INTERNATIONAL STANDARD

ISO 19698

First edition
2020-09

Sludge recovery, recycling, treatment and disposal — Beneficial use of biosolids — Land application

Valorisation, recyclage, traitement et élimination des boues — Utilisation bénéfique des boues d'épuration — Épandage

Reference number
ISO 19698:2020(E)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 275, *Sludge recovery, recycling, treatment and disposal*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Biosolids are organic–based materials from industrial or municipal sludge and municipal biosolids derived products, in the form of solids, semi–solids, semi–liquids, and liquids which have been treated to meet applicable standards, guidelines or requirements including the reduction of pathogens, vector attraction and contaminant criteria.

The land application of biosolids, which is considered an integrated approach to sustainable management of this resource, can be beneficial in many ways such as:

- increasing soil organic matter;
- increasing biological activity in soil;
- decreasing soil bulk density and improving soil porosity;
- improving water infiltration rate, water holding capacity and erosion prevention;
- improving soil aggregate stability;
- increasing cation exchange capacity, which can result in a lower frequency of fertilizer application;
- increasing soil pH;
- providing additional nutrients to the soil for plant growth;
- recovering phosphorus from the urban and industrial environment;
- providing potential for carbon sequestration in soil; and
- decreasing the use of mineral fertilizers and related greenhouse gas (GHG) emissions related to production and application of mineral fertilizers.

This document does not prioritize, or suggest a hierarchy amongst various beneficial use options, but aims to identify and address the different criteria that could be considered to develop a sustainable and environmentally successful land application programme. These criteria include the nature of the treatment process, the selection of an appropriate application site, the method of application, the rate of application and the establishment of protective barriers or setbacks to environmentally and socially sensitive areas such as surface water and residences.

Control of non–beneficial substances, odour and potential risk to human, animal and environmental health are important parts of any beneficial use strategy. These can be managed by employing tools such as point source control, appropriate treatment methods and land–use restrictions.

Application of this document presupposes awareness of applicable legal requirements.

Sludge recovery, recycling, treatment and disposal — Beneficial use of biosolids — Land application

1 Scope

This document provides guidance on the conditions of beneficial use of biosolids produced from industrial and municipal sludge and municipal biosolids derived products (e.g. composts, growing media) in the production of food and feed crops, energy crops, forestry crops and for the remediation of disturbed sites.

This document applies to biosolids for land application and includes biosolids from wastewater treatment (municipal, industrial and private onsite systems).

This document does not apply to hazardous sludge that originates from wastewater which, due to its nature, physical, chemical or infectious properties, is potentially hazardous to human health and/or the environment during use, handling, storage or transportation and which requires special disposal techniques to eliminate or reduce the hazard.

This document includes:

— general guidelines for the land application of biosolids and biosolids derived products;

— specific guidelines for the land application of biosolids and biosolids derived products for food and feed crop production and for non–food and non–feed crop production (e.g. horticulture, fibre for bio–mass, silviculture, etc.); and

— specific guidelines for the land application of biosolids and biosolids derived products for other beneficial uses (e.g. land reclamation or rehabilitation).

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
alkaline stabilized biosolids
biosolids or non–toxic sludge which has undergone alkaline treatment to meet specific requirements for reduction of pathogens and vector attraction

3.2
alkaline treatment
process where biosolids or non–toxic sludge is mixed with alkaline additives to enhance wastewater solids stabilization by increasing the pH of the biosolids up to 12 or higher for a minimum amount of time

3.3
batch
definite quantity of material manufactured or produced under conditions which are presumed to be uniform

3.4
biocenosis
community of biologically integrated and interdependent plants and animals

3.5
biosolids
organic–based materials from industrial or municipal wastewater sludge and their derived products, in the form of solids, semi–solids, semi–liquids (pasty), and liquids which have been treated to meet specific standards, guidelines or requirements including the reduction of pathogens, vector attraction and contaminant criteria

3.6
cation exchange capacity
measure of the soil's ability to hold positively charged ions (cations)

3.7
compost
organic soil improver obtained by decomposition of a mixture consisting principally of various plant residues, occasionally with organic materials of animal origin, and having a limited mineral content

[SOURCE: ISO 8157:2015, 2.2.8.6]

3.8
composting
natural aerobic biological process, carried out under controlled conditions, which converts organic material into a stable humus–like product

Note 1 to entry: During the composting process, various microorganisms, including bacteria and fungi, break down organic material into simpler substances.

3.9
contaminant
biological, chemical, physical, or radiological substance released to the environment from anthropogenic sources which, in sufficient concentration, can adversely affect living organisms through air, water, soil, and/or food

3.10
dewatered biosolids
biosolids that have undergone a reduction of the water content to produce paste-like biosolids or solid biosolids by the use of one or several technologies, usually by natural or mechanical means

Note 1 to entry: These treatments lead to the production of biosolids whose mechanical characteristics allow a storage in heap on a minimum height of 1 m. As an indication, the dryness obtained is generally within a range between 15 % and 40 % (wet mass).

3.11
foreign matter
material of anthropogenic origin as opposed to natural objects such as sand, stones and wood fibres

EXAMPLE Plastics, glass, metal, small/large or sharp debris.

3.12
industrial sludge
mixture of water and solids separated from various types of industrial wastewater (e.g. food processing plants) as a result of natural or artificial processes and meet specific standards, guidelines or requirements including the reduction of pathogens, vector attraction and contaminant criteria

3.13
mineralization
final stage of the biodegradation of organic matter or organic substances into carbon dioxide, water and the hydrides, oxides and other mineral salts

[SOURCE: ISO 11074:2015, 3.3.19]

3.14
mesophilic anaerobic digestion
biological conversion of organic matter to biogas and residual solids at temperatures between 20 °C and about 40 °C, typically 37 °C with a mean residence time of 15 to 30 days

3.15
micronutrient
element, such as boron, manganese, iron, zinc, copper, molybdenum, cobalt, and/or chlorine, which are essential, in relatively small quantities, for plant growth

[SOURCE: ISO 8157:2015, 2.1.3.3, modified — Note 1 to entry has been deleted.]

3.16
municipal biosolids
biosolids produced from municipal sludge which has been treated to meet jurisdictional standards, guidelines or requirements including the reduction of pathogens and vector attraction

3.17
municipal sludge
mixture of water and non–stabilized solids separated from various types of municipal wastewater as a result of natural or artificial processes

3.18
organic matter
matter consisting of plant and/or animal organic materials, and the conversion products of those materials

[SOURCE: ISO 11074:2015, 2.1.8]

3.19
organic compound
any of a large class of chemical compounds in which one or more atoms of carbon are covalently linked to atoms of other elements, most commonly hydrogen, oxygen or nitrogen

3.20
plant nutrient
chemical element, which is essential for plant growth

[SOURCE: ISO 8157:2015, 2.1.2]

3.21
sample
part of a defined bulk product taken for the purpose of characterization

[SOURCE: ISO 14488:2007, 3.8]

3.22
setback
buffer
determined distance, sometimes based on risk assessment, that provides protection to environmentally sensitive features such as humans and water

3.23
sludge
mixture of water and solids originating from various types of wastewater during natural and artificial treatment

3.24
sodium adsorption ratio
measure of the amount of sodium (Na) relative to calcium (Ca) and magnesium (Mg) in the water extract from saturated soil paste

3.25
soil quality
all current positive or negative properties with regard to soil utilization and soil functions

[SOURCE: ISO 11074:2015, 2.1.15]

3.26
stakeholder
person or organization that can affect, be affected by or perceive themselves to be affected by a decision or activity

[SOURCE: ISO 28007-1:2015, 3.6, modified — Note 1 to entry has been deleted.]

3.27
thermophilic anaerobic digestion
biological conversion of organic matter to biogas and residual solids, that takes place between 49 °C and 57 °C

3.28
total organic carbon
TOC
amount of carbon found in an organic compound

3.29
trace element
element present in very low concentrations

3.30
vector
living organism capable of transmitting a pathogen from one organism to another either mechanically (by simply transporting the pathogen) or biologically by playing a specific role in the life cycle of the pathogen

[SOURCE: EPA/625/R-92/013 Revised July 2003: Control of Pathogens and Vector Attraction in Sewage Sludge]

3.31
vector attraction reduction
treatment processes that stabilize and reduce the odours and other aspects of biosolids that attract flies, rodents and other potential vectors

4 Benefits of biosolids land application

The land application of biosolids can be beneficial in many ways including:

— adding organic matter to the soil which can have a positive impact on soil biological activity, soil porosity, soil bulk density, soil water infiltration rate, aggregate stability and cation exchange capacity;

— increased soil organic matter can also reduce soil erosion;

— potential to increase carbon sequestration in the soil while reducing chemical fertilizer input and greenhouse gas emissions from their production (see Annex A); and

— responsible utilization of essential macro and micro nutrients that could otherwise be wasted.

Alkaline stabilized biosolids, in the context of the many positive soil effects, can also be an economical and effective soil amendment to increase the pH of acidic soils.

The use of biosolids should go through a global assessment taking into account the various factors, in order to ensure the positive effect on crops and soils.

See Annex B for further information regarding benefits of biosolids.

5 Nutrients in biosolids

5.1 General

Biosolids contain organic matter and plant nutrients. See Annex C for average concentrations of organic matter and plant macronutrients in biosolids.

5.2 Nitrogen

5.2.1 General

Growing plants require a continuous source of nitrogen (N), which is an essential component of proteins that build cell material and plant tissue. It is also necessary for other plant functions.

Nitrogen applied to soils in mineral fertilizers, biosolids or other organic amendments is subjected to biochemical and physical processes which form the nitrogen cycle. Inorganic forms of nitrogen are the available forms to plants. All forms of nitrogen can be present in the soil at any point of time, mainly because nitrogen readily shifts from one form to another.

