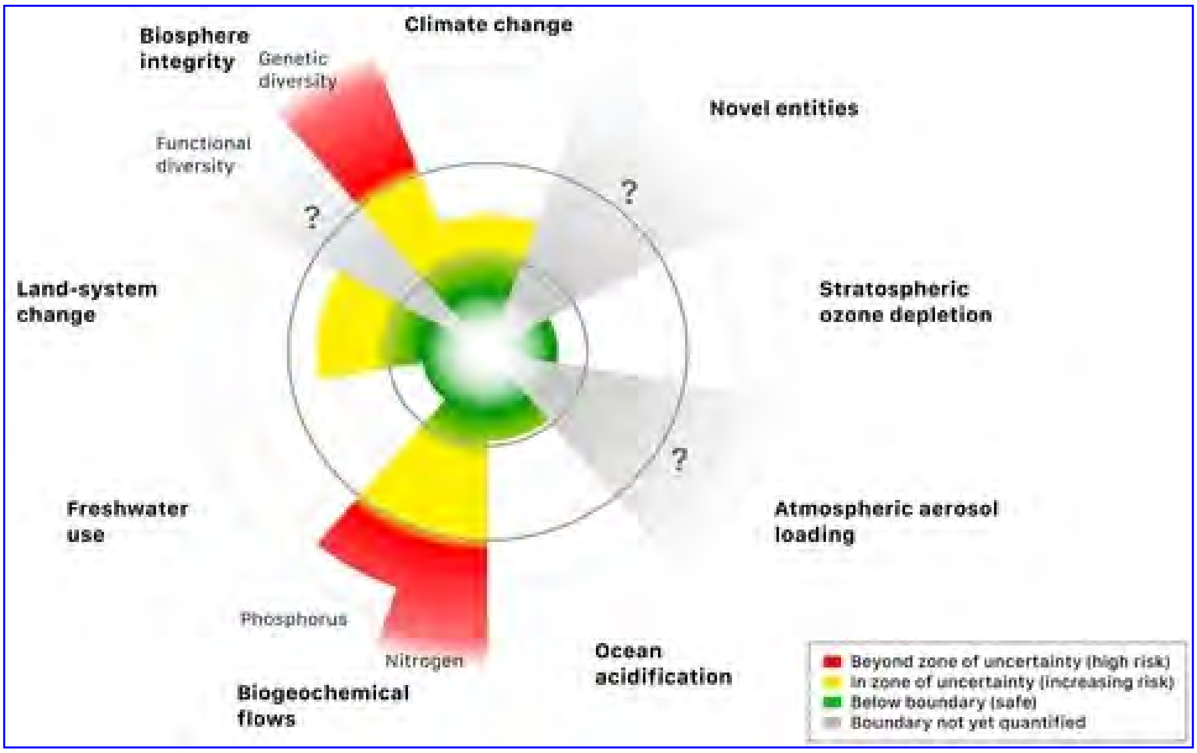

Figure 2 Earth System Boundaries (credit UCL)

As Figure 2 shows, we are exceeding the earth system boundaries for fixed nitrogen by 6 times and for phosphorus by 5 times. These are abundant in sewage sludges and it is environmentally responsible to recover or recycle the N and P in wastewater and sludges. Phosphate is the more important because it is irreplaceable whereas nitrogen gas is abundant in the atmosphere (albeit biological activity or energy is needed to fix it). Phosphate is essential for life because it is part of DNA and cells' energy pathways. It can never be substituted. Children accumulate phosphate in their bones, teeth, etc. but adults excrete 98% of the phosphate in their diets because they are just turning over cells. This and other phosphate ends up in urban wastewater. At the current rate of extraction, today's phosphate mines will be exhausted by the end of this century. Estimates of future reserves range from 200 to 400 years (Rosemarin et al., 2010); this is not long in the history of human kind. Morocco and Western Sahara have the largest proportion of the world's reserves (about 60% of the total). The USA (11%) and China (3.6%) have both implemented measures to restrict exports because they have realised the strategic significance of phosphate. As regards threats to the human population, phosphate depletion is on a par with climate change. As Isaac Asimov explained:

> *"…life can multiply until all the phosphorus is gone, and then there is an inexorable halt which nothing can prevent…. We may be able to substitute nuclear power for coal, and plastics for wood … but for phosphorus there is neither substitute nor replacement."* (Asimov, 1974).

Anaerobic digestion of sewage sludge became established from the beginning of the 20th century. The biogas produced is about 65% methane and because of this it is valuable as continuous, base-load, non-fossil energy, irrespective of time of day, time of year or weather. It can be upgraded to biomethane or biohydrogen. Sewage sludge is also a good base medium for digesting with other organic residuals [biowastes].

It was sewage collection and treatment (public health engineering) that cut waterborne disease and increased life expectancy in towns and cities in the mid-19th century, so it is no surprise that untreated sewage sludge contains pathogens (disease causing organisms). Therefore appropriate practices and procedures are necessary for treating and using sludge, just as they are for manures. The content and species of human pathogens in sewage sludge reflects the health of the population. By contrast, some animals can have symptomless infection with organisms that are extremely pathogenic to humans (e.g. *Escherichia coli* O157:H7 in cattle), i.e. the organisms are present in manure but not in sludge.

It is possible to find in sewage sludge and biosolids measurable amounts of most of the chemicals used in society. However, mere presence is not the question; the question should be whether there is unacceptable risk. As Paracelsus said five hundred years ago "*the dose makes the poison*". Sewage sludge might be a source but is there a receptor and is the concentration sufficient and is there a pathway to deliver a harmful dose to that receptor? In the case of sewage sludge produced in developed countries and used or disposed in accordance with today's rules, the consensus of informed scientific opinion is that the answer to this question is 'no'. Through a combination of hazardous substances regulations, which have eliminated some chemicals, changes in industrial practices and restricting discharges from factories, the concentrations of hazardous substances in sewage are dramatically less than they were a few decades ago (Figure 3). Despite this the "urban myth" of "heavy metals" in sewage sludge persists but it is false.

Continued vigilance and research are essential, but as this ROCK will explain, adverse effect has not been demonstrated for today's sewage sludge. The benefits far outweigh the risks.

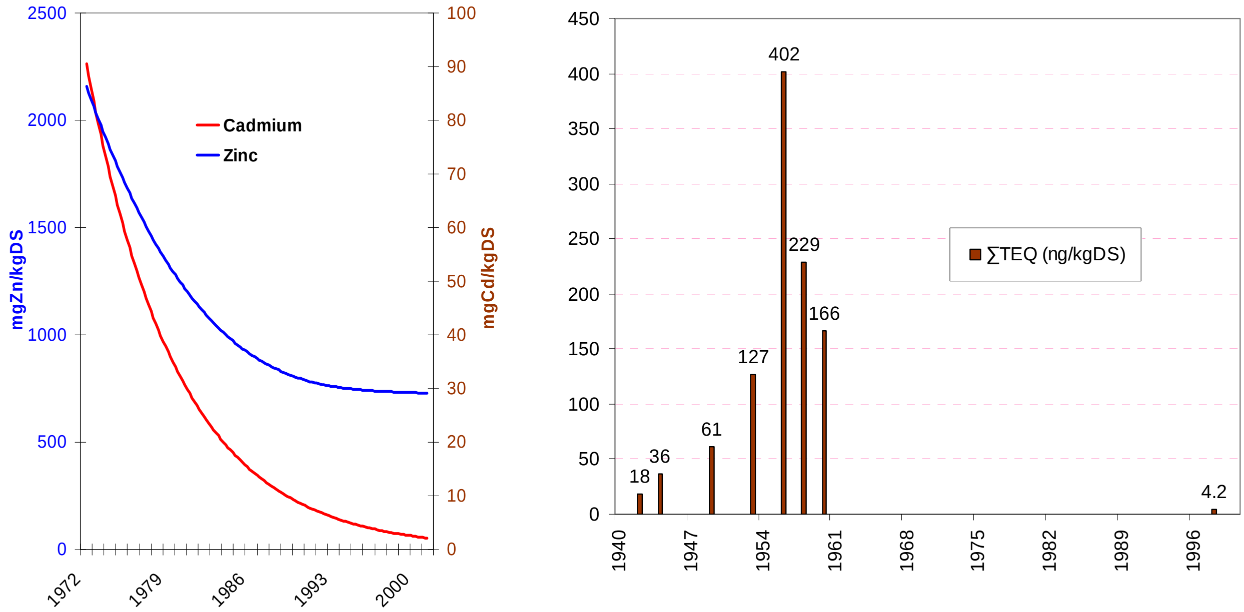

Figure 3 Changes in concentrations of potential pollutants in digested sewage sludge from Mogden WwTW in west London. Left: zinc and cadmium 1972 to 2002. Right: dioxins and furans 1940 to 2000

2 How sludge is produced

Wastewater treatment works (WwTW) can be thought of as the kidneys of our society; kidneys clean blood, WwTW clean water. The basic approach of wastewater treatment is shown in Figure 4. Sewage is screened to remove solids larger than 6 mm in 2 dimensions and then the velocity is slowed so that “grit” (which includes sand) settles out. Screenings and grit are washed, compacted and disposed. This leaves a suspension of fine solids and dissolved materials in water; the fine solids are settled out by reducing the velocity even more; this leaves ‘primary sludge’ and ‘settled sewage’. Settled sewage passes forward to biological [secondary] treatment where naturally occurring microorganisms feed on the very fine organic matter and dissolved matter that did not settle out in the primary treatment. Biological treatment is aerobic; it is generally performed using either ‘biological filters’ comprising beds of clinker or stone through which air diffuses and on which bacteria grow, or ‘activated sludge’ (invented in 1914 in Manchester and now used all around the world) where air is blown into the liquid. The objective is that when the reclaimed water is discharged, any resultant biological activity does not strip oxygen from the receiving water. These processes produce excess biomass, just as breweries produce excess yeast; this is called ‘secondary sludge’ and is combined with the ‘primary sludge’.

Very often there are also steps to remove nitrate (which was formed during secondary treatment) by biological denitrification, and phosphate, either by chemical precipitation or by causing the biomass to take up excess phosphate and storing it within its cells as polyphosphate. These ‘tertiary’ sludges add to the total production of sludge. Very often the content of carbon in sewage is too small in relation to the content of nitrogen and phosphate to support tertiary biological treatment and additional carbon such as methanol or acetic acid are purchased to supplement the carbon as necessary. Food waste and some industrial waste streams could supplement the carbon (CIWEM, 2011a).