5.2.2 Nitrogen content and availability in biosolids

Nitrogen content and availability in biosolids can vary greatly depending on the source of the wastewater and the treatment process. Biosolids produced from some industrial sludges can have a high content of nitrogen while it is the opposite for others such as paper mill biosolids. Forms of nitrogen that can be present in biosolids include organic nitrogen (i.e. nitrogen bound in organic molecules such as proteins), nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3) and ammonium (NH_4^+).

As plants can only assimilate mineral nitrogen, a primary factor in determining the nutrient value of biosolids should be the mineralization rate of its organic nitrogen. The nitrogen mineralization rate is dependant in part on the sludge treatment process. Other factors that can influence the availability of the nitrogen are intrinsic to the land application sites such as:

— temperature (air and soil);

— moisture;

— soil porosity;

— pH and texture;

— microbial activity; and

— method of application to the land.

Two main mechanisms for nitrogen loss should also be considered:

— volatilisation of the ammonia; and

— nitrate leaching.

5.2.3 Determination of biosolids application rate according to nitrogen content

The rate for biosolids application should be determined to provide the amount of nitrogen needed by the crop vegetation, or in reclamation scenarios, by the biosolids application management plan, to attain a desired result. For information regarding application rates for reclamation projects see 14.6. Whatever the project target is, special care should be applied to minimize or manage the amount of nitrogen that could be leached below the root zone of the crop, or through the soil to the ground water. Specifics related to nitrogen management on agricultural and non–agricultural lands are further explored in 8.2.2 and 14.6.2.

Biosolids application rates should be adjusted to avoid excess trace elements or phosphorus loading. In such case, if insufficient nitrogen is applied in the biosolids, inorganic fertilizer nitrogen can be applied. The addition of biosolids in a fertility plan adds multiple beneficial aspects.

5.3 Phosphorus

Phosphorus (P) is a macronutrient that is present in many organic materials including biosolids, and is important for healthy plant development. Specifically, phosphorus is needed for plant growth, rigidity of cell walls, and for the development of the root system. Phosphorus is of particular value as it is a limited natural resource.

Phosphorus is present in biosolids in organic and inorganic (phosphate) forms. Organic phosphorus undergoes mineralization through a (bio)degradation process in the soil before plant assimilation. Inorganic phosphorus is often predominant in biosolids[6].

The solubility and availability of phosphorus in biosolids is also dependant on soil pH. Plant available phosphorus is the phosphorus that is in the soil solution or is weakly adsorbed by soil particles and organic matter. Biological wastewater treatment does not change the availability of phosphorus. Nitrogen and phosphorus are found in similar concentrations in biosolids but often crop requirements are significantly lower for phosphorus. Subsequently application rates are based on the most restrictive element: nitrogen or phosphorus.

5.4 Potassium

Potassium (K) is soluble in wastewater and remains in the liquid stream. Therefore, potassium is not typically found in biosolids in high concentrations and the ratios K:N or K:P are much lower than with livestock manures, thus additional potassium can be required through the addition of inorganic fertilizers for soil health and plant growth.

5.5 Calcium

Most biosolids contain concentrations of calcium, approximately 2,1 % – 3,92 % (wet mass), similar to the content in animal manures. When lime is added to biosolids during an alkaline stabilization process, (e.g. 30 % lime addition by dry mass to the biosolids) the calcium content is increased. Applying biosolids at agronomic rates can supply a sufficient amount of calcium to correct deficiencies or the application of alkaline stabilized biosolids may be used to increase the soil pH where necessary or maintain the soil pH within a range that is optimum for plant growth.

5.6 Sulfur

Most biosolids contain sulfur, approximately 0,01 % to 2,42 % of SO_3 (wet mass) which promotes plant growth, development and seed formation. In biosolids, sulfur exists in available and slow–release forms resulting from the oxidation of sulphides and decomposition of organic matter respectively. When biosolids are applied at agronomic rates the sulfur demand of the crops can also be met.

6 Nuisance and risks associated with biosolids land application

6.1 General

The beneficial use of biosolids can pose potential nuisance and risks which should be considered to help determine appropriate mitigation measures for public health and environmental protection.

Many of the potential environmental and health risks associated with the land application of biosolids are related to storage prior to spreading. These potential risks include:

— flystrike[1)] in stockpiles < 8 weeks aged;

— ground and surface water contamination;

— leaching of contaminants during heavy rainfall events and floods;

— ammonia volatilisation; and

— public and occupational health risks from uncontrolled access and/or inappropriate storage, transport or handling.

The following factors can influence the severity of these risks:

— quantity stored;

— biosolids quality;

— length of time biosolids will be stored;

— time of the year (that is, effects of moisture, temperature and wind gradients); and

— storage design and location.

6.2 Odours

Biosolids are an abundant source of food for microorganisms due to the fact that they contain proteins, amino–acids and carbohydrates. The degradation of these energy sources leads to the emission of odorous compounds in organic and inorganic forms such as hydrogen sulfide, mercaptan, ammonia, amines and organic fatty acids. These compounds can be released from biosolids during treatment, storage, transport and spreading, causing trouble with the neighbourhood.

6.3 Vector attraction

Vectors which include insects, rodents and birds can transmit pathogens to human and other hosts, physically through contact, and biologically by playing a specific role in the life cycle of the pathogen. Pathogens in biosolids may pose a risk when they are brought in contact with humans and other susceptible hosts such as plants or animals. Vectors can be attracted to a land application site by odour and the potential for food sources.

6.4 Pathogens

6.4.1 General

Biosolids can contain microorganisms, some of which could be pathogens. The species and concentrations of organisms that are present in biosolids are dependent on the wastewater treatment

1) Flystrike (Myiasis) is often caused by the green bottle fly (*Lucilia sericata*) and related fly species laying eggs on rabbits, sheep and other animals and is used in Australia as a measure for vector attraction reduction efficiency.

stream and catchment, as well as the type of treatment. Pathogens can be harmful to animal and human health and may include for example:

— viruses (e.g. adenoviruses, hepatitis, norovirus);

— bacteria (e.g. Salmonella and Campylobacter);

— protozoa (e.g. Cryptosporidium and Giardia); and

— helminths (e.g. Ascaris, Ancylostoma).

The major routes of potential human exposure to pathogens could be:

— air, as land application of biosolids can result in the formation of bio–aerosols;

— direct soil ingestion due to unrestricted access by the public to application sites;

— eating vegetables raw, as some crops are directly in contact with the ground; and

— water, as a consequence of potential run-off and leaching.

6.4.2 Viruses

Various types of enteric viruses can occur in wastewater and biosolids including Hepatitis A virus, Norovirus, and Adenovirus.

6.4.3 Bacteria

Amongst bacterial species that could be found in the biosolids are *Salmonella spp.*, which can be common in the environment with exposure routes including food and water. *Salmonella enterica* can cause gastro-enteritis in humans and could potentially regrow during storage of biosolids.

The presence of *Salmonella spp.* at low levels (or absence) in biosolids along with low levels of faecal indicators such as *Escherichia coli* (*E. coli)* and faecal coliforms should provide a high degree of assurance that other bacterial pathogens such as *Campylobacter spp.* do not present a health risk.

Specific bacterial pathogens that can be prevalent in industrial biosolids are *Campylobacter spp.* from meat processing facilities, or *Listeria spp.* in dairies.

6.4.4 Protozoa

Protozoan pathogens found in biosolids can include *Entamoeba histolytica* (amoebic dysentery), *Giardia intestinalis* (gastro–enteritis), *Cryptosporidium* (gastro–enteritis) and *Balantidum coli* (gastro–enteritis). The protozoan pathogens generally occur as oocysts. They can be less resistant to inactivation compared to helminths ova and are inactivated by heat and/or lime treatment.

6.4.5 Helminths

A wide range of helminths can often be found in biosolids including nematodes (roundworms and hookworms), cestodes (tapeworms) and trematodes (flukes). Helminth ova can be highly resistant to the environmental factors that reduce the numbers of indicator bacteria and enteric virus. Due to their resistance to inactivation, the presence/absence of viable helminth ova may be used as a criterion to evaluate the quality of biosolids to be applied to land. However, measurement of helminth ova is difficult.

For more information on pathogen limits, see Annex D.

6.5 Trace elements

Trace elements in biosolids come from a variety of sources and their concentrations in biosolids depend on the inputs to the wastewater stream. As rural and urban jurisdictions can have different inputs to the wastewater stream, trace element concentrations in biosolids can differ.

Trace elements including fluoride, manganese, selenium, and boron are naturally present in the environment, in very low concentrations. Other trace elements with heavier molecular weight (known colloquially as 'heavy metals') including chromium, cobalt, nickel, copper, molybdenum, zinc, mercury and cadmium are also naturally present in very low concentrations.

Plant micronutrients are required for optimal crop health, but excess presence should be avoided to prevent detriment to plant health. For example, boron is important for a number of aspects of plant health and development including cell wall integrity, seed development and protein metabolism, however, excess boron can be toxic to many crops.

Long–term increases in trace element concentrations can cause toxicity in plants, with further potential to enter the food chain at concentrations that can cause human and animal toxicity. Migration rates for trace elements are generally low, but are affected by soil pH, where in areas of low pH some are more mobile and/or more bioavailable. Inadvertent, excessive or repeated application in setback areas or in aquifer recharge areas can have long–term health or environmental risk potential.

For information regarding the source of trace elements in biosolids and examples of jurisdictional trace elements standards in biosolids and soil after biosolids application, see Annex E.

6.6 Organic compounds

6.6.1 General

Some of the organic compounds which can be found in biosolids include:

— halogenated compounds such as polychlorinated biphenyl (PCB), polychlorinated dibenzodioxins and furans (PCDD/F), polybrominated diphenylethers (PBDE);

— perfluorinated compounds (PFC) including perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA);

— other organic compounds such as linear alkyl benzene sulphonates (LAS), nonylphenol and nonylphenol–ethoxylates (NP, NPEO), polycyclic aromatic hydrocarbons (PAH), di–(2–ethylhexyl) phthalate (DEHP); and

— antibiotics, personal care products and pharmaceuticals.