Perhaps 60% or less of the sludge was present in the sewage directly and 40% or more was grown during wastewater treatment. The term ‘wastewater biosolids’ [generally biosolids] was coined to recognise that (a) much of the material was not sedimented from sewage and (b) to differentiate that which is fit for beneficial uses (CIWEM, 2011b).

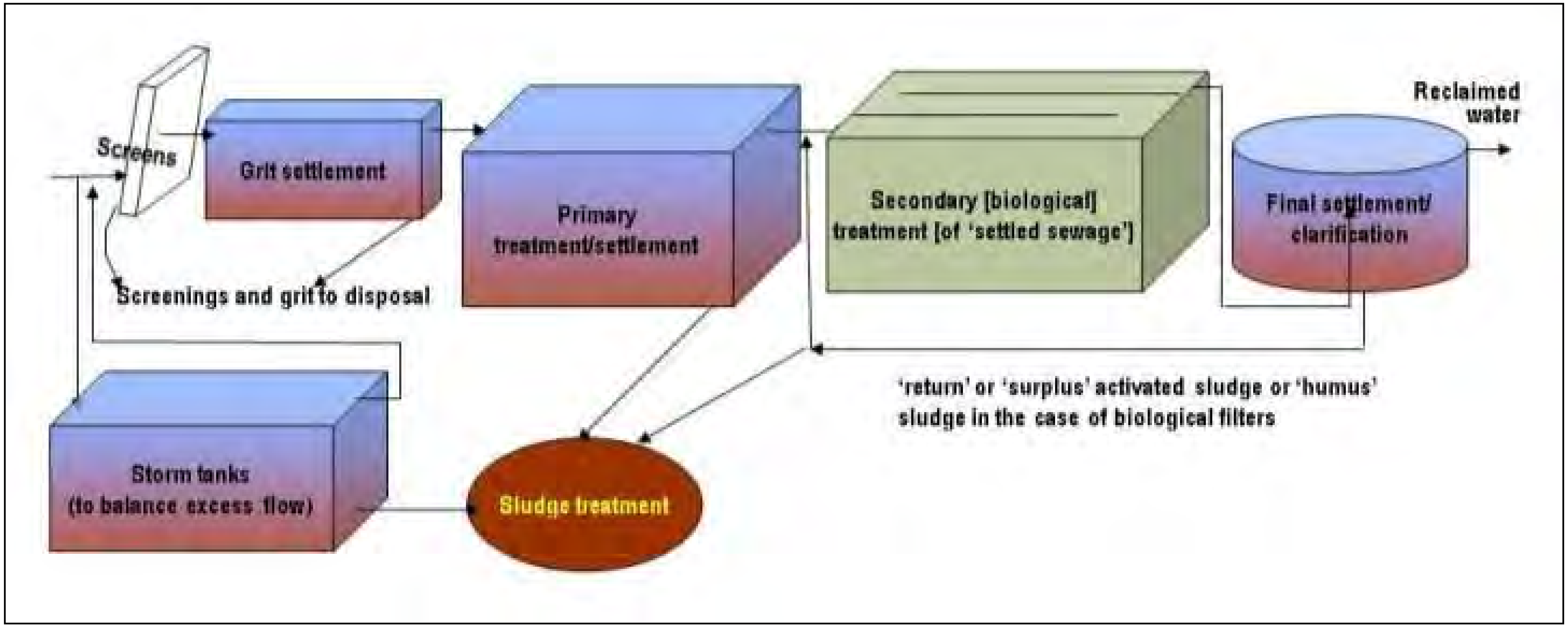

Figure 4 Schematic of a conventional wastewater treatment works

Appendix I and Appendix II list the data reported by Member States of the EU and some other European countries for sludge production (Gendebien, 2009) and (Eurostat, 2016). The per capita production varies widely reflecting (a) differences in the proportions of people connected to main drainage and (b) a lack of precision in defining where the production should be measured (raw, treated, etc.). There is a surprising degree of agreement that the total production was about 10 million tonnes DS/y. Eurostat reveals that 88% of the sludge produced was used or disposed; which suggests that 12% remained on the works. Gendebien (2009) reported that overall 37% of the sludge was recycled to farmland but Eurostat (2016) reported that 54% of the sludge produced [or 61% of that disposed] was used in agriculture or composted. Some regulations define that sewage sludge that has been composted is subject to compost rules rather than sludge rules and this drives WwTW to compost their sludge. Germany, Italy, France, Austria, Czech Republic, Sweden, Finland, Romania, Slovakia, Lithuania, Slovenia, Estonia and Luxembourg are all examples of countries where more than 30% of the sludge applied to land has been composted.

The total amount of phosphate in urban wastewater in EU_{27} is about 1,145,000 tonnes P_2O_5 per year. This is equivalent to 34% of the total 3,400,000 tonnes P_2O_5 per year imported by the EU_{27} (Rosemarin et al., 2010). About 614,000 tonnes P_2O_5 ends up in sewage sludge; that is 54% of the phosphate in wastewater. Sludge and compost applied to land (Eurostat, 2016) contains about 330,000 tonnes P_2O_5 which is about 29% of the phosphate in urban wastewater, the rest (71%) is squandered by failing to capture it (48%) or by ‘losing’ it in landfill or ash, etc. There is considerable potential to improve capture, recovery and conservation of phosphate, which surely must be a priority in the transition to a circular economy.

3 Sludge as a resource

To transform from a linear economy [extract, manufacture, use, dispose] to a circular economy requires changing from “dispose” to “reuse”, “recycle” or “recover”. Collecting sufficient quantities to make recovery financially viable can be an issue but in the case of wastewater we have established infrastructure for collection and treatment. What value can be recovered?

3.1 Water

Recovery of water is really outside the scope of this ROCK but it should never be forgotten that the pressure on [primary] water resources, which are already stretched in many places, is going to increase with population growth, urbanisation and climate change. Toilet training embeds aversion to wastewater but science and experience show that water recovered from urban wastewater can be used safely even for direct potable use – when there is nothing else to drink, the answer is not to drink nothing. Windhoek in Namibia has the first and longest-running direct potable reuse facility in the world; it has operated since 1968 and currently provides some 35% of the overall drinking water supply. Singapore's national water agency introduced ultra-clean, high-grade reclaimed water, which it brands as NEWater, in 2003. NEWater can meet 30% of Singapore's total water demand currently, and is set to meet up to 55% of its demand by 2060. Many other examples have come on stream since then.

3.2 Energy

Recovery of energy is discussed under sections 4.2 and 4.5. It need not preclude recovering other resources. Energy recovery and distribution of that energy have an economy of scale, which could be achieved by co-digesting sewage sludge with other organic residuals and/or establishing regional energy centres fed from several WwTWs. WwTW have the twin advantages as AD centres of being fed by existing infrastructure and of having the technology and expertise to treat process liquors.

3.3 Chemicals, metals, etc.

Use of sewage sludge to provide some nutrients to crops and to help maintain soil organic matter is referred to in Section 6 and Figure 2.

Osaka in Japan has ten WwTWs, one of them is a hub for incinerating all of the sludge. The hub WwTW it does not have capacity to treat the ammonia in the dewatering liquor biologically. Their solution has been to recover saturated ammonia solution from the dewatering liquor by steam stripping under reduced pressure. The ammonia solution is used in the incinerator to reduce NO_x and meet emission limits, which is a much higher financial value than fertiliser ingredient though that would be an alternative. Struvite (magnesium ammonium phosphate) is also recovered to prevent its adventitious deposition in the stripper [see also 4.1].

In 2015 there was much media coverage of a report from Westerhoff et al. (2015) that, if they could all be recovered, the metals in sludge for a community of one million people could be worth about US$13 million annually with US$2.6 million being accounted for by gold and silver (Figure 5).

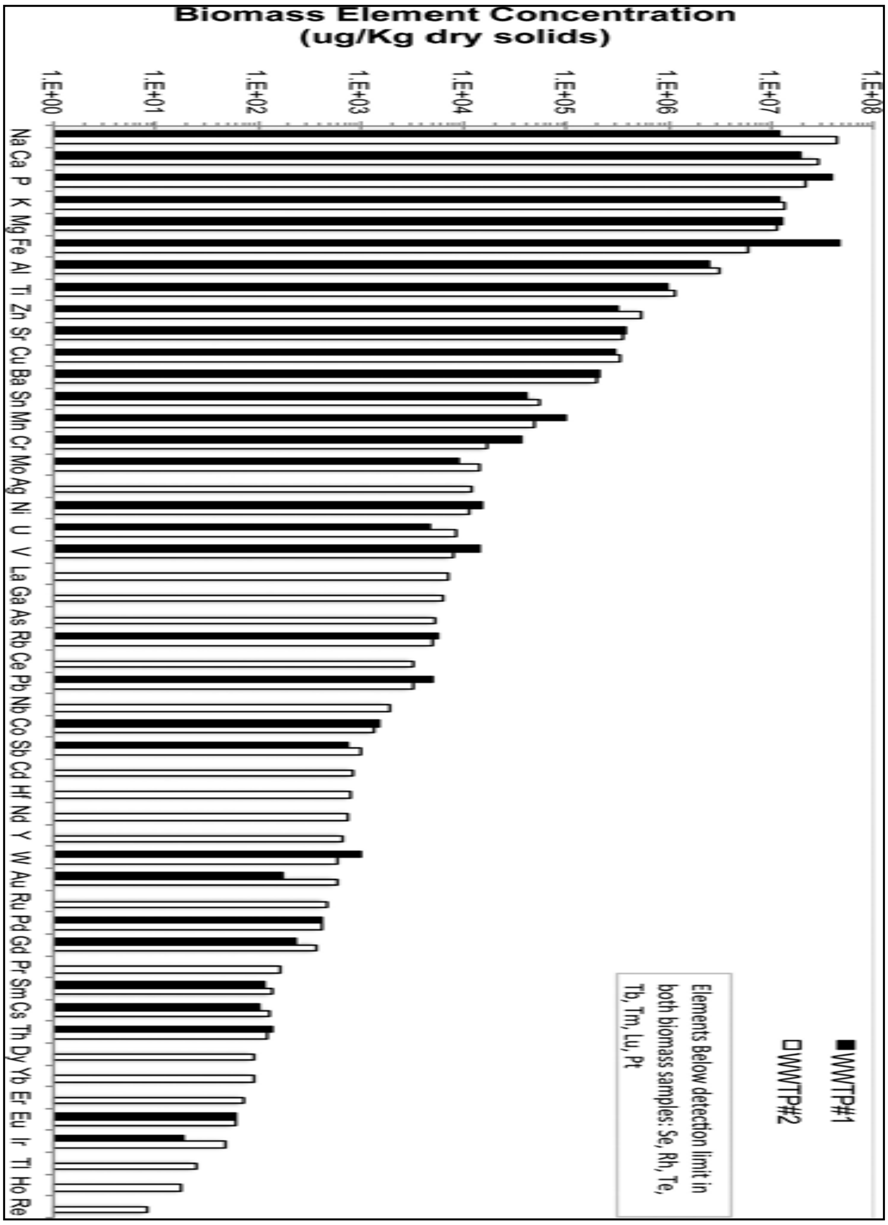

Figure 5 Elemental composition of sludges from two WwTW in Arizona (from Westerhoff et al., 2015)

The concentration of gold in the two sludges (0.3 to 0.6 gAu/t) was a similar order of magnitude to that in the ore processed at the top 50 gold mines in the world but whereas they each process 1 to 2 million tonnes of ore per year, the sludge production from a WwTW for 1 million people is only about 0.026 tonnes DS/year. Thus it appears that all of the sludge from about 50 million people would be required to achieve the critical mass currently considered financially viable for gold recovery. In exceptional situations (mining or jewellery areas) where concentrations are much greater than the WwTWs analysed by Westerhoff et al. (2015) extraction might be viable. For example the ash from incinerating sludge at the Suwa facility in Nagano prefecture, northwest of Tokyo, contains 1890 gAu/t ash probably due to the large number of precision equipment manufacturers in the vicinity that use gold. For the generality of WwTWs, the quantity x concentration is unlikely to be interesting for recovery.