These organic compounds can be partially degraded during the wastewater and sludge treatment processes, but many can be found in biosolids depending on their lipophilic characteristics. Concentrations of organic compounds in biosolids can range broadly depending on the influent characteristics and the treatment processes employed (i.e. magnitude can be of 1 or 2 $\log_{10}$).

See examples of standards for maximum concentration of organic compounds in biosolids in Annex F.

NOTE Numerous scientific research and analysis campaigns have been undertaken to quantify these substances in biosolids and to provide a better understanding of their transfer into the environment and the food chain. This information has been used to assess potential risks for animals and human beings when biosolids are applied on land. A synthesis is made in Annex G.

6.6.2 Source control of potential contaminants

Inputs of potential contaminants to the sewer network occur from domestic, commercial or industrial discharges but also from urban run-off.

Source control is an effective tool to reduce the transfer of potential contaminants into the wastewater treatment system and therefore to improve biosolids quality.

Regarding domestic sources, potential contaminants are most often in direct contact with consumers through the use of detergents or personal care products before being released to the sewer. Therefore, marketing of a new substance or product that could have harmful effects on public health or the environment should be subject to an authorization granted by regulatory authorities like the REACH regulation in the EU. Approval procedure should include a risk assessment to determine the potential impact of the new substance or product on the wastewater treatment process including biosolids quality.

Reductions in domestic discharges of potential contaminants may also be possible through increased public awareness of appropriate waste disposal practices and the provision of accessible waste collection points. Return of unused pharmaceuticals to specific collection points should also be encouraged. Ecolabels and public education should be provided and extended where possible to raise awareness of ecological impacts of various domestic products on urban wastewater.

Industrial or commercial activities as well as hospitals or health establishments are also at the origin of potential contamination of biosolids. Any non-domestic discharge to the sewer should be subject to permission. Consequently, competent authorities should issue requirements on the origins and contents of any non-domestic discharge to the sewer. These requirements shall be integrated, where applicable, into discharge permits that should set quality criteria limits in terms of maximum concentration of potential contaminants and also in terms of their daily flow rates. Compliance with these limits should be monitored on a regular basis.

Concerning urban run-off, the overall mass balance suggests that its contribution to the potential contaminant flows in the wastewater system is generally low in comparison with other sources and discontinuous depending on rainfall episodes.

There are a number of possible measures that can help reduce potential contaminants entry into the wastewater system from run-off. For industrial and other impermeable urban grounds, interception through pre-treatment systems should be implemented to retain contaminants bound to suspended solids. Regular maintenance and inspection of this equipment should be undertaken.

6.7 Environmental considerations

6.7.1 General

The climatic and physical environment in which biosolids are utilized can play a significant role in risk management and the avoidance of nuisance concerns. These factors should be taken into consideration in the development of a sustainable biosolids management programme.

6.7.2 Climate and season

The timing of biosolids application should be considered in relation to the potential for nutrient losses through leaching or runoff. Timing of biosolids application should take into consideration precipitation (rain or snow), season of application and soil moisture.

It is not recommended to apply biosolids when the soil is saturated, snow-covered, frozen or during periods of heavy rainfall, since these conditions will increase the risk of runoff. Application of biosolids during heavy rainfall or on top of snow can increase the risk of nutrient movement/leaching. Precipitation can increase the potential for macropore flow (movement of water through pores in the soil) through previously dry and cracked soil and surface run–off during heavy rainfall or snowmelt.

6.7.3 Topography

Sloping land can increase the potential for surface runoff, surface soil erosion, and subsurface leaching losses, which could lead to adverse surface or groundwater impacts.

Biosolids may be applied to sloping sites provided any potential for overland flow, surface soil erosion, and subsurface leaching loss is minimal.

Mitigation of adverse effects may be achieved by setting maximum slopes, above which application is prohibited and setting standards that become more restrictive as the slope of the land increases. For example, if a slope is a concern, biosolids application could be subject to a reduced application rate or restricted to fields with crop residue or increased setbacks to surface water.

6.7.4 Protection of water sources

Potential risk of water pollution should be avoided. Key considerations in evaluating a land application area should include:

— depth to groundwater with consideration given to seasonal variations;

— soil and sub–soil hydraulic conductivity;

— proximity to wells, and surface water;

— subsurface/tile drainage; and

— flood potential.

Nitrate leaching should be considered as an indicator of potential groundwater pollution risk that can occur if the amount of available nitrogen in the biosolids applied does not correspond to plant needs or if the biosolids degrade rapidly.

Biosolids use can be prohibited or restricted when the site is located near drinking water catchment areas, or in nitrate vulnerable zones. Extra care should be taken in selecting land application sites in known areas of hydrogeologic sensitivity.

The risks of groundwater pollution are higher on sites where the groundwater level might be very near to the surface or where soil hydraulic conductivity is high, e.g. when dealing with sandy soils.

Jurisdictions can require that buffer strips of a minimum width in which biosolids are not to be applied, are established, along streams, watercourses and other bodies of water.

Buffer width should be determined by run–off risk, but would normally be at least 10 m. In some jurisdictions due to scarcity of water a larger distance of 100 m should be applied. For a range of buffer zones in different regions, see Annex H.

6.7.5 Identification of sensitive uses and associated setbacks

If the land application site is close to a residence or residential area biosolids should meet all applicable odour standards and setbacks. Aspects such as the type of biosolids (odorous or dusty biosolids), application systems (potential aerosol or dust generation due to application method or incorporation), biosolids transport and storage and weather conditions should be evaluated carefully.

Moreover, the residents and other stakeholders potentially affected should be informed.

6.8 Biosolids treatment

6.8.1 General

Biosolids should be stabilized through treatment to applicable standards, to reduce volatile solids, which indirectly result in pathogen reduction and reduced vector attraction potential.

The purpose of stabilization should be to reduce sludge putrescibility, which causes odours. A putrescible product is a matrix which contains organic substances that can be decomposed by microorganisms in the order of days.

A stabilized sludge is characterized by low putrescibility, i.e. in a treatment process the level of microbial activity has slowed to a point where it will not resurge under altered conditions.

The degree of treatment (e.g. temperature and time) can result in varying grades of biosolids based on the resultant level of indicator organisms such as *E. coli* and percentage volatile solids in the treated biosolids. Accepted treatment practices require a temperature of 35 °C, with a minimum retention time of 30 days, for mesophilic anaerobic digestion, and a minimum temperature of 55 °C, with a minimum retention time of 20 days for thermophilic anaerobic digestion.

High-quality (stabilized) biosolids should have pathogens and vector-attracting compounds, such as volatile solids, substantially reduced or removed.

Various methods to determine the degree of stabilization and hence quality of biosolids exist.

— The BOD_5 to COD ratio can provide a value to define the degree of stabilization. A value lower than or equal to 0,15 is accepted as an indication of sufficient stabilization. The benefit of employing this approach is its validity for both aerobic and anaerobic treatment processes.

— The biological methane potential (BMP) test allows the residual production of biogas from sludge anaerobically treated to be measured and employed to determine stability.

The above methods require a number of days for results to be obtained, however faster assessments are often required for operation and technical/legal control purposes. If that is the case, the volatile solids to total solids ratio may be measured, where reduction of volatile solids content of 30 % to 50 % should be used as an indication of good stability (depending on the stabilization process).

Ultimately, biosolids type and quality should be matched with appropriate end use applications based on:

— characteristics of the biosolids (nutrient content, odour, pathogens, trace elements);

— potential risks to human and environmental health (exposure, set back distances, proximity of water (surface or groundwater);

— characteristics of the soil (pH, nutrient content, trace element content, texture);

— characteristics of the site (topography, proximity to surface water, depth to ground water and bedrock);

— proximity to neighbours (distance to roads, dwellings, recreation areas, wells); and

— the end use of the crop/vegetation grown on the application site, including:

  — food crops for direct animal/human consumption;

  — food and feed crops which require further processing prior to consumption;

  — biofuel or biomass crops/non-food or feed crops/silviculture; and

  — land reclamation (recreational and non-recreational).

6.8.2 Foreign matter

Jurisdictions commonly place restrictions on the foreign matter content in land applied biosolids to mitigate risks to human health and the environment. There may be separate restrictions for sharps, total plastic content and total foreign matter.

6.8.3 Odour reduction

Odour is a parameter related to biosolids stability and degree of treatment. Biosolids which have undergone a higher degree of treatment will emit fewer odours and should be considered higher quality. Biosolids should be adequately treated to avoid being associated with odours which generate complaints from the public and attract vectors.

Odour emission reduction should be applied as a key component of any biosolids land application programme. The following three main approaches to mitigate odours at land application sites may be used:

— maximizing the quality of biosolids thereby minimizing the odour generating potential of the biosolids, e.g. subjecting the biosolids to further treatment such as anaerobic digestion or lime stabilization;

— managing the site and application of biosolids to minimize the potential for odorous emissions; and

— storing odorous biosolids at production or in a non–sensitive location until the odours have abated.

The following can be implemented for odour emissions reduction[7]. One or both approaches may be used to minimize odour issues:

— increasing distance from nearby residents; or

— selecting application techniques to reduce odour emissions (e.g. injection or incorporation into the soil within a set time limit).

6.8.4 Vector attraction reduction

Vector attraction reduction processes should be implemented to reduce the potential transport of pathogens from the application site, and thereby minimize human exposure. Vector attraction reduction may be achieved by:

— biological processes such as aerobic or anaerobic digestion or composting which break down volatile solids, thereby reducing the organic content of biosolids;

— reducing the available food nutrients for microbial activity and odour producing potential by heating, composting, anaerobic or aerobic digestion of the biosolids;

— chemical or physical conditions which stop microbial activity such as reducing the moisture content or raising the pH of the biosolids; and

— physical barriers between vectors and volatile solids in biosolids such as incorporation or injection of biosolids into the soil.