4 Sludge treatments

The purposes of sludge treatment are to:

- reduce sludge volume to minimise handling and transport costs,
- reduce the number of pathogens in the sludge and
- prevent it smelling objectionable.

Treatments reduce the content of unstable reactive organic matter. Human pathogens are disease-causing microorganisms that have evolved to live in our bodies, and so cannot grow after the host has excreted them but could infect another human if they were consumed. Sludge treatments accelerate the natural die-off of pathogens, for example by depriving them of food, exposing them to antagonists, lethal temperature and/or chemical conditions.

Sludge treatment (and indeed all of sludge management) should be designed, constructed and operated with contingency for breakdowns and interruptions. Hazard Analysis and Critical Control Point (HACCP) is a very useful paradigm for design and operation.

4.1 Dewatering

One of the purposes of sludge treatment is to reduce the volume of material because it reduces off-site transport requirements. Untreated sludge from the primary and final clarifiers is typically 98% water and after gravity thickening it contains about 95% water. To dewater sludge (i.e. to reduce the moisture content from 95% to 80% or less) a conditioning chemical is added, which causes the individual sludge particles to form 'flocs', which make it easier to separate the water and solids by filtration or centrifugation. Dewatered sludge usually contains about 20-35% dry matter (80-65% moisture) depending on the type of sludge and the method of dewatering. It looks quite solid and can be stacked in a heap. Dewatering is a key pre-treatment to many subsequent processes.

It is easiest to calculate the effect of water removal by considering the dry solids content. Thus 100 m^3 sludge at 2 %DS (98 %MC) contains 2 tDS; dewatered to 25 %DS (75 %MC) it would be 8 m^3; the specific gravity is approximately 1.

The effectiveness of sludge dewatering is critical to the efficiency of subsequent processes. The costs of haulage and spreading when cake is recycled are directly related to the effectiveness of dewatering. This is also true of the cost of thermal drying because dewatering affects the amount of water that has to be evaporated.

The better the dewatering, the better the cake will stack, the easier it is to compost or to sanitise with lime and the smaller the energy requirement for drying.

Figure 6 Examples of different types of dewatering machines (clockwise from top left: plate and frame filter press, Bucher filter press, belt filter press, decanter centrifuge)

The three principal methods of dewatering are plate and frame filter press, filter-belt press and decanter centrifuge. In each case a conditioner is added to the sludge so that the particles ‘flocculate’ and the water is free to be removed. Selecting the correct conditioner and the optimum dosing rate for a particular sludge are essential but optimum dose is not a constant because the surface properties of sludge vary continuously. Automatic in-line dose optimisers using parameters related to dewatering (e.g. torque in the machine, liquor turbidity, torque in the feed-pump) is technically feasible and financially worthwhile but has failed to be commercialised at the time of writing. There is no universal answer for dewatering; each works needs to find the best solution for its particular sludge and circumstances and then ensure it is operated optimally: operators are important to outcomes.

Water removal is in the order filter press > centrifuge > belt filter press. However capital cost, operating cost, labour, footprint, etc. confound the choice. High shear centrifuges have a small footprint, good water removal, low labour and easy automation but not infrequently are associated with Sudden Increase [in *E. coli*] Regrowth and Odour (SIRO or ROSI). *Escherichia coli* (*E. coli*) is used as an indicator for pathogens (as it is in potable water). It is measured by culturing in specific media. Chen et al. (2011) have shown that when sludge is treated at 55 ^{o}C, *E. coli* can go into a non-culturable state, i.e. they appear to have been killed. Passage through a high shear centrifuge renders them culturable again (sudden increase). Pathogens do not follow this VBNC (viable but not culturable) transition. After awakening from the VBNC state *E. coli* can regrow. The odour increase can be explained by shear forces exposing biodegradable matter that had been surrounded by stabilised matter previously. Some WwTWs that have changed from BFP to centrifuge because of the better dewatering have had to change back because of odour (e.g. Charleston, NC, USA).

Figure 6 includes a Bucher press, which is a relatively new entrant to sludge dewatering but has been dominant in fruit juice extraction for years; it has exceptional water removal effectiveness. It uses sleeves of filter cloth supported on flexible “ropes”. The assembly is squeezed and twisted between each incremental filling, this disrupts cake off the cloth. It operates unattended, there is no SIRO effect and as a rule of thumb it extracts 30% more water than any of the other methods (priv. comm. Nick Mills, Thames Water, 2016).

Liquor treatment

Conventionally filtrate or centrate (the water separated by dewatering machines) has been returned for treatment through the works where it can be 25% or more of the nitrogen and phosphate load on a treatment works. Another method is emerging, which is to treat dewatering liquor in a compact side-stream plant to remove most of the nitrogen and phosphate before returning the liquor to the main plant. Conventionally this involved biological processes to remove nitrogen but the more pioneering WwTWs are recovering ammonia solution and/or phosphate by physico-chemical processes. These physico-chemical recovery processes are financially competitive with merely returning the liquor to the WwTW and at least equal to sidestream biological treatment (Evans, 2009). They have smaller global warming potentials. Magnesium ammonium phosphate (struvite) is easy to recover and it is a good fertiliser. Ammonia solution has industrial uses in addition to its fertiliser use. Recovering phosphate and ammonia is consistent with moving from a disposal to a recycling society.

4.2 Biological treatments

The most widely practised type of sludge treatment is '**anaerobic digestion**' (AD); AD facilities are sometimes called biogas plants. AD was pioneered early in the 20th century. AD stabilises the sludge, reduces pathogen numbers and produces biogas (64% CH_4, 35% CO_2). Biogas is a clean, continuous and renewable alternative to fossil fuel. Digestate is a good nutrient rich soil improver that substitutes for all of the phosphate and some of the other mineral fertiliser needs of growing crops.

Liquid sludge is treated in heated tanks (mesophilic at 35 °C or thermophilic at 55 °C) from which air is excluded (Figure 7). Bacteria that can live without air (anaerobes) feed on the organic matter and make biogas (65% methane, 34% CO_2 and 1% other gases). Two classes of bacteria are involved: ‘acidogens’ break large organic molecules into volatile fatty acids (VFAs) and ‘methanogens’ which convert the VFAs into methane. Acidogens multiply rapidly and like a low pH whereas methanogens multiply slowly and like a higher pH. Conventionally they are expected to coexist in a single digester but some have found ‘2 phase’ digestion beneficial by installing a small digester with 2 days hydraulic retention time (HRT) in front of a 15 day digester. Acidogens predominate in the 2 day HRT tank because methanogens do not have the generation time to maintain a population. Digesters in series also reduces short-circuiting.

Figure 7 Anaerobic digesters, CHP building in the foreground, gas holder (left) and dewatering building and cake stacking area in the background

After cleaning to remove water, H_2S and siloxanes, biogas can be burnt in engines that turn generators to make electricity and heat. It is a clean, continuous and renewable alternative to fossil fuel. It can be compressed and used as low-emission vehicle fuel (Figure 8). Alternatively the CO_2 can be removed, which upgrades the biogas to biomethane that can be injected into the natural gas grid or compressed.

Figure 8 Vehicle refuelling with compressed biogas at a WwTW in Stockholm, Sweden.

Properly digested sludge has a tar-like, ammoniacal smell. AD converts the nutrients to forms that are more available to plants. It is a N:P:S (nitrogen:phosphate:sulphur) fertiliser with organic matter. It also contains micronutrients (trace elements) and maintenance quantities of potassium (K) and magnesium (Mg).

AD with combined heat and power generation (CHP) became popular in the 1930s. It is still the most widely practised form of sludge treatment because of its capacity to make renewable energy whilst at the same time conserving all of the plant nutrients and reducing the quantity of sludge produced. In 2005, 65% of sludge in England and Wales was treated by AD; by 2015 it had increased to 85% and by 2025 it will be 96%.

Innovations have focussed on increasing the amount of sludge that can be treated, improving mixing in digesters and making the sludge more digestible (increasing biogas yield and solids destruction). Examples of techniques to increase digestibility are breaking open cells using ultrasound, microwaves or high pressure homogenisers or by hydrolysing them enzymatically or thermally. These pre-treatments can also improve the later dewatering and sanitisation of the sludge and the odour of the digestate. Thermal hydrolysis (pressure cooking at 160 ºC) is by far the most effective and whilst the capital cost is high, the whole life cost is often the most competitive of the alternatives.

Sometimes other organic wastes are co-digested with the sludge (e.g. France, USA). Denmark, Germany and the Netherlands have all made biogas from anaerobic digestion of biomaterials (organic fraction of municipal solid waste, sludge, manure and organic wastes from industry) part of their national energy strategies. At the time of writing, UK regulators still had difficulty accepting the use of existing AD infrastructure on WwTWs for co-treating other organic residuals.

Figure 9 A co-digestion facility at Studsgard in Denmark

Composting is another type of natural biological sludge treatment (like AD) but this time it is aerobic, i.e. it is essential that air can pass into and through the composting material. It has been used for centuries and gardeners know well the value of compost for improving the fertility and workability of soil. Dewatered sludge is too dense for air to move through it so straw, woodchips, sawdust, greenwaste or some other material is added to open up the structure. This 'bulking agent' also provides extra carbon to feed the composting bacteria and balance the nitrogen content of the sludge. Ammonia is volatilised during the first 2 weeks of composting. Aerobic bacteria feed on this mixture and give off heat which raises the temperature of the compost. Hot composting (at least 55 °C) kills pathogens because they cannot tolerate the high temperatures and other conditions in the composting material. The product of composting is crumbly, nutrient-rich brown soil improver. The nitrogen in compost is only released very slowly. Mature compost is also a good basis for making growing media (Evans & Rainbow, 1998).

Some countries have rules specific for composted materials that are less onerous than their sludge regulations regarding permitting, recording, etc. In these countries composting is favoured as a sludge treatment. Most compost is used in agriculture, field-scale horticulture or for land reclamation but the fate of the sludge might not be recorded as “agriculture” when it is used under the compost rules (Appendix II).

Reedbed treatment of sludge started in the 1980s and has been steadily gaining acceptance. The beds are sealed; they contain drains set in a bed of aggregate on which reeds are planted. Sludge is applied to the beds sequentially in shallow layers. Odour is contained within the reed canopy, even in winter. The reeds excrete oxygen from their roots which maintains the root zone aerobic. Bacteria initially, and later earthworms, mineralise the sludge and sanitise it. The mineralised sludge builds up in the beds (until it is about 40%DS). After about 10-15 years a cycle of digging out the beds in rotation is started. This is especially useful for sludge from extended aeration treatment, but it is also suitable for sludges from other types of wastewater treatment. Energy and chemical use are very small.

Figure 10 Sludge reedbeds in Denmark

4.3 Chemical treatment

Lime stabilisation is practised widely in Europe and other countries. It entails mixing dewatered sludge with quicklime (calcium oxide) or some quicklime containing additive.

Quicklime has been used to disinfect materials for centuries. It is limestone that has been burnt in a kiln, which makes it very reactive with water. When quicklime is added to moist dewatered sludge, heat is generated the pH rises (the mixture becomes alkaline), and ammonia is liberated; these three effects kill pathogens and may prevent odour. Odour is probably less when slowly reacting lime is used. Good mixing is essential. Cheap systems invariably give the worst (most odorous) product. The high pH prevents reinfection and fermentation. Some of the nitrogen in the sludge is lost during the process. The product is valuable on land as a liming material that also contains phosphorus and other nutrients.

Lime is very useful for agriculture where soils are acid. On neutral soils it should be used with caution to avoid inducing trace element deficiencies. On limestone and chalk soils the lime in the sludge has no benefit, but since the soils are lime-saturated already it is not detrimental either.

4.4 Drying

Drying is essentially the evaporation of water (or most of it) from dewatered sludge. In many cases the sludge is digested first and the biogas is used to heat the dryer. Evaporating water requires a lot of energy. To dry 1 tonne cake at 25%DS requires approximately 540 kWh – 80 calories per g to heat the water from 20 °C to 100 °C and 540 calories per g to turn 100 °C water into vapour. This is offset to some extent by reduced haulage costs and has to be evaluated in comparison with all of the other options. The cost of fuel for drying could be reduced by using “waste” [or low grade] heat in low temperature dryers.

Sludge can be dried by natural evaporation in the open air. This was widely practised in the past and is still appropriate where drying conditions are predictable and land is not too expensive.

Computer controlled greenhouse drying requires a smaller area of land, it is independent of rain or snow, and air from the greenhouses can be treated so that there are no odour emissions. The greenhouse method uses only 1% of the energy needed for thermal drying (apart from solar of course).

Desiccation (drying out) and high temperatures kill pathogens. Dried sludge is often granulated (small round particles) or pelleted (small cylinders). This makes

Figure 11 Retail bag of Milorganite thermally dried biosolids garden fertiliser

it an attractive and clean material that is easy to spread by hand or with fertiliser spreaders. In some places it is available to gardeners, for example Milorganite (produced by Milwaukee WwTW) is sold in every state of the USA; sales started in the 1920s. Dried sludge can also be used as fuel (e.g. electricity generators and cement kilns) but this squanders the phosphate.

4.5 Incineration and other thermal processes

Incineration (or some other thermal process) is really the only major alternative to using sludge on land in the EU where landfill is discouraged and disposal at sea is banned. However it has not proved to be the panacea that was expected in the 1990s when fluidised bed incineration was introduced because they have seldom been built with the contingency for planned and unplanned shutdowns. Incinerators require planned shutdowns for inspection and maintenance, which could take 2 or 4 weeks or longer. If something can go wrong it will (Murphy's Law) and the constituents of the chain of processes in an incinerator have proved to be no exception. Facilities should be planned in the anticipation that sludge can be managed properly through at least 6 weeks' shutdown.

Dewatering is one of the keys to successful incineration. Water does not burn; it is therefore necessary to reduce the moisture content so that there is sufficient heat from burning the dry matter to evaporate the remaining water. This is called autothermal combustion, i.e. no external heat source is required except for starting up the incinerator. Water vapour adds to the volume of gas for emission clean-up. Flue-gas clean-up is a very significant part of the cost of incineration. A few incineration systems dry the sludge first to eliminate water vapour and reduce the volume of exhaust gas that has to be cleaned, which reduces the capital and operating costs of incineration significantly but the cost of drying must be added.

Incineration results in ash, which is normally disposed in landfills. Although the ash contains the phosphate from the sludge it is in chemical forms that are unavailable to plants (and therefore it has no direct use as a fertiliser). Some processors of rock phosphate accept sludge ash into their processes in part as a commitment to recycling. The price they charge or pay depends on the concentration of phosphate. Excessive iron might make the ash unacceptable because iron increases the cost of P extraction, however sludge ash generally contains less cadmium in relation to P than rock-phosphate, which is an attraction for the processor. At the least phosphate-rich ash should be mono-filled so that it will be available for processing for when the price of rock-phosphate warrants it, as it assuredly will.

Work to find uses for incinerator ash has not yet been very successful. This is hardly surprising because the quantities produced are small compared with the outputs of sand or aggregates quarries.

Figure 12 Fluidised bed sludge incinerator at Bradley, Yorkshire

A variation to incineration has been developed in Japan. Ash is heated to such a high temperature that it melts and forms a glass. Melting furnace technology is even more expensive than conventional incineration.

In some areas there are large numbers of people and also intensive livestock production and consequently there is insufficient land to use all of this organic resource. In such circumstances incineration might be the most practicable alternative to recycling.

The EU's Incineration Directive (CEC, 2000) ensures that when wastes (including sludges) are burnt, the risks from emissions to air are within acceptable limits. Modern fluidised bed incinerators are able to meet these exacting standards consistently.

Some treatment works dry their sludge and then supply it as fuel for use in cement kilns and other energy intensive processes. Whilst this is substitution for fossil fuel, it squanders the phosphate and care is needed that the phosphate content of the cement is not raised excessively.

In energy terms the energy used to evaporate the water to dry the sludge should be deducted from the fuel value of the dried sludge.

Some coal-fired electricity generators have been converted to be able to burn a small proportion of either dried or dewatered sludge together with coal. However, quite rightly, burning sludge in these facilities should bring them into the purview of the Incineration Directive (CEC, 2000), which some operators consider an unwelcome additional responsibility.

There has been at least 30 years' work to try to convert sludge into ash and oil or gas by gasification or pyrolysis as an alternative to incineration. In essence the sludge is dried and then burnt in a restricted amount of air such that there is enough combustion to heat the rest of the sludge and convert the carbonaceous matter to oil or gas. Either of these fuels has the advantage (over electricity) that it can be stored until it is required, or transported to a place where it can be used. However, despite considerable investment in research and development, only one operational sludge facility was built in the 20th century. This was the oil from sludge plant at Subiaco, Perth, Australia; it closed after about 18 months' operation. Reliability was one of the issues but most importantly the oil did not match any of the industry's specifications and the quantity was too small for industry to adapt its processes to accommodate it.

‘Flash pyrolysis’ with a retention time of around 1 minute and bed temperatures of 850-900 °C might prove to be viable. After extended trials Thames Water is building a 20 tDS/day pilot at Crossness WwTW in London (commissioning 2017, priv. comm. Pete Pearce, 2016). Thermally hydrolysed, mesophilically digested sludge will be dewatered then dried to at least 90 %DS in low temperature belt dryers using low-grade or waste heat. 95-97% of the organic matter is converted, nearly all of it to syngas (not oils), a few percent remain as tertiary and quaternary tars which are removed in the gas clean up and represent maybe 5% of the input energy in the sludge. The syngas has a high calorific value (17-18 MJ/m^3) as it has a high methane content, typically about 30% CH_4, 30% H_2 and 30% CO. It needs to be scrubbed for particulates, NH_3 and H_2S, which is quite straightforward. The volume of pyrolysis gas is much smaller than that of incineration because it is not bulked out by combustion air (and the remaining nitrogen) to move, preheat and then flue gas treat. The syngas will be used in CHP engines where 40-44% energy conversion to electricity is expected. In contrast, steam powered turbines on small incinerator systems (such as the largest WwTWs) only achieve around 15% energy conversion from sludge to electricity. P can be recovered easily from the char by acid leaching. The char is mesoporous after leaching and potentially valuable as an absorbent.

Super critical water oxidation (SCWO) is another possible alternative to incineration. Orange County Sanitation District, Los Angeles is very likely to build a pilot (20 tDS/day) in 2017 or 2018. Los Angeles has extremely strict air-emission permitting limits. Liquid sludge is pressurised to 221 bar then heated to about 374 °C through a heat exchanger, i.e. above its thermodynamic critical point. Under these conditions water becomes a fluid with unique properties, the density is between water vapour and liquid at standard conditions, it exhibits high gas-like diffusion rates along with high liquid-like collision rates and it behaves much less like a polar solvent than subcritical liquid water. As a result, the solubility behaviour is "reversed" so that organics become soluble in the water, allowing single-phase reaction of the aqueous waste with dissolved oxygen. The reversed solubility also causes salts to precipitate out of solution, meaning they can be treated using conventional methods for solid-waste residuals. Efficient oxidation reactions occur at low temperature (400-650 °C) with reduced NO_x production. The product is water and oxidised inorganics, which dewater easily and from which resources could be recovered easily, presumably. Johnson Matthey in London has operated SCWO since 2003 to recover precious metals from spent catalysts.