6.8.5 Pathogen reduction

6.8.5.1 General

To reduce the likelihood of spreading pathogens into the environment and to improve consumer confidence, biosolids subjected to advanced biosolids treatment should be utilized in sensitive or higher risk areas or applications where there is significant public exposure.

Pathogen reduction in biosolids may be achieved by different types of technologies which include heat exposure, moisture reduction, significant increase or decrease in pH and long-term storage.

Advanced treatment can achieve biosolids hygienization and potentially result in classification as a Group 1 category, whereas conventional treatment focuses on significantly reducing the pathogen content of biosolids. Examples of conventional and advanced treatment are outlined in 6.8.5.2 and 6.8.5.3.

After land application, natural conditions such as heat, sunlight, drying, soil pH and predation by native soil microorganisms can further reduce pathogen concentration. Incorporation of the biosolids into the soil can also reduce the potential for pathogen contact with animals and humans.

In the case of agricultural land application, it should be noted that:

— natural environmental processes do reduce pathogens; and

— pathogens in the upper layers (horizons) of the soil have low motility.

Some exceptions to these general conditions include, for example, farm sites where there is a highwater table, active soil erosion, or exposed bedrock.

For more information on pathogen limits, see Annex D.

6.8.5.2 Conventional treatments

Conventional municipal sludge treatments may include:

— thermophilic aerobic stabilization at a temperature of at least 55 °C with a mean retention period of 10 – 15 days;

— thermophilic anaerobic digestion at a temperature of at least 53 °C with a mean retention period of 10 – 15 days;

— conditioning with lime ensuring a homogenous mixture of lime and sludge; the mixture should reach a pH of more than 12 directly after liming and keep a pH of at least 12 for a specified period of time;

— mesophilic anaerobic digestion at a temperature of 35 °C with a mean retention period of 20 – 30 days;

— extended aeration at ambient temperature as a batch, without adding feedstock or withdrawal during the treatment period;

— simultaneous aerobic stabilization at ambient temperature;

— biosolids dewatering in conventional (sand/clay) drying beds or solar drying beds (with a target minimum of 75 % dry matter); and

— storage in liquid form at ambient temperature as a batch, without adding feedstock or withdrawal during the storage period.

If the initial concentration needs to be reduced, biosolids should at least achieve a 2 log reduction in *E. coli*.

6.8.5.3 Advanced treatments

Advanced municipal biosolids treatments may include:

— thermal drying ensuring that the temperature of the sludge particles is higher than 80 °C with a reduction of water content to less than 10 %;

— thermophilic aerobic stabilization at a temperature of at least 55 °C for 20 h as a batch, without adding feedstock or withdrawal during the treatment;

— thermophilic anaerobic digestion at a temperature of at least 53 °C for 20 h as a batch, without adding feedstock or withdrawal during the treatment;

— thermal treatment of liquid sludge for a minimum of 30 min at a temperature of at least 70 °C followed by mesophilic anaerobic digestion at a temperature of 35 °C with a mean retention period of 12 days;

— conditioning with lime reaching a pH of 12 or more and maintaining a temperature of at least 55 °C for 2 h;

— mixing with lime and the mixture should reach a pH of more than 12 directly after liming and keep a pH of at least 12 for a minimum of time; and

— composting at a temperature of minimum 55 °C for at least two weeks or 65 °C for at least one week.

The process should be initially validated by appropriate tests on pathogen reduction to attain specific requirements.

The relevant process parameters should be monitored at least daily, and preferably continuously if practicable. Records should be kept and made available upon request to the competent authority for inspection purposes.

The treatment process should consider adopting a quality assurance system and meet at least one of the accepted pathogen reduction standards.

6.9 Biosolids quality criteria — Groups of biosolids

6.9.1 General

Biosolids may be divided into two groups as described in 6.9.2 and 6.9.3.

Examples of treatment-based standards can be found in Annex I.

6.9.2 Group 1 biosolids

Group 1 biosolids are essentially free of pathogens and present a very low risk to people handling them, and may be marketed with fewer restrictions for its use, in comparison to Group 2 biosolids. Due to the fewer restrictions placed on the use of Group 1 biosolids, it is typically required to meet more stringent standards for pathogens, metals and other contaminants (e.g. organic compounds).

Marketed biosolids or biosolids derived materials should comply with relevant local standards or requirements that define quality criteria in accordance with their specific use.

NOTE National regulations can apply. In some jurisdictions Group 1 is referred to as Class A.

6.9.3 Group 2 biosolids

Group 2 biosolids, which do not attain Group 1 stabilization criteria, can potentially contain higher levels of pathogens but shall meet minimum applicable standards for metals, pathogens and other contaminants (e.g. organic compounds). Therefore, their use shall be subject to appropriate restrictions.

NOTE In some jurisdictions Group 2 is referred to as Class B.

6.10 Potential uses

Use of biosolids should depend on the quality and includes:

— biosolids derived products that are sold to the general public;

— agriculture – biosolids suitable for land used for the grazing of livestock, crops consumed raw, crops consumed cooked or processed;

— agriculture – biosolids suitable for land application for the production of non–food and feed crops (e.g. horticulture, bio–mass, fibre, agro forestry);

— institutional landscaping – recreational – biosolids suitable for urban land application (e.g. parks, race courses);

— institutional landscaping – non recreational – biosolids suitable for urban land application such as freeway road and landscaping where public access is limited. Subject to specific site management and environmental protection practices; and

— forestry, land rehabilitation – mine sites or similar land application such as landfill final surface rehabilitation, subject to specific site management and environmental protection practices;

NOTE Some countries do not allow biosolids application on crops which can be consumed uncooked, root crops, fruit crops or in organic farming production.

6.11 Biosolids and soil monitoring

Addition of trace elements into the soil should be limited and controlled, as the removal of excess trace elements from the soil is very difficult and plant uptake of these elements can lead to plants unfit for human or livestock consumption.

The concentration of trace elements in biosolids as well as the loading rate should be limited.

The parameters that should be measured include any applicable requirements as well as other parameters that are use–dependent.

For information regarding the source of trace elements in biosolids and examples of jurisdictional trace element standards in biosolids and soil, see Annex E.

The application of biosolids containing trace elements should only be undertaken after calculating the potential loading capacity based on first performing an analysis of the soils to determine current levels of trace elements and secondly analysing the trace element levels in the biosolids.

Calculation methods are available in Annex K.

7 Biosolids application programme development and management

7.1 General

A biosolids programme should be planned to include two stages:

— programme development; and

— programme management.

There should be careful consideration of all factors when developing the programme. Open communication with stakeholders should be a priority to ensure that decisions made in the early stages are well–informed and minimize the risk of unanticipated opposition that can de–rail the progress of the programme.

There should be conscientious and vigilant programme management to maintain the confidence of all the stakeholders, which should include a practitioner experienced not only with the technical aspects, but also experienced in a variety of other areas including health and safety, applicable regulatory frameworks, data management and risk communication.

The biosolids programme should include procedures to identify all applicable legal requirements and to demonstrate how these legal requirements are met.

7.2 Community consultation

7.2.1 Involving the community

Biosolids management should involve the local community. The following aspects should be considered:

— citizens care about the decisions made by their authorities, as well as the processes used;

— the management of biosolids is a community expense;

— decisions about biosolids management can have impacts on cultural and community values, especially if there is a mishap or if plans do not work as expected; and

— understanding 'community' knowledge systems and aspirations can ultimately strengthen the 'technical' approaches, helping to develop a solution that is justifiable and acceptable to the community.

More information on conducting a community consultative workshop can be found in Annex O.

7.2.2 Consultation principles

7.2.2.1 Knowing the community

— Community assets and contributions, social networks, existing groups, etc. should be used.

— An analysis of key stakeholders should be undertaken (e.g. affected people, environmental groups, local businesses, agricultural, mining, forestry, community/industry).

— The involved stakeholders should be identified.

— Defensible criteria should be made for why the invitation includes some stakeholders and not others.

— Invitation should be inclusive rather than exclusive.

7.2.2.2 Timing consideration

— Consultation should be undertaken as soon as possible, when there is still the flexibility to make changes to address issues raised by interested and affected persons, rather than embarking on consultation within a crisis.

— It should be known that if consultation is too far in advance, it is likely that few will be very interested; if consultation is too late, stakeholders will think engagement on the issue is being avoided or there is no intention of taking their views into account.

7.2.2.3 Transparency and open mindedness

— Project objectives should be clear.

— There should be clear indication which aspects of the proposal are open to change, and why there might be elements that may not be able to change.

— Views should be kept open to the responses stakeholders make and the benefits that might arise from consultation.

— While consultation is not an open–ended, never ending process, it should not be seen merely as an item on a list of things to do that should be crossed off as soon as possible.

7.2.2.4 Dissemination of information

Dissemination of information on the project to the community and key stakeholders should be:

— relevant and necessary: as there is a lot of information available;

— clear and concise: to gain the community's attention, information should get key messages across clearly and efficiently;

— targeted: information should be targeted to its intended audience;

— accessible and innovative: in addition to more traditional methods such as newspaper and radio advertising, other methods may be appropriate, such as internet-based resources or social media; and

— appropriately timed: communication to the wider public should be timed so that people who are generally at work can attend public presentations and meetings.

7.2.2.5 Consultation process

Consultation, or at least communication with stakeholders, should continue after the decision has been made. This may be established through a local advisory committee.

Consultation does not necessarily require that all parties agree to a proposal, although it is expected that all parties will make a genuine effort. While it is possible that an agreement is not reached on all issues, points of difference can become clearer or more specific.