At a much lower level of sophistication, sludge can be mixed with clay to make ceramic building materials; there are very few examples of this anywhere in the world but it is an interesting application. Naturally occurring organic-rich clays are valued for brick manufacture because as the bricks are fired the organic matter in the clay burns contributing energy to the process and at the same time results in bricks of lower density that are lighter to transport and to handle. Sludge can be mixed with clay that contains little or no organic matter to produce similar effects.

One consequence of all of these alternatives to sludge use on land is that phosphate is lost, or at least it is concentrated in the ash or char from which it is currently more expensive to recover than extracting phosphate from rock phosphate. The concern is that (at the current rate of extraction) the current mines will be exhausted by the end of the 21st century and the phosphate industry estimates the life of the known reserves of rock phosphate to be only 200-400 years at the current rate of exploitation. As discussed above, phosphate is essential for life. Cadmium (a potentially toxic element) is present, to a greater or lesser extent, in all rock phosphate. The lower-cadmium sources are only about 15% of the known reserves. Mining will be forced into higher-cadmium sources as the global reserves run down. A consequence of not recycling sludge will be that 'new' cadmium will be brought into the anthropogenic cycle more quickly than if sludge were recycled.

5 Risks of using sludge on land

As stated earlier, sewage contains pathogens and many of the chemicals used in society. Their fate and behaviour have been researched extensively. The risks that they could present to soil, crops, humans and animals eating crops, water passing through soil and to the environment in general are managed by layers of protection.

A hazard is something that has the potential to do harm; risk is the consequence of exposure to a hazard in a particular circumstance. Risk to a receptor depends on there being a source (in this case sludge) and a pathway that can deliver a harmful dose to that receptor. When the concentration in the source is small or when the pathway cannot deliver a harmful dose, there is no risk.

Initially the major concern was for the safety of people working in the sewers and of the biological processes used in wastewater treatment. If there were toxic gases in sewers (possibly from chemical reaction between different factory discharges) it could be fatal for any workers in the sewers. If a toxic chemical were discharged in excessive amount, it could kill the biological treatment processes. When that risk had been controlled, concern passed to the health of the water-body into which the treated water was discharged and the biota living in it and then to the land on which sludge was used, the plants growing on the land, the organisms living in the soil and animals eating the plants.

The first controls on sludge use on farmland in the UK were published in 1976 (DoE, 1976). They limited the rates at which potentially toxic elements could be added to soils and the ceiling concentrations permitted in soils. In 1986 the European Commission published the “sludge directive” (CEC, 1986), which all Member States are obliged to transpose into their national legislations; in 1989 the UK was the first MS to do this (Statutory Instrument 1989). In essence the 1989 controls were very similar to those established in 1976. At the time of writing (2016) there are 40 years of experience of using sludge with these controls and there have been no cases of adverse effects.

In 1992 the US EPA published a risk assessment that completed 11 years’ work and cost $15 million (USEPA, 1992). Initially samples were collected from a stratified selection of the nation’s wastewater treatment works (208 WwTW); these were analysed for a wide range of inorganic and organic chemicals (412 analytes) to establish which were present in concentrations that would warrant further investigation.

Having established the ‘landscape’ of potential pollutants, a deterministic risk assessment was undertaken that considered 14 exposure pathways and the lifetime risk to ‘most exposed individuals’. In 2001 the US EPA completed a probabalistic risk assessment of dioxins, furans and dioxin-like PCBs (Greenwood et al., 2004), see section 5.2 and Figure 13.

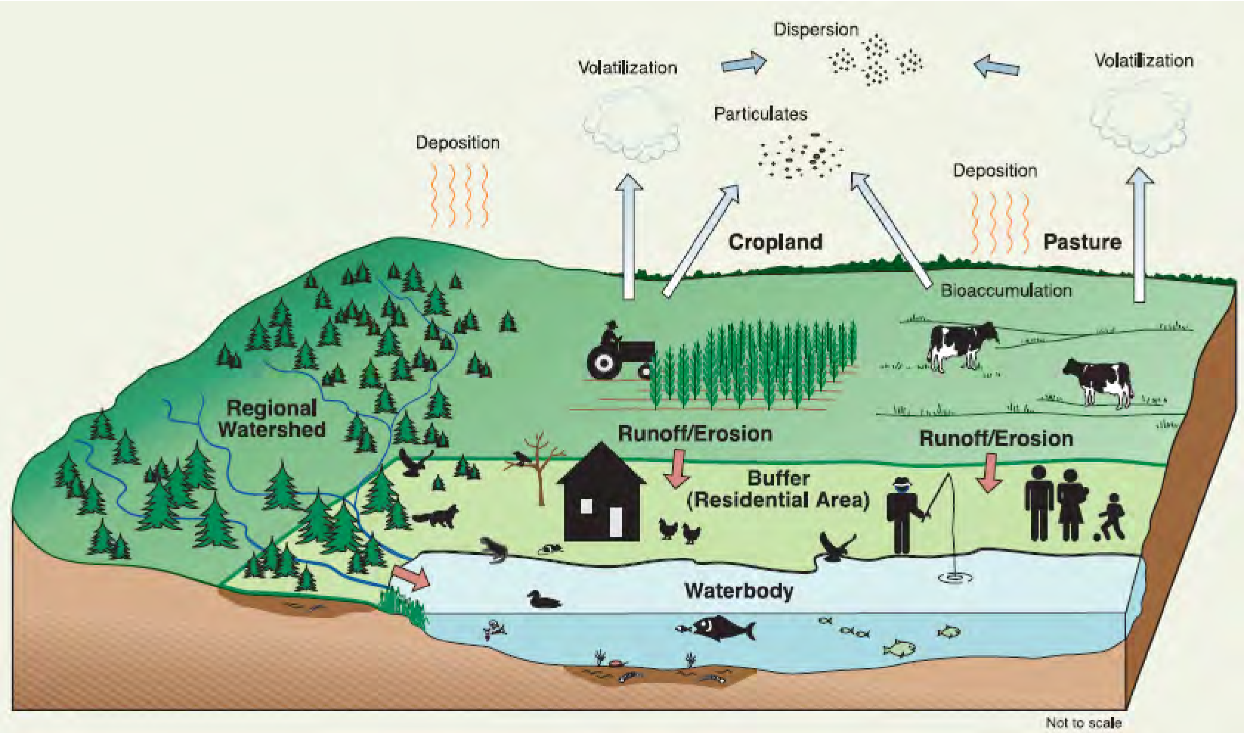

Figure 13 The integrated modeling scenario used for the USEPA dioxin reassessment (Greenwood et al., 2004)

In 2002 the US National Research Council published an evaluation of these risk assessments and concluded the methodology and conclusions had been sound. It recommended that in the light of public uncertainty, the EPA should be given more funds so that it could refresh the whole exercise (National Research Council, 2002).

Although the European directive does not have as much rigorous scientific underpinning it as the USA’s federal regulation (Standards for the Use and Disposal of Sewage Sludge, 1993), the soil protection outcomes are quite similar. The major difference is in the area of stability and hygiene, see section 5.3.

5.1 Metals and inorganic chemicals

Inorganic elements do not biodegrade, therefore they either accumulate in soil or they are washed out (leach) depending on their interactions with soil. The metals and inorganic chemicals of concern in sludges do not leach (or at least only very slowly), so they accumulate; however they can be moved in the general earth moving performed by earthworms. Although the total amounts do not change much, the availabilities (i.e. how easily they are taken up by plants) of these chemicals do change as they interact with the organic and mineral fractions of soil. In general, availabilities decrease with time.

Historically sludges contained much greater concentrations of potentially toxic metals than they do at present (Figure 3). Concern developed in the late 1960s/early 1970s that these might be affecting the fertility of soil or yields of crops if they were allowed to accumulate in soil to excessive concentrations. Wastewater operators worked with factories to reduce the amounts of metals they were discharging to sewers. Factories are given limits (Trade Effluent Consents) that they must not exceed. These Consents are normally written as both concentration and total amount per year so that a factory cannot use dilution as a solution to disposing of its wastewater. Wastewater operators have a right to enter premises and take samples. This cooperation, backed up by legal sanction if necessary, has been a major contributor to decreasing the concentrations of potentially toxic elements in sludges. Other contributors have been changes in industrial practices, changes in the materials industries use and in some cases the demise of industries.

Whilst not suggesting that the practices before 1976 were sustainable, the farmers and their families on the farms where these sludges were used (with much larger concentrations of metals, Figure 3, and at much larger application rates than today) did not display any adverse effects, even the ones eating the crops (e.g. salad crops) grown on sludge-treated land (Sherlock, 1982 and USEPA, 1985).

Reassuringly there is consensus between the EU and the USA that the metals that need to be regulated are zinc, copper, nickel, cadmium, lead and mercury. Additionally the USA regulates chromium, molybdenum, arsenic and selenium; the UK also regulates these elements and additionally fluoride. Zinc and copper are minor nutrients and deficiency in crops and in the animals eating them is quite widespread. Selenium is possibly deficient in the diets of European humans (Sneddon, 2012). Overall the risk from metals and other inorganic chemicals is very small in countries in the EU, USA and other countries that have controlled them at source.

5.2 Organic chemicals

A broad spectrum of organic chemicals (OCs) is used by modern society (e.g. detergents, personal care products, pharmaceuticals, plasticizers, fire-fighting foams, etc.). Some are discharged into urban wastewater from industrial and domestic sources; others enter via atmospheric deposition onto paved areas and surface run-off. Hydrophilic ones remain in the water; the ones that partition to sewage sludge are predominantly lipophilic. This distinction is important in principle for the potential implications for the agricultural use of sludge as a soil improver because mostly chemicals move through soil and are taken up by plants in aqueous solution. The OCs that partition to sludge in WwTW in preference to water also partition preferential to soil organic matter when added to soil. Thus the extent to which chemicals that are predominantly lipophilic will move or be taken up by plants is limited.

OCs that are volatile can be evaporated from soil; they might then be redeposited in rain, etc. This process of volatilisation, deposition, volatilisation … is known as “hopping”. Hopping accounts for the global redistribution of persistent volatile OCs. They tend to accumulate around 55-60º latitude where soil organic matter is high and temperatures are too low for volatilisation. Bioavailability of OCs decreases with time because of binding and restricted bio-accessibility as a result of occlusion within soil aggregates and fine pores (Jones et al., 2004).

Research on OCs in sludge has been undertaken for more than thirty years and the increasing body of evidence does not demonstrate risk to human health when sludge is recycled to farmland. However, there are 143,000 chemicals registered in the EU for industrial use and potentially most could be found in sludge. Presence in itself is of much less significance than whether there is a pathway and whether a harmful dose could be received by a receptor.

Biodegradation occurs to varying degrees during wastewater and sludge treatment processes but probably some will still be present in the resulting sludge. The amounts vary from trace values of nanograms or micrograms per kilogram up to approximately 1% in the dry solids for certain bulk chemicals, such as linear alkylbenzene sulphonate (LAS), which is used widely as a surfactant in detergent formulations. However, LAS degrades rapidly in aerobic soil (half-life approx. 14 days). A review of the scientific literature on the potential environmental and health impacts of OCs in sludge found that the presence of a compound in sludge, or of seemingly large amounts of certain compounds used in bulk volumes domestically and by industry, does not necessarily constitute a risk when the material is recycled to farmland. Furthermore, the chemical quality of sludge is improving continually and concentrations of potentially harmful and persistent organic compounds have declined to background values. Thus, recycling sewage sludge on farmland should not be constrained by concentrations of OCs found in contemporary sewage sludges (Smith, 2009).

Endocrine active substances (EAS) can be found in sludge but there are far larger sources of EAS in the natural environment, for example dairy cows and leguminous plants (Hanselman et al., 2003). Viewed as a whole, sludge does not add significantly to EAS in agriculture.

The substances of greatest concern (e.g. dioxins and furans, Figure 3) have been eliminated by hazardous substances legislation and regulation of combustion facilities (CEC, 1985). REACH is a European Union regulation concerning the Registration, Evaluation, Authorisation & restriction of Chemicals. It requires that an evaluation of the environmental impacts of chemicals produced, used or imported (including in products) is included in the registration. This will further safeguard the safety of sludges.

5.3 Biological risks – pathogens

The approach to preventing pathogen transmission has been the multiple barrier approach illustrated in Figure 14. Numbers of pathogens are reduced at each stage, or eliminated. There have been no recorded cases of disease transmission from sludge use on land where the application rules have been applied.

Some sludge treatments (e.g. thermal hydrolysis) eliminate pathogens; sludge from this sort of treatment does not change the disease risk compared with the ambient risk of growing crops on farms. Some other types of treatment reduce the pathogen content but do not eliminate it, so a second barrier to transmission is applied in the form of restrictions on the time between application and crop harvest and also on the types of crops that can be grown. The EU has not distinguished between sludge from treatments that eliminate pathogens and those that leave some residual risk and all sludges are subject to the two-barrier approach. The USA defined Class-A [pathogens at ambient level, no need to restrict use] and Class-B [second barrier required to prevent risk of transmission]. In consultation with the food industry the UK adopted a broadly similar categorisation; ‘enhanced’ and ‘conventional’ treatment.

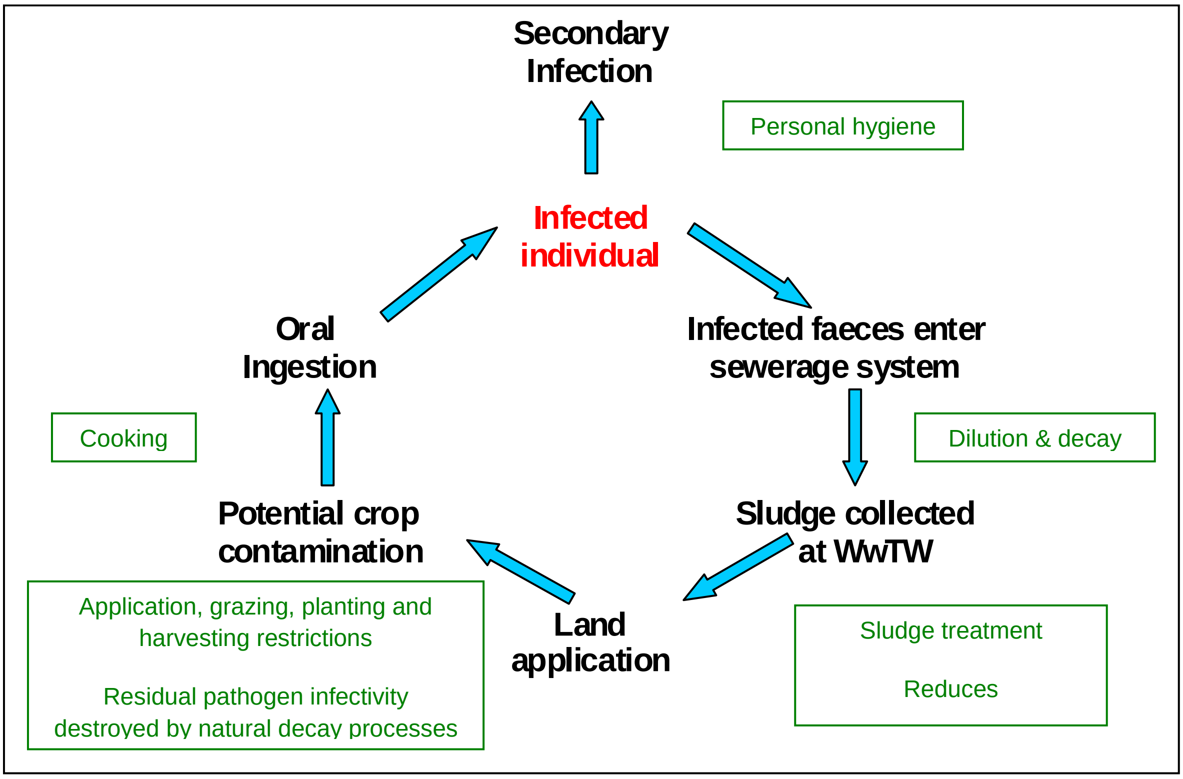

Figure 14 Barriers to disease transmission

Gale (2005) developed quantitative risk assessments based on the source, pathway, receptor approach for seven pathogens, namely salmonellas, *Listeria monocytogenes*, campylobacters, *Escherichia coli* O157, *Cryptosporidium parvum*, *Giardia*, and enteroviruses. He used literature data for pathogen decay through the system (

Figure **15**) and laboratory data for pathogen destruction by mesophilic anaerobic digestion (i.e. 'conventional' or 'class-B' treatment). He found that assuming linear decay in the soil, a 12-month harvest interval eliminates the risks from all seven pathogens. The highest predicted was only one infection of *C. parvum* in the whole of the UK (population 60 million) every 45 years.

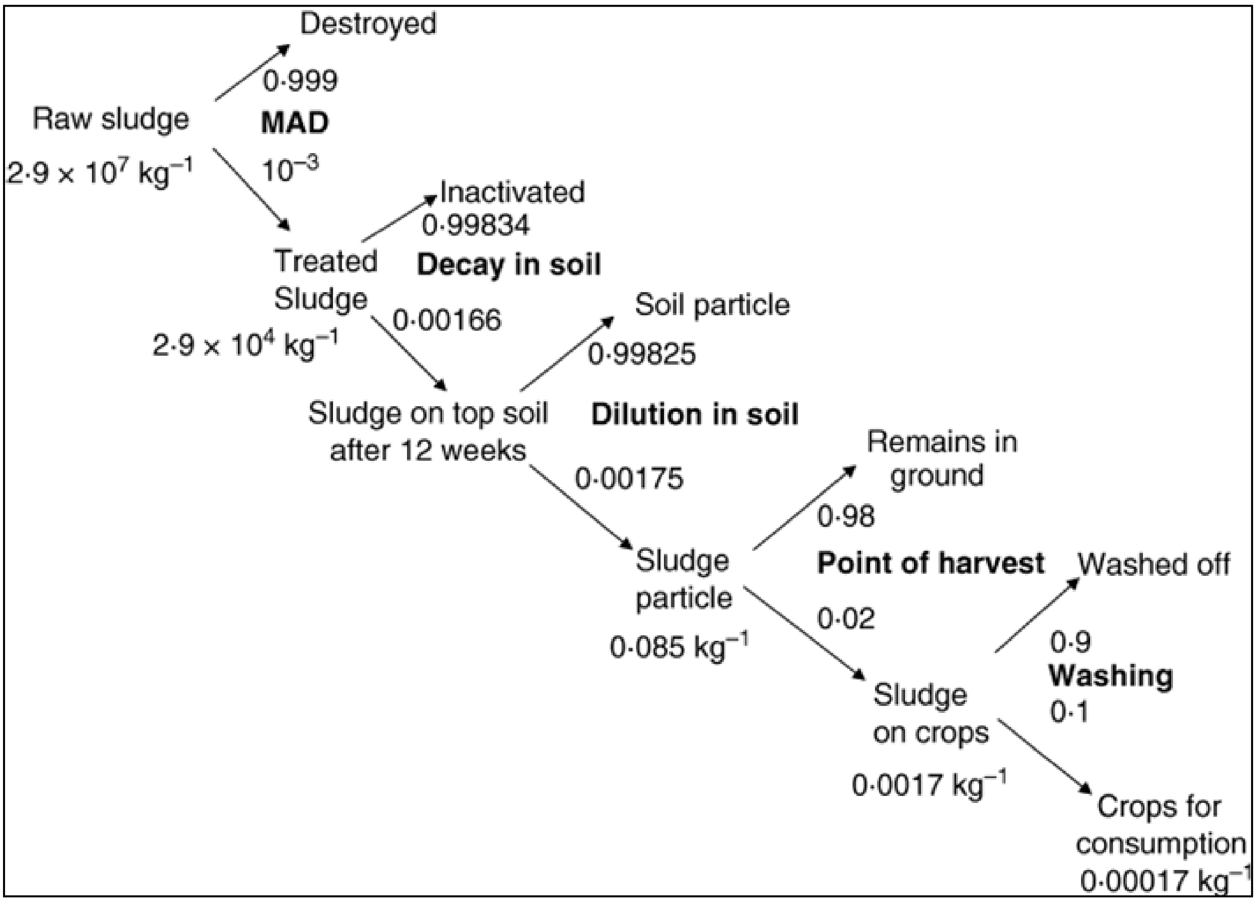

Figure 15 Event tree for transmission of Giardia cysts in raw sewage sludge (29 million cysts /kgDS) to root crops (0.00017 cysts /kgDS) for consumption (Gale, 2005)

There has been an increase in antibiotic resistant bacteria but is there a risk that sludge will be a vector for the spread of this phenomenon? In general, when an antibiotic is used it is a selective pressure on the bacteria, i.e. the most susceptible die first and the most resistant are the last to die. Sir Alexander Fleming (discoverer of penicillin) described this in an interview about antibiotics. Antibiotic resistant bacteria can be a problem in hospitals because antibiotic use is widespread and therefore there is continuous selective pressure. In the wider environment (including urban wastewater), there is no such pressure on susceptible bacteria, neither is there advantage in transferring resistance genes; resistance drops to the ambient level because bacteria that have resistance have no advantage. Thus there is no reason to suppose that urban wastewater and sludge would be vectors for antibiotic resistance (Brooks et al., 2007a).