Consultation is a two-way process involving the exchange of information. It should not only include presentation of the material but also active listening to all stakeholders and constructive discussions among the various parties involved.

For information regarding consultative workshops, see Annex O.

7.3 Programme development

7.3.1 General

The development of a biosolids management programme should begin with a biosolids master plan possibly in conjunction with an environmental management system plan.

Biosolids development and management programmes should include the characterization of the material in terms of quality and quantity and the identification of the availability of end–uses while considering economic, environmental, applicable regulatory and social factors.

The programme should endeavour to consider the various perspectives of all stakeholders, which is important for the overall success of the programme.

7.3.2 Programme design and decision considerations

The programme development should first identify the purpose of the project including the problem and/or any opportunities, for example:

— the programme may no longer be socially/environmentally/economically acceptable; or

— the programme is non–compliant with applicable regulations.

The next step in programme development should identify the legal requirements and how these legal requirements are addressed, as they can limit the options available.

The third step should be the identification of all stakeholders. Stakeholder identification may be an iterative process where, as some stakeholders are invited to participate, they identify additional stakeholders. As stakeholders are identified, their area of interest, needs, and preferred method of providing input should be recorded.

While stakeholder identification is occurring, programme development should be simultaneously looking at social considerations, for example:

— is biosolids application acceptable to the local culture, or state of the area (rural/urban)?

— what are the potential benefits to the community?

— what is the attitude of influential citizens?

— is the community environmentally sensitive?

— has the community experienced negative or positive environment–related projects in the past?

— what is the potential for modifying public opinion?

— are the biosolids generated in the same region as the application site(s)?

NOTE Stakeholders are an important resource for understanding the social considerations of the programme.

Technical considerations of programme development should include:

— biosolids quality;

— level of treatment;

— biosolids quantity;

— available and accessible land;

— storage requirements;

— transport/hauling options;

— seasonal considerations; and

— odour management.

Similar to the technical considerations, the economic considerations should be documented in applicable protocols. General economic considerations should include:

— staff/human resources;

— operating/capital costs;

— assessment of available options;

— cost benefit analysis of the options; and

— in–house or contracted servicing options.

The final step in programme development, which can be most critical should be decision making. Clear communication should be undertaken with stakeholders throughout the programme development to encourage buy–in and limit issues at this final stage when the options are presented for consultation and approval (e.g. public, regulatory, political, internal).

7.4 Programme management

7.4.1 General

Programme management should address the ongoing day to day operation of the chosen management option. The management considerations listed in 7.4.2 should be addressed in order to successfully manage a programme. The time or effort for each should depend on a case–by–case basis. For example, some jurisdictions have more extensive data management and reporting requirements than others.

7.4.2 Programme management considerations

The programme manager may consider adopting more stringent standards. One of the following framework examples, or other frameworks, should be chosen:

— best management practices (voluntary);

— industry standards; or

— international standards.

Contracts may be administered for the selected management option. Contract development may include:

— competitive procurement process;

— strategic sourcing (contract duration for best value);

— insurance;

— financial securities;

— identification of roles and responsibilities; and

— the fair distribution and attribution of risks.

Biosolids management should include clear and readily available emergency response policies and procedures. These policies and procedures should include:

— applicable regulatory, legal and contractual requirements (spills, accidents); and

— wastewater treatment plant, land applicator or jurisdictional protocols.

Similarly, a programme specific health and safety protocol should be prepared. The protocol should include:

— biosolids or biosolids derived product safe handling document;

— traffic control at application sites;

— dust control and road maintenance;

— injury/accident reporting/procedures;

— training and certification;

— loading /hauling/unloading/use considerations;

— hazards; and

— personal and collective protective equipment requirements.

Record keeping and data management requirements should be considered an important aspect of the biosolids management programme. An information management system/database should be developed and include:

— reporting;

— tracking biosolids from wastewater treatment plant to application field;

— tracking of biosolids quality data, communications, incidents, application site information/maps etc.;

— tracking of nutrients and trace elements over the life of the programme which may allow additional biosolids application in the future;

— possible use of computer technologies and applications [geographic information system (GIS), spreadsheets, IT support]; and

— easy access to information, such as a dedicated system that can accurately track all sources of historical information.

Programme management should be operationally flexible and include contingencies to ensure that if the preferred management option suddenly becomes unavailable, the programme can respond and continue without a crisis developing. Operational flexibility considerations should include:

— maintaining programme flexibility by securing options (diversified end use strategy); and

— operational contingencies (contingency plan for alternate end use or disposal) such as:

    — backup storage availability,

— merchant capacity and availability of alternate processing facilities,

— emergency dewatering,

— disposal options (land filling), and

— availability of other companies/contractors for haulage/handling/spills clean–up.

Records should be accessible to wastewater treatment plant and land application operators and maintained for a period of time, as applicable.

NOTE Regulations can apply to determine the period of time.

7.4.3 Biosolids and soil monitoring

7.4.3.1 Biosolids sampling and analyses

The first step in determining biosolids quality should be the adoption of a statistically sound sampling methodology to collect representative samples that accurately characterize the material being land applied.

Biosolids quality analyses results can vary according to a number of factors, including:

— the frequency of sampling and the extent to which the monitoring programme captures changes in biosolids quality;

— the origin of the wastewater (industrial or municipal) discharged to the wastewater treatment plant;

— consistency in processing upstream to the wastewater treatment plant, particularly in the case of an on–site industrial wastewater treatment plant;

— consistency of sludge processing at the wastewater treatment site itself, i.e. addressing the effects of fluctuations in the quality of the final product;

— the type of sample (e.g. grab samples versus composite samples), sample number and size relative to the total volume of biosolids;

— the timing of sample collection;

— quality assurance procedures; and

— analytical methods and techniques, including detection limits, reproducibility, quality assurance and quality control.

Biosolids should be regularly tested to determine:

— compliance with applicable requirements regarding trace element content, volatile solids and pathogen reduction;

— efficiency of sanitation processes if relevant; and

— nutrient content that will be used to determine application rate and to provide final users with reliable information.

7.4.3.1.1 Frequency of sampling

Biosolids should be sampled prior to land application, to ensure minimum quality standards are met and risks to human health and the environment are minimized. The location and timing of sampling should be considered to ensure that the goal of obtaining samples is to be representative of what is being land applied.

A newly commissioned biosolids production process should be sampled more frequently in order to verify its efficacy. During this phase of monitoring, a large number of samples should be collected at set intervals. Routine sampling should be carried out once the efficiency and stability of the existing treatment process are established. The frequency of routine sampling should not be as intense as in the verification stage.

Verification monitoring should also be carried out if changes are made to an existing process, or if routine samples exceed the limits set for pathogens. If during routine monitoring, indicator bacteria (e.g. *E. coli*) numbers exceed the limits specified, then verification sampling should be applied for all pathogens. Once the treatment process is determined to be satisfactory, sample number and frequency of sampling may be reduced. See sampling frequencies examples in Annex M.

7.4.3.1.2 Sample handling

Each biosolids sample should be clearly identified, including the following:

— date, time and location of sampling;

— corresponding batch (if applicable);

— identity of the individual who performed the sampling;

— date that the sample was sent to the laboratory; and

— appropriate packaging to ensure sample integrity.

Samples should be sent to laboratory within 24 h after sampling and should be prepared as per laboratory instructions (i.e. for microbiological analyses chilled at least to 5 °C).

7.4.3.1.3 Biosolids analyses

Where multiple analytical methods are available for the testing of the biosolids, analytical methods that have a level of detection one order of magnitude below the local guideline should be used when possible for parameters that are likely not to be detected. For detectable parameters, a cost–effective analysis method may be used that provides an accurate result. Laboratories that are used to perform analyses should be accredited to ISO/IEC 17025[8] or an equivalent quality standard.

For a list of soil and biosolids tests and methodologies, see Annex N.

7.4.3.1.4 Chemical analyses

The parameters and frequency of analysis should depend, to a certain extent, on:

— the potential contamination risk due to industrial, commercial or institutional effluent discharge to the wastewater treatment plant;

— the final use of biosolids; and

— the volatile solids content of the biosolids or a measurement that is an indicator of the volatile solids.

Common parameters that may need to be monitored either by concentration in the biosolids or by loading limits to the soil include:

— nutrients (N, P, K);

— organic matter;

— metals (As, Cd, Co, Cu, Cr, Hg, Ni, Mo, Pb, Se, Zn); and

— moisture/dry matter.

Other parameters that may be monitored include:

— pH;

— mineralization rate of nitrogen and phosphorous;

— persistent organic compounds;

— carbon to nitrogen ratio; and

— salts.

Depending on the nature and volume of the industrial discharge to the sewer system, an assessment of the specific pollutants that could impair biosolids quality should be undertaken. See Annex L for examples of source control/pollution prevention tools. If there are such pollutants, an adapted monitoring programme and associated limit values should be used.

7.4.3.1.5 Biological analyses

Depending on the use of the biosolids, biological analyses may be needed to check limits for pathogens and stability. One or more of the following tests may be required:

— *E. coli*;

— Faecal coliform; and

— Salmonella.

Other tests that are less common include:

— Enteric virus;

— Helminth ova; and

— Specific oxygen uptake rate.

For biosolids produced by food industries some specific biological testing may be required such as Enterococci, *Campylobacter* or *Listeria*.

When receiving the analysis results, applicable limits should be immediately checked and registered.

Results should be electronically transferred to a monitoring database and a paper copy kept by the biosolids producer.

7.4.3.2 Soil sampling

The receiving soil should be sampled to gain knowledge about relevant physical and chemical properties that will inform how to best use the biosolids. Soil should be assessed prior to initiating a land application programme and periodically thereafter to determine:

— compliance with applicable requirements regarding trace element content;

— nutrient content which will be used to verify that excess nutrients are not present (at the end of the season after harvest or at appropriate intervals);

— pH to determine if adjustment is needed (e.g. add alkaline material to acidic soils); and

— soil texture.