The risk of airborne transmission has been studied extensively in all the climate zones in the USA, which would also cover the climate zones in Europe (Brooks et al., 2007b). The risk to third parties and even the occupational exposure risk were very small bordering on zero.

5.4 Odour

Odour is probably the most serious risk to the sustainability of a sludge recycling programme because of the number of people that could be affected. Odour, in the sphere of risk perception, has a very high "outrage factor". Sludge treatment should be designed and operated and sludge application sites and methods selected so that odour is tolerable to the neighbours. If sludge is injected below the soil surface as a liquid there will be no odour risk but otherwise it is inevitable that there will be sludge on the surface of the soil [until it becomes incorporated] and, if it is odorous, some odour could be emitted.

Sludge can be treated so that its odour is not offensive. It is difficult to set numerical limits for odour because instruments have difficulty matching the discriminatory powers of the human nose and because odour dispersion depends on climatic conditions. 4% of human genes are coded for odour; they are expressed differently in different people, which is the reason that perceptions of odour differ between individuals. It is obvious when there is unacceptable odour because there are complaints and this is probably the best measure. The job is being done properly if there are no odour complaints.

Regulators say that of the limited number of complaints they receive about the use of sludge on land, complaints about odour are far and away the most common. Complaints about the use of sludge on land are very infrequent in relation to the total areas of land treated with sludge. This demonstrates that sludge treatment can be operated to produce sludge with a tolerable odour.

Although odour control is not a direct requirement of the sludge directive (CEC, 1986) it is a sensible precaution for operators to be aware of this aspect and to take all reasonable efforts to ensure that their activities are inoffensive to the neighbours in this regard.

5.5 'Unknown' risks

The preceding sections have discussed the risks of hazardous substances, etc. that we can reasonably anticipate, but what about the unknowns? Is there something harmful in this cocktail that hitherto has not been identified? An operational scale field trial was established to answer this question (Evans and Smith, 2012). The trial used two different sludges from Mogden WwTW (Figure 3). The works serves about 1.8 million people and has industrial as well as domestic input. The trial was a randomised block design and treatments were replicated three times. The treatments were 'control' (which received no sludge or fertiliser), sludge, nitrogen fertiliser and sludge plus nitrogen fertiliser. One block was farmed with a typical arable rotation of crops (winter wheat, spring barley and a break crop, which was, depending on the year, field beans, spring rape or linseed). The other block was a mown grass-clover ley. None of the treatments affected the efficiency of Rhizobia (nitrogen-fixing, nodule-forming bacteria). Soils were sampled bi-monthly and the soil microbial respiration quotient (SMRQ) was measured. This is a non-specific indicator of stress. The SMRQ increased for all treatments as soil dried out and temperature increased in summer; it then returned to 'normal' in autumn. The SMRQ did not change following sludge application, however it did increase temporarily after a selective herbicide had been applied; this demonstrated the sensitivity of SMRQ. The fact that SMRQ did not increase following sludge application showed that there was no toxic unknown, neither a single chemical nor a cocktail of chemicals.

5.6 'Emerging' risks

Publicity has been given to personal care products (PCP), pharmaceuticals and nanomaterials in the environment, but what are the risks via sludge?

PCP (perfume, deodorant, toothpaste) and pharmaceuticals are designed to be persistent so that their efficacy is long-lived. Ingesting them and wiping them on skin must be a far greater risk than exposure via the tortuous pathway of wastewater collection and treatment, partitioning between water and sludge, application to soil, movement to plant roots, crossing the root barrier, translocation within plants to the harvested parts and eventual consumption.

In the pharmaceuticals area there has also been concern about antibiotic resistance, this has been discussed in section 5.3.

Nanoparticles (10^{-9} to 10^{-6} metres) behave differently from larger particles or dissolved species. Use in consumer products is increasing (for example nanosilver in fabrics to avoid microbial generation of odours); during a garment's life 80% of its nanosilver might be washed out. When released into water, some nanoparticles dissolve and some clump together into larger ones. In sludge, silver particles would become coated with low-reactivity silver sulphide. Again, direct exposure of a wearer or user of nano containing products must far exceed the risk via the convoluted wastewater – sludge – soil route.

6 Benefits of using sludge on land

For centuries “town manure” was valued by farmers. Before the advent of water closets, faecal and other matter accumulated in cess pits beneath or adjacent to houses. “Rakers” were paid to empty the cess pits. They took the contents together with the manure from the animals kept in towns (horses for transport, cows for fresh milk, etc.) to farms. Rakers sold the town manure to farmers that grew crops to feed the townsfolk and their animals. This completed nutrient cycles.

In 1847 the price of town manure was hit when guano (accumulated, dried seabird droppings) was mined from South America and imported to Europe. It was more concentrated than town manure and easier to handle. This meant rakers got less income from farmers and had to charge more for emptying cess pits. Their problems were compounded by increasing adoption of water closets, which diluted the contents of cess pits and eventually led to the waste being piped away, the Great Stink, urban sewerage and public health engineering, etc. as we know it today (Evans and Orman, 2013).

Sewers conveyed wastewater to treatment works where sludge was concentrated and recycling of organic matter and nutrients to farmland resumed. Over time the process has become more controlled and sophisticated. As discussed in section 4, hazards have been researched and their risks controlled to acceptable levels. The lifetime risk level set by the USEPA for its sewage sludge risk assessment was 1 in 1 million, which is safer than drinking water and much safer than many daily activities such as travelling by car (Appendix III).

Since the introduction of the controls that started in 1976 (section 5), recycling sludge to farmland has entailed sampling the sludge regularly and analysing it for potentially toxic elements (PTEs) and nutrients, mapping the farms where sludge is to be used, sampling the soils of the fields and analysing the samples for PTEs, calculating the application rates to match crop nutrient requirements and so as not to exceed PTE loadings, and then applying the right amount to the right place and at the right time. As a result of the success in controlling the inputs of hazardous substances into urban wastewater, their concentrations have not limited sludge application to farmland for decades. Application rates are determined nowadays by the nutrient content of the sludge (section 6.1). Application equipment (such as that shown in Figure 16) frequently has flotation tyres to minimise soil compaction and computer controlled application, which is achieved by continuous weighing linked to forward speed measured by ground-speed radar. Like other precision farm equipment, sludge applicators frequently have geographic positioning using

GPS (global positioning satellites) so that a digital map can be loaded into the on-board computer, which can also record precisely where the sludge has been applied.
Justus von Liebig enunciated the 'law of the minimum' in the 19th century, which

Figure 16 Precision sludge application equipment

is that the growth of a plant will not exceed that obtained from the most limiting element (i.e. any one of the nutrients, light, water, etc.). With this in mind it is especially important to check the potassium status of soil because, relative to nitrogen, phosphate, etc., sludge does not supply much potassium.

6.1 Nutrients

The principal nutrients in biosolids are nitrogen and phosphate. The nitrogen is present as organic-N (slow release) and ammoniacal-N (equivalent to mineral fertiliser). Nitrogen availability can be calculated from:

$$(NH_4\text{-N} – \text{losses}) + (N_{org} \text{ x release})$$

NH_4-N losses are similar to mineral fertiliser, i.e. volatilisation and loss of nitrate by leaching or denitrification. The release of organic nitrogen depends on soil temperature and is best determined by field trials; in southern England it is 10-15% whereas in northeast Spain it is 40%.

The importance of phosphate has been discussed already. A single application of biosolids can supply the phosphate requirements for a whole crop rotation. Biosolids also contain some potassium and magnesium and very useful amounts of sulphur. Sulphur used not to be of much interest but since air quality legislation has cleaned up emissions, less sulphur is deposited in rain etc. and sulphur demand is now widespread (Defra, 2010). Sludge also contains micronutrients (trace elements).

With the benefit of field trials, very reliable agronomic advice about the fertiliser replacement value can be given so that farmers are able to use the right amounts of mineral fertiliser to complement the nutrients coming from the sludge and provide optimum nutrition for their crops.

6.2 Organic matter

Organic matter is important in soil because it feeds the soil biomass, it is a reserve of plant nutrients and it binds individual mineral particles together into aggregates and waterproofs these aggregates. In the organic matter of temperate soils the carbon:nitrogen ratio tends to around 12 as a consequence of biological activity which volatilises or immobilises C or N. Increasing soil organic-C also increases soil organic-N. A well-structured soil (i.e. with good sized aggregates) drains excess water, retains a supply of plant-available water and resists erosion by wind or water. Thus, maintaining soil organic matter is very important, as farmers and gardeners have known for centuries. The amount of soil organic matter is the result of a dynamic equilibrium between decay by microbial action and addition from crop residues, manures, etc. Decay is greater under arable crops than grass. Using sludge on farmland helps to maintain soil organic matter and the desirable soil properties associated with it (Figure 17).

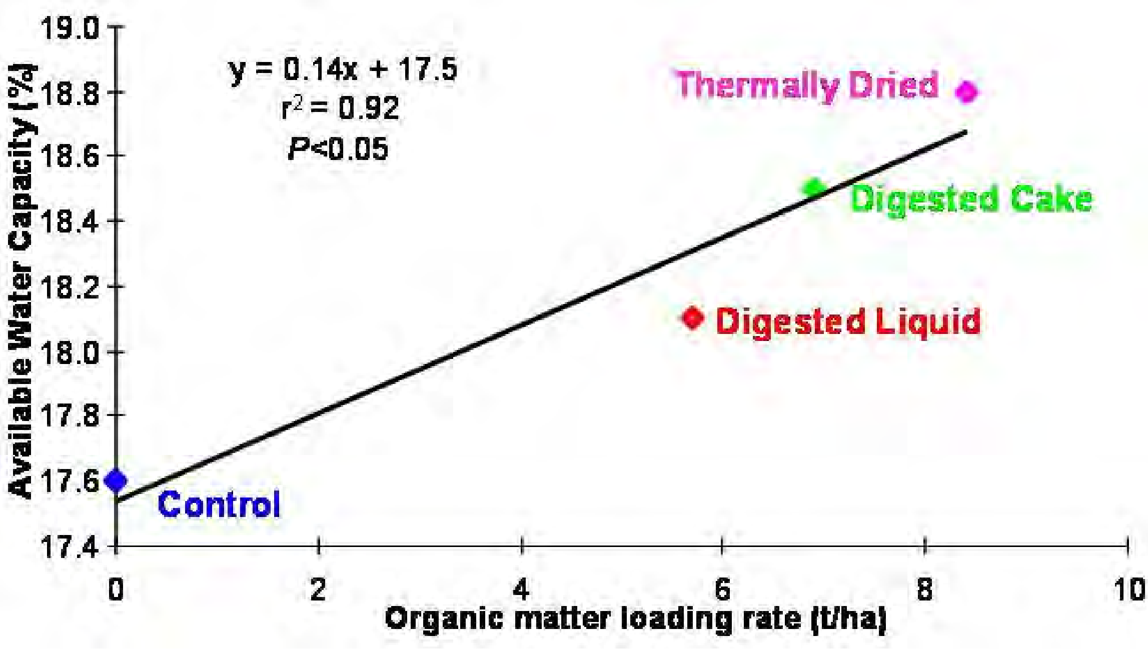

Figure 17 Soil structure improvement as reflected in an increase in available water capacity (ADAS Gleadthorpe)

Increasing a soil's available water capacity results in improved drought tolerance, that is well understood. Another factor is starting to be appreciated; it has been found that there are either biologically active substances (biostimulants) in sludge that can be assimilated by plants or that there are substances in sludge that stimulate microbes to produce stress-ameliorating biostimulants. These biostimulants may enhance plant stress tolerance and growth because they alter the content of plant growth hormones (indole-3-acetic acid and cytokinin) and thus improve plant drought resistance (Zhang et al., 2009). The biostimulants idea is surprising but it is consistent with and explains field observations that drought tolerance exceeds that which would be predicted from available water capacity alone.