Soil should be sampled using an unbiased pattern such as a rectangle or grid to obtain representative samples of the site as a whole. Samples from non–representative areas such as fence lines, fertilizer or biosolids storage areas, swampy areas, and near roads or buildings should be avoided.

The number of samples to be taken should be representative of the area of application and representative of site variability with respect to topography and soil type/texture.

Refer to the ISO 18400[9] series for more information on soil sampling.

7.4.4 Continuous improvement

All biosolids management programmes should be flexible in order to adapt to changing conditions. Changes may include:

— regulatory updates;

— programme diversification (availability of other application options);

— biosolids quality or quantity;

— improvements in application equipment; and

— public acceptance.

These changes can require a total rethinking of the management programme or minor improvements. Stakeholders should ensure that contractual programme requirements allow for modifications to address changes and permit continuous improvement.

Biosolids programme managers should:

— implement an environmental quality management system (e.g. ISO 14001)[10] including:
  — control of documents,
  — maintenance and updates of procedures,
  — programme audits (internal and third party external), and
  — incident reporting, review and assessment;

— strive for a quality, leading edge programme such as:
  — staying connected and informed by:
    — connection to professional associations/membership in committees (stay in the loop); develop a local, national, international network,
    — updates on research and technology,
    — awareness of regulatory changes and emerging issues, and
    — training (participate in conferences, workshops, webinars);

— develop a long-term programme strategy (to guide programme) such as:
  — working with stakeholders to establish vision, goals, and programme principles,
  — forecast changing conditions (population, demographics, production, land availability, land access, regulatory and social trends, political and economic and environmental/climate change).

7.4.5 Voluntary agreement and quality assurance

Voluntary biosolids land application agreements with interested parties (such as food retailers and processors, farmers and landowners) may be used to address the question of perception and increase the acceptance of using biosolids in agricultural crop production programmes.

Any land application of biosolids should be consistent with these voluntary agreements.

There should be a quality assurance system for the biosolids production and land application process as a whole. This system should include quality assurance which begins prior to wastewater treatment, with oversight of chemicals used and source control of potential pollutants. This system should include the production of biosolids within the wastewater treatment process, through to biosolids stabilization and vector attraction reduction, land application, methodologies and practices, final application site standards and end use. To demonstrate transparency and ensure stakeholder confidence is maintained throughout the process, this quality assurance system should be regularly validated by independent audit. The principal criteria should include the following.

- Biosolids quality, particularly:
  - control of potential pollutants from point sources;
  - sampling and analysis strategy to monitor biosolids quality for the concentrations of regulated parameters such as trace elements; and
  - treatment of biosolids to significantly reduce its content of pathogens and its volatile organic fraction which through aerobic, anaerobic or fermentative decomposition is directly related to the potential to generate odour.
- Soil quality, particularly:
  - a soil sampling strategy to monitor soil quality for the concentrations of regulated elements (nutrients, trace elements) often in relation to certain soil conditions, such as soil type, pH, content of organic matter, cation exchange capacity, or other key conditions, in order that soil limit values are not exceeded; and
  - a process for assessing soil or substrate quality prior to the biosolids application, and a predictive mechanism to identify anticipated outcomes to ensure that limit values are identified prior to the actual application, and assurance provided for the integrity of those soil limit values throughout the biosolids management process.
- Biosolids application rate, particularly:
  - the specific rate and the purpose that the specific rate is intended to serve (e.g. supplemental organic matter application rate, agronomic application rate, other specific purpose rate);
  - quantity of nutrients which can be applied, particularly nitrogen, and phosphorus in accordance with crop or other vegetation requirements;
  - predicted average quantity of regulated elements (other nutrients, trace elements) that can be applied to land and over what period, usually in terms of kg/ha/yr, or mg kg^{-1} increase in soil over baseline;
  - amount of biosolids dry solids that can be applied per year or multiple of years; and
  - timing and method of applying the biosolids, in relation to post–application land use. The rationale for the timing and method shall be provided, with specific emphasis on their design with respect to the protection of animals, food consumers and the immediate environment from pathogen transfer, and/or the retention of plant nutrients, and/or the risk of run–off and off–site migration.

Appropriate records should be maintained throughout the biosolids management process, which in addition to the above criteria should include information on:

- biosolids sources;
- quantities applied; and
- location of the receiving land.

8 Objectives of agricultural land application

8.1 General

The utilization of biosolids closes the nutrient cycle and is a sustainable nutrient recovery solution. Biosolids land application should be used to sustainably utilize this resource to improve soil physical properties such as nutrient retention, organic matter content, and moisture holding capacity and to provide nutrients to crops and plants while minimizing potential environmental and human health risks.

Proper biosolids treatment and management should take the following into consideration:

— appropriate storage;

— safe biosolids transport;

— application based on the crop nutrient requirements; and

— proper site selection to minimize potential adverse effects.

See information on the benefits of land application of biosolids and the effect of biosolids on soils in Clause 4 and Annex B.

8.2 Agronomic considerations

8.2.1 Nitrogen management — General

Most plants obtain nitrogen from the soil solution. N occurs in the soil in several organic and inorganic forms (oxidation states). Nitrogen in organic forms is found in amino acids, proteins and more resistant organic materials (like humic substances). Inorganic forms include ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-).

Nitrogen applied to soils in inorganic fertilizers or biosolids (or other organic amendments) is subjected to biochemical and physical processes which form the nitrogen cycle. Inorganic forms of nitrogen are the available forms to plants. All forms of nitrogen can be present in the soil at any point of time, mainly because nitrogen readily shifts from one form to another.

8.2.2 Nitrogen in biosolids

8.2.2.1 General

Nitrogen forms in biosolids are organic nitrogen, ammonium (NH_4^+), and nitrate (NO_3^-). The last two forms are available to plants. Nitrate concentrations are very low in most biosolids.

Ammonium–N once converted into nitrate–N is available to plants after application. Organic nitrogen has to be converted to inorganic forms by decomposition of the organic matter (mineralization). Organic nitrogen provides slow release nitrogen for crops.

The concentration of ammonium–N and organic–N and their proportion in biosolids depend on the origin of wastewater and on the type of wastewater and biosolids treatment processes.

8.2.2.2 Determination of biosolids application rate according to nitrogen content

The rate for biosolids application should be determined to provide the amount of nitrogen needed by the crop or vegetation to attain a desired yield while minimizing the amount of nitrogen that will percolate below the root zone to the ground water.

Biosolids application rate may be calculated using the nitrogen balance approach. The steps of this approach include:

a) determine the net nitrogen requirement of the crop;

b) determine the plant–available nitrogen from the biosolids;

c) calculate the residual nitrogen in the soil from test results and previous nitrogen applications;

d) calculate the annual biosolids application rate by subtracting the net plant requirement from the plant–available nitrogen in the biosolids + residual nitrogen in the soil expressed in kg/ha/year;

e) make sure that nitrogen supply from biosolids does not exceed maximum applicable constraints (e.g. nitrate vulnerable areas).

8.2.2.3 Net nitrogen

Net nitrogen should be calculated using the amount of inorganic nitrogen that the plant needs (plant uptake), minus the amount of nitrogen the soil supplies.

The amount of nitrogen supplied by the soil is constituted by the residual nitrogen in the soil plus the mineralized nitrogen from previous year's application of biosolids or other manures, soils improvers, organic fertilizer and crop residues. This quantity reduces the amount of nitrogen needed from a new biosolids application.

The net nitrogen requirement should be calculated according to Formula (1).

$$N\text{ req} = N\text{ need} - N\text{ soil} \qquad (1)$$

where

N req is the amount of N needed from biosolids application, in kg/ha;

N need is the crop N requirement, in kg/ha;

N soil is the residual soil N from previous applications, in kg/ha, measured by specific analysis.

8.2.2.4 Plant available N

Plant available nitrogen (PAN) in biosolids includes the inorganic nitrogen initially in the biosolids, plus the organic nitrogen mineralized during the first year of application, minus the nitrogen lost to the atmosphere by ammonia volatilization and denitrification.

As low nitrate concentration is present in most biosolids, it could be ignored in the estimation of the PAN, as well as the potential NO_3– denitrification.

The PAN should be calculated according to Formula (2).

$$N\text{pa} = (N\text{inorg} + N\text{org}) \times 10 \qquad (2)$$

where

Npa is the plant available nitrogen from the biosolids applied, in kg/t;

Ninorg is the inorganic nitrogen in the biosolids, $N\text{inorg} = N\text{–}NH_4^+ \times (1 - V/100)$, in %;

Norg is the organic nitrogen in biosolids × K_0 as applied, in %;

K_0 is the mineralization rate of N-org during the year of application, % of initial of N-org;

V is the loss of NH_3 by volatilization, in %;

10 is the factor to convert from % to kg/t.

8.2.2.5 Biosolids mineralization rates for the year of application

Mineralization rate of nitrogen in the soils is particularly dependant on:

— the type of wastewater treatment that affects the type of biosolids;

— the type of treatment for biosolids: anaerobic digestion, thickening, dewatering, liming, composting, and in some cases a combination of some of these treatments;

— the conditions and the duration of biosolids storage;

— the weather conditions (temperature, rainfall); and

— the type and the particularities of the soil (pH, structure, texture, drainage, water retention capacity, etc.).

Estimates of N mineralization rates are shown in Table 1. Actual mineralization rates may vary considerably depending on climatic and soil conditions at the application site.

Table 1 — Estimates of nitrogen mineralization rates for biosolids from various treatment methods

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

8.2.2.6 Mineralization rates for years following application

The availability of nitrogen for years following biosolids application is closely related to the agro–pedo–climatic system, the type of biosolids, and the application methods (dose and period of intake).

The level of mineral nitrogen in years following application is therefore highly variable from one year to another and from one context to another.

Factors influencing organic nitrogen mineralization are as follows:

— nitrogen absorption efficiency by the previous crop;

— whether or not there is a plant cover in intercropping (autumn and/or winter); and

— seasonal temperatures as well as rainfall, thus impacting the intensity of leaching.

Average values of mineralization exist, but they are subject to significant deviation depending on local conditions; therefore, they should not be used as a guide or a reliable indicator.

The measurement of the PAN in the soil prior to the next crop is therefore essential to assess the need for supplementary N fertilization and thus to proceed to the optimal adjustment of the fertilizing plan.

8.2.2.7 Volatilization of ammonia

The loss of ammonia gas (NH_3) to the atmosphere after biosolids application can reduce the amount of PAN.

The volatilization is affected by several factors:

— soil and biosolids pH;

— wastewater treatment process;

— biosolids application method:

  — incorporation versus injection,

  — days before incorporation, and

  — surface application on a living crop or crop residue versus bare soil;

— moisture content of biosolids and soil; and

— air temperature and wind speed.

Losses from volatilization are close to zero when biosolids are injected or immediately incorporated into the soil, when the soil has a low pH, or when wind and air temperature are low. In contrast, losses from volatilization are larger when biosolids are applied to the surface of the soil and the soil is dry and warm. Table 2 presents potential ammonia (NH_3) losses due to volatilization.

Table 2 — Suggested values for ammonia loss after biosolids applications to agricultural and forest lands

Application method	Volatilization rate (% of ammonia lost)	
Agricultural application	Liquid	Dewatered
Dewatered or liquid		
Incorporation by tillage		
0–2 day to incorporation	20	40
3–6 days to incorporation	30	50
> 6 days to incorporation	40	60
Injected into the soil	0	0
Composted or drying bed	n/a	0
Lime-stabilized[a]	90	90
Forest application[b]		
Open stand	10	25
Closed stand	5	15

[a] Analysed for Ammonium (NH_4^+) before lime addition.

[b] Assumes surface applied, liquid and dewatered.

8.2.2.8 Nitrogen based biosolids application rate (BAR–N)

The results of the net N requirement [see Formula (1)] and the PAN in biosolids [see Formula (2)] should be used for the calculation of the biosolids application rate (BAR) according to Formula (3):

$$Rba = Nreq/Npa \quad (3)$$

where

Rba is the biosolids application rate, in metric ton/ha;

$Nreq$ is the mass of N needed from biosolids application, in kg/ha;

Npa is the plant available nitrogen from the biosolids, kg/t.

8.3 Phosphorus management

8.3.1 General

Plant available phosphorus is the phosphorus that is in the soil solution or is weakly adsorbed by soil particles and organic matter.

Nitrogen and phosphorus are typically found in similar concentrations in biosolids but often crop requirements are significantly lower for phosphorus. Therefore, application rates based on nitrogen requirements will often over apply phosphorus. This over application can be equivalent to crop requirements for 3 to 5 years. Although high application rates of phosphorus typically do not negatively impact soil, it can adversely affect surface water if it is moved off site by runoff or soil erosion. However, the strong tendency for phosphorus (phosphate) to be adsorbed on colloidal surfaces and form insoluble complexes with cations means losses are reduced if measures are taken to reduce runoff and soil erosion.

When biological treatment is used to treat sludges, approximately 50 % – 80 % of the total phosphorus applied to land is available to plants in the first year. In contrast, after chemical treatment, in which alum or ferric chloride is added to the wastewater to precipitate the dissolved/soluble phosphorus, the availability of phosphorus is reduced. Phosphorus bound in these aluminium or iron complexes is not readily available to plants (<25 % compared to inorganic fertilizer).

8.3.2 Determination of biosolids application rate according to phosphorus content

Phosphorus input should be considered when calculating the land application rate based on nitrogen. To limit the build–up of a phosphorus reservoir in the soil the following factors should be considered:

— crop removal rate of phosphorus;

— the resultant phosphorus load when the biosolids rate of application is based on nitrogen rate;

— the type of treatment process used to produce the biosolids (e.g. biological vs alum or ferric treatment);

— the binding capacity of phosphorus; and

— soil pH.

Biosolids application rate may be calculated using the phosphorus balance approach. The steps of this approach include:

a) estimate the phosphorus requirement that allows a succession of crops to grow at the desired yield;

b) estimate the plant–available phosphorus from the biosolids;

c) calculate the multiyear biosolids application rate by dividing the succession of crop requirements by the plant–available phosphorus from the biosolids; and

d) compare nitrogen and phosphorus application rates and keep the more restrictive.

The content of phosphorus in biosolids is usually expressed as total phosphorus (TP). When determining crop/plant requirements of phosphorus, the determination should be expressed as phosphorus oxide (P_2O_5) as in inorganic fertilisers.

The portion of the phosphate that is plant available in the year of application is influenced by:

— the treatment process used to generate the biosolids;

— the climatic conditions in the application area (temperature, moisture); and

— soil health (soil microbiological activity).

These factors influence organic matter decomposition and chemical reactions in the soil which transform bound phosphorus into plant available phosphate (PAP). The detailed calculation of PAP can be found in Annex J.

Excessive fertilizer application can lead to environmental degradation as a result of nutrient leaching and the eutrophication of waters (e.g. causing algal blooms and deoxygenation of water bodies). Phosphorus should be managed using best management practices to reduce run–off and soil erosion, and to decrease the risk of phosphorus movement into water bodies.

Best management practices such as lower application rates on slopes, mulching, maintaining crop residue on the soil surface, vegetated buffers and setbacks from surface water and time of application can decrease the risk of phosphorus losses.

8.4 Annual biosolids application rate

Application of this subclause presupposes awareness of applicable legal requirements which can vary depending on the country.

The annual biosolids application rate (ABAR) is the maximum amount of biosolids in metric tons (dry mass) that can be applied to a hectare of land in a 365–day period. It is limited by the most limiting of nitrogen, phosphorus and trace elements.

The ABAR may be calculated for nitrogen (BAR–N) as per 8.2, phosphorus (BAR–P) as per Annex J and the annual trace element loading rate (ATELR) for each of the trace elements as per Annex K. The ABAR for the biosolids is the lowest ABAR calculated for nitrogen, phosphorus or trace elements. As an additional constraint, the trace element concentration in the soil after biosolids application shall not exceed the values listed in Table K.5.

9 Storage, staging, fencing and signage

9.1 General

Biosolids should be stored in areas where public access can be restricted or controlled. The landowners and/or farmers should take a risk-based approach to ensure that the selected biosolids storage site provides an adequate level of protection to the public. Exclusion by means of fencing and warnings in the form of signs help to manage this risk. Options include:

— fencing off the area with temporary fencing or placing the biosolids in an existing compound to prevent unauthorized access; and

— posting signs at all site entrances to the property from the time of delivery of the biosolids to the property until the biosolids have been incorporated into soil and livestock exclusion periods are met.

For land treated with Group 2 biosolids, a restricted access through means such as road closures and security for a specified period of time after the application may be considered to mitigate human and animal health risks.

Midterm storage of biosolids (more than 3 months or during the winter period) should be undertaken on dedicated works where public access can be restricted or controlled and environmental risks properly managed. The biosolids producer should take a risk-based approach.

Short-term in–field storage is used for staging prior to land application. Minimum in–field storage may be undertaken to reduce nuisance potential. An appropriate location should be selected when biosolids are stockpiled. Criteria to be considered include:

— flat (slope gradient ≤ 3 per cent);

— raised land set well back from waterways and flood prone land;

— restricted unauthorized access;

— soil texture;

— proximity to dwellings or sensitive areas; and

— depth to groundwater.

9.2 Signage

Signs should:

— be placed in an appropriate and visible location(s);

— be weatherproof (e.g. made of metal or plastic);

— carry warning that clearly indicates the expectations and/or limitations for access to a site; and

— avoid the use of inflammatory language or fear–based warnings, as these can raise undue concerns.

The signage may identify the following information:

— purpose of the exclusion or withholding period;

— requirement under which the sign is posted (if applicable);

— contact details of the responsible person;

— anticipated date of completion of the application;

— length of time restrictions will be in place;

— any mandatory wording regarding public health;

— any specific restrictions (e.g. general public not permitted on site, no dog walking);

— any specific recommendations;

— a map of the site, demonstrating precisely where the activities have occurred; and

— alternatives to utilization of the site, for example if there is another pathway through an area while the area is under restriction, as an extra piece of information.

10 Haulage and field deliveries

When biosolids are transported to a land application location to be temporarily stored and used, the following management practices could alleviate potential issues related to hauling and temporary field storage:

— before haulage of the biosolids, it can be economically beneficial to reduce the volume of biosolids by dewatering of the biosolids;

— delivery and in–field storage management of biosolids should be planned in advance and coordinated between biosolids producer, hauler and land owner, and road conditions should be factored in the plan;

— if possible, the time between haulage and land application should be reduced and so should the storage time. This could prevent the escape of leachate or odours from the stored pile. If the land application is not close to the delivery date, storage should be planned in advance to minimize the potential for odour nuisance, nutrient leaching and volatilization;

— the haulage equipment should be suitable to ensure that the solids concentration is maintained and there is no loss of leachate or odours (i.e. covered, sealed rear gates etc.); and

— haulage contractors may need to be licensed depending on local applicable requirements. Moreover, transport of biosolids between countries or jurisdictions may be subject to additional requirements.

The following aspects of haulage should be evaluated prior to transportation of biosolids:

— selection of routes based on a risk assessment to determine a route with minimal environment and community impact in the case of load loss or increased truck movements (increased carbon emissions);

— fugitive emissions impacts (i.e. carbon tax costs);

— infrastructure requirements (i.e. site access upgrades, transit roads, receiving points for liquid biosolids etc.);

— efficiencies in haulage and deliveries (i.e. multiple site deliveries, back loads etc.);

— record management requirements (i.e. volume/weight collected, biosolids source/stock pile location/collection location, haulage contractor – name, company, contact number, vehicle capacity, delivery location(s), proposed route, application method etc.);

— training requirements of haulage and land application contractors to ensure all health and safety information in handling biosolids; and

— emergency response requirements (i.e. spill prevention and response, clean–up methods, accident response, etc.).