7 Conclusions

It is possible to find in urban wastewater most of the chemicals used in modern society. Some partition to the sludge and some to the water. Some chemicals are biodegradable and some are not. However, controls on manufacturing, marketing and discharging chemicals have been based since the 1970s on the fate and behaviour of these chemicals in the environment. It is also possible to find pathogens (disease causing organisms). Sludge treatments and land application practices have been designed to prevent disease transmission. The controls on the uses of sludges have also developed since the 1970s. With the application of modern regulations (including control of contaminants at source) and the source controls and treatments, the uses of sludges are in everyday terms “safe” i.e. something that need not be of concern. However continual vigilance is needed to research emerging hazards and evaluate the risks they pose.

Urban wastewater is also the fate of much of the phosphate used in society. Phosphate is essential for life and cannot be substituted. The world’s reserves of phosphate are being extracted at an unprecedented rate. Today’s mines will be exhausted by the end of this century. Estimates of future reserves (at the current rate of extraction) range from 200 to 400 years, which is not long in the history of humankind. In the context that phosphate is essential and cannot be substituted, this should be of concern. Recovery and recycling of phosphate from urban wastewater should be imperative.

If sludge has to be burnt, phosphate should be recovered before or after combustion or at the very least the ash should be stored so that the phosphate can be recovered in future.

Anaerobic digestion of sewage sludge produces biogas that is continuous, base-load energy. Sludge is also a good base for co-digesting biowastes; there is evidence of synergy, i.e. the biogas yield from co-digestion is greater than the sum from separate digestion. Agronomically, digestate is a useful nutrient rich soil improver with predictable fertiliser replacement value. Using treated sewage sludge on land completes nutrient cycles and helps to conserve soil organic matter and contributes to reducing the exceedance of the earth system boundaries for nitrogen and phosphate.

Will anybody make a fortune from the resources in sludge? Probably not except maybe in very exceptional circumstances. The law of economy of scale applies. However we only have one planet and therefore we should not squander the resources in wastewater. Biogas, ammonia, phosphate, etc. can offset some of the cost of treating and recycling or disposing sewage sludge. This is integral to wastewater management. If it is not done properly, the effects can back up through the wastewater treatment chain.

Sludge treatment should be designed and operated with contingency for breakdowns and planned shutdowns. Hazard Analysis and Critical Control Point is a good basis for designing and operating sludge treatment and sludge management.

Despite the evidence and the sustainability virtues, some policy makers and stakeholders have dogmatic objection to sludge. Their objections are not evidence based. Because of this sludge has been excluded from "end of waste" criteria and from fertiliser regulations in the UK and the EU. Some produce specifications exclude produce from sludge-treated land. The transition from a linear to a circular economy will not be achieved whilst irrationality such as this persists.

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Appendix I Production and use of sewage sludge in the EU
(Gendebien, 2009)

Member State		Year	Biosolids production (t DS)	Use in Agriculture (t DS)	Use in Agric %	Population	gDS /cap.day
Austria	AT	2005	266,100	47,190	17.7%	8,372,930	87.1
Belgium	BE	2006	102,566	14,646	14.3%	10,827,519	26.0
Denmark	DK	2002	140,021	82,029	58.6%	5,547,088	69.2
Finland	FI	2005	147,000	4,200	2.9%	5,350,475	75.3
France	FR	2002	910,255	524,290	57.6%	64,709,480	38.5
Germany	DE	2006	2,059,351	613,476	29.8%	81,757,595	69.0
Greece	EL	2006	125,977	56.4	0.0%	11,125,179	31.0
Ireland	IE	2003	42,147	26,743	63.5%	4,450,878	25.9
Italy	IT	2006	1,070,080	189,554	17.7%	60,397,353	48.5
Luxembourg	LU	2003	7,750	3,300	42.6%	502,207	42.3
Netherlands	NL	2003	550,000	34	0.0%	16,576,800	90.9
Portugal	PT	2002	408,710	189,758	46.4%	10,636,888	105.3
Spain	ES	2006	1,064,972	687,037	64.5%	46,087,170	63.3
Sweden	SE	2006	210,000	30,000	14.3%	9,347,899	61.5
United Kingdom	UK	2006	1,544,919	1,050,526	68.0%	62,041,708	68.2
Bulgaria	BG	2006	29,987	11,856	39.5%	7,576,751	4.0
Cyprus	CY	2006	7,586	3,116	41.1%	801,851	9.5
Czech Republic	CZ	2006	220,700	25,400	11.5%	10,512,397	21.0
Estonia	EE	2005	not reported	3,316		1,340,274	
Hungary	HU	2006	128,380	32,813	25.6%	10,013,628	12.8
Latvia	LV	2006	23,942	8,936	37.3%	2,248,961	10.6
Lithuania	LT	2006	71,252	16,376	23.0%	3,329,227	21.4
Malta	MT		not reported	not reported		416,333	
Poland	PL	2006	523,674	88,501	16.9%	38,163,895	13.7
Romania	RO	2006	137,145	0	0.0%	21,466,174	6.4
Slovakia	SK	2006	54,780	0	0.0%	5,424,057	10.1
Slovenia	SI	2006	19,434	27	0.1%	2,054,119	9.5
Sub-total EU_{15}			8,649,848	3,462,839	40.0%	397,731,169	59.6
Sub-total for EU_{12}			1,216,880	190,341	15.6%	103,347,667	32.3
Total EU_{27}			9,866,728	3,653,180	37.0%	501,078,836	53.9

Appendix II Production and use of sewage sludge in Europe

Source: Eurostat - median values of data for 2005 to 2014

	Production ktDS/y	Disposal ktDS/y	Agriculture + Compost ktDS/y	Landfill ktDS/y	Other ktDS/y	Per capita production gDS/cap.d	Population
Germany	1956.6	1948.7	892.5	0.9	1055.3	65.6	81,757,595
United Kingdom	1770.7	1389.5	1131.7	8.8	249.0	78.2	62,041,708
Spain	1156.2	1065.0	926.9	165.7	-27.6	68.7	46,087,170
Italy	1079.6	1003.2	505.7	451.2	46.3	49.0	60,397,353
France	976.8	941.2	881.1	41.3	18.8	41.4	64,709,480
Poland	533.3	533.3	137.4	81.6	314.3	38.3	38,163,895
Netherlands	352.1	336.4	0.0	0.0	336.4	58.2	16,576,800
Portugal	338.8	189.1	164.4	12.8	11.9	87.3	10,636,888
Austria	258.7	258.6	114.3	21.1	123.3	84.6	8,372,930
Czech Republic	216.3	216.3	154.7	16.3	45.3	56.4	10,512,397
Switzerland	210.0					71.2	8,081,000
Sweden	208.8	183.1	109.6	6.7	66.9	61.2	9,347,899
Hungary	170.3	120.7	78.4	24.8	17.5	46.6	10,013,628
Finland	145.6	145.7	141.3	3.0	1.5	74.6	5,350,475
Denmark	140.0	114.9	74.0	1.4	39.5	69.1	5,547,088
Belgium	134.5	121.9	17.3	0.0	104.6	34.0	10,827,519
Greece	134.0	134.0	0.0	79.8	54.2	33.0	11,125,179
Romania	99.6	57.4	2.7	53.9	0.8	12.7	21,466,174
Ireland	85.7	85.7	69.5	0.3	15.9	52.8	4,450,878
Slovakia	57.4	57.4	35.7	8.5	13.3	29.0	5,424,057
Lithuania	45.1	18.2	18.2	0.0	0.0	37.1	3,329,227
Bulgaria	42.9	29.0	13.6	14.0	1.4	15.5	7,576,751
Croatia	31.0		0.0		0.0	20.0	4,253,000
Slovenia	26.1	25.7	1.9	5.0	18.8	34.8	2,054,119
Latvia	22.3	20.9	9.6	1.2	10.1	27.2	2,248,961
Estonia	21.8	21.8	17.3	3.7	0.8	44.6	1,340,274
Luxembourg	13.1	8.3	7.9	0.0	0.4	71.5	502,207
Cyprus	7.8	7.5	5.5	0.0	2.0	26.7	801,851
Serbia	2.1	2.1	0.0	0.0	2.1	0.8	7,164,000
Malta	0.8	6.1	0.0	0.8	5.3	5.3	416,333
Bosnia-Herzegovina	0.8	0.8	0.0	0.8	0.0	0.6	3,829,000
Total	10239	9042	5511	1003	2528	53.5	524405836
As % of production		88%	54%	10%	25%		
As % of disposal			61%	11%	28%		

Appendix III Examples of risks involved in normal activities
(Clayton, 2011)

Activity	Risk Of	Cases per million
Travel 1 000 miles by air	Fatal accident	3
Travel 1 000 miles by car	Fatal accident	20
Travel 1 000 miles by motorcycle	Fatal accident	400
Working 10 years in a factory	Fatal accident	300
1 glass of wine per day for 10 years	Cirrhosis	1 000
1 cigarette per day for 10 years	Heart attack or lung cancer	2 500
Living 1 year at age 30	Death from all causes	1 000
Living 1 year at age 55	Death from all causes	10 000