11 Application techniques

Biosolids may be:

— surface applied (spread, sprayed or projected on land);

— incorporated into the soil; and

— injected into the soil (liquid biosolids).

Sometimes surface application is considered a preferred technique to avoid the seed bank disturbance in grazing lands and pastures. However, incorporation with discs, tiller or plow may reduce the potential risk of exposure. Application can be done by conventional farm equipment such as manure spreaders. Liquid biosolids may be injected to the land by injection nozzles that are installed on the delivery tanker. The same nozzles could be used for surface application of liquid biosolids.

Typically, forest land application is a type of surface application, through the use of tankers and sprayers that spray liquid biosolids into the forest, or projects partially dewatered biosolids by a special applicator vehicle. The applicator vehicle comprises of a large container, which feeds a high–speed side throw discharge unit called the aerospreader. The biosolids are applied via aerospreader over the forest site in pre–measured amounts from the roads that provide routes in the forest. In that case, land application planning should consider other uses of the forest by the community and provide a map of land application to potential users of the forest trails (e.g. use of the trail for sports activities, biking and hiking).

The preference of the application technique should depend on:

— objectives of the land application;

— potential for risks; and

— type of biosolids (liquid or dewatered).

Application site may need appropriate signage and fencing. See 9.2 for more information.

12 Specific pathogen mitigation measures for agricultural land application

The degree of pathogen management should depend on the quality of the biosolids being applied, as well as the type of crop being grown (food vs non–food). The goal of pathogen management is to add yet another barrier to human exposure and further mitigate any human or environmental impacts resulting from the beneficial use of sewage biosolids. In the case of Group 1 biosolids, additional practices such as incorporation are not necessary to reduce risks posed by pathogens, whereas Group 2 biosolids may require the use of pathogen management practices such as:

— incorporation or injection;

— withholding periods; and

— restricted access and signage.

Land treated with Group 2 biosolids can consider having restricted access for a specified period of time after the application to mitigate human and animal health risks. An example of restricted activities on biosolids amended site and withholding periods are provided in Annex Q.

13 Record keeping

13.1 General

Data generation and its recording should be an integral step in the quality assurance programme. With the level of technology currently available, a comprehensive database may be created to simultaneously integrate several important functions that need to be monitored. These include operational efficiency, operating costs, information on and for customers, and short and long term strategic planning.

Geographic information system (GIS) mapping of biosolids land application may be used to help organize and maintain compliance and record keeping and facilitate future land application plans. GIS could also support modelling steps regarding migration of contaminants and identify buffer zones for land application.

Record keeping should be done in a transparent and unambiguous manner and might also be requested in order to satisfy applicable regulatory requirements. Recorded data should be kept for at least 10 years. The following information should be recorded:

— biosolids quality;

— quantity per batch;

- type and treatment of biosolids;
- location of the receiving land;
- soil sampling and analysis;
- quantity and date of application; and
- additions of trace elements, nutrients and non-beneficial constituents to the soil.

Additional information may be recorded, either separately but preferably in an integrated database. Examples of such additional information are:

- types of crops grown;
- consultation with other organisations, regarding sensitive zones, application restrictions, etc.;
- operational control, including site scheduling and co–ordination of soil sampling and analysis, vehicle routing and scheduling, farm and field data (access, etc.), customer requirements, etc.;
- “non–complying product reports” to record events that were not in compliance with the quality system and the corrective actions that were taken;
- marketing and customer satisfaction;
- strategic planning, seasonal and long term;
- exceptional weather event precautions; and
- complaints and how they are addressed.

13.2 Spreading records

A spreading record book should be maintained and the information sent to the biosolids spreading operator. This document should specify:

- contact details with the final user;
- origin and batch number of the biosolids;
- application area;
- application rate;
- location of biosolids stockpile or staging area if applicable; and
- weather conditions (e.g. temperature, precipitation, wind speed and direction).

A detailed map to an appropriate scale should be attached to facilitate application area, stockpile and potential buffer zone identification. Once the application is completed the spreading book information should be returned to the biosolids generator. The information should include the application dates and final rate plus any incidents or complaints that might have occurred. The information should also be integrated into the end users field management plan.

13.3 Field inspection

Field inspection should be implemented during the delivery and spreading operations. The following information should be recorded for:

- staging:
  - appropriateness of the location;

  - optimization of storage area to limit pushing up requirements;
  - cleanliness of access;
- application area:
  - uniformity of spreading;
  - preservation of soil structure;
  - maintaining buffer zones.

Delivery and spreading activities should be inspected as necessary by the biosolids generator or their contractor.

14 Objectives of land reclamation

14.1 General

The properly managed land application of biosolids in a reclamation scenario will enhance soil fertility, soil structure and plant growth, while ensuring environmental protection. Biosolids have been shown to improve the productivity of soils and can also regenerate degraded sites into productive land.

For more information on biosolids land application benefits see Clause 4, Annex B and Annex P.

The objectives in the rehabilitation of disturbed land should be to restore the productivity of a depleted or degraded site to a level that will permanently support a self–sustaining ecological community, usually including plants, microbes, insects and possibly higher animals.

In accomplishing this objective, several equally important objectives can be achieved: erosion mitigation, dust control, improved terrain stability, and improved visual or aesthetic quality.

The goals and objectives in using biosolids for rehabilitation programmes should be clearly defined and quantifiable. The goals of a rehabilitation programme may be "restoration" directed, but may also be less prescriptive about final productive requirements. The goals may range from minimal ecological recovery (rehabilitation) where a community of plants are sustainable, to a more complete requirement that involves restoration to a productive state measurably similar to that observed prior to disturbance. Future productivity requirements in accordance with a subsequent land use or reclamation/restoration/rehabilitation plan may also be specified.

As site soils drive productive capability, the outcomes of reclamation, rehabilitation or restoration programmes can be strongly tied to soil development objectives.

Biosolids have consistent properties that lend themselves to assisting in the achievement of land reclamation objectives through significant contribution to soil development. Specifically, the following properties have benefit in reclamation, restoration, and rehabilitation projects or programmes:

- stabilized organic matter, which may be used as an adjunct to soil organic matter. Complex organic matter supplies carbon and important organic binding sites valuable to soil development;
- nutrients, a virtually complete suite of macro and micronutrients required for plant growth, microbial, fungal, and animal growth, reproduction, and survival; and
- water, particularly in slurry or dewatered biosolids, which may assist in the early germination of plants and agglomeration of soils.

Biosolids, while decidedly beneficial in specific reclamation applications, should be used with care, due to the presence, in trace quantities, of non–beneficial constituents, such as pathogens, non–nutrient trace elements, and organic compounds. Potential transfer of pollutants toward water resources and vegetation should be considered. See Annex R for more information regarding the benefits of biosolids use for reclamation.

14.2 Site management

14.2.1 General

Where land application is identified as an option, it should be assessed if land reclamation can constitute a feasible and sustainable outlet. In this feasibility assessment a land suitability map should be drawn up. The amount of land requiring reclamation within economic transport distance of biosolids production site should be evaluated as well as the opportunity of coordinating future projects. Since the use of biosolids on a reclamation site is usually a one–off opportunity, a planned sequence of reclamation projects should be managed to ensure the future continuity of the outlet.

This strategy may be carried out with consecutive projects at different disturbed sites or with a progressive reclamation project at a single site of sufficient size. Biosolids use and project scheduling may be driven by the land owner's constraints and demands, as well as the production rate of the biosolids.

Projects can often be discrete and not include the potential for repeat orders. The possibility of small but continuous reclamation schemes for municipalities (roadside verges, urban dereliction) should be considered.

When applying biosolids for reclamation purposes the subsequent and future land use should be taken into consideration. An area with industrial activities today can be used for commercial, recreational, agricultural or residential activities in the future. The use of biosolids in land reclamation should not impact future land use opportunities. Site selection should take the following into consideration:

— physical site characteristics;

— existing substrate;

— climate;

— existing vegetation;

— water resources;

— land area, location and access;

— biosolids form (e.g. liquid, dewatered); and

— proximity to potential sensitive features (e.g. residential areas).

14.2.2 Soil/substrate properties

Soil properties or final tailings substrate properties, in cases where there is no remaining soil, can have a major influence on the suitability of a site for application of biosolids.

The ease with which added water and/or nutrients can enter into (infiltration) and move through the soil profile (permeability and internal drainage) can determine how quickly the nutrients will be adsorbed, dispersed or may be leached within the soil.

The actual volume of soil should be used to determine the assimilatory capacity of the soil (how much added liquid and nutrients the soil can accept), and knowledge of the soil's ability to hold nutrients within the soil profile should be taken into account in the site assessment.

The physical and chemical characteristics of the receiving soil or substrate should be determined prior to application of biosolids. Characteristics for consideration should include:

— trace elements;

— macro and micronutrients;

— organic matter;

— pH;

— electrical conductivity;

— cation exchange capacity (CEC);

— sodium adsorption ratio;

— texture;

— required or used carbonate content in the site (lime) (to change the acidity of the soil);

— bulk density;

— porosity;

— depth and characteristics of the soil profile (there may be no soil profile due to extensive soil disturbance); and

— depth to groundwater.

The biosolids characteristics, soil assessment and regulatory framework should be taken into account in an estimate of whether and how much of the available biosolids can be used, having regard to trace elements, nutrient addition, and soil development.

The need for a soil pH adjustment to reduce trace element solubility, and therefore their availability, should also be considered. In such cases, operations for pH adjustment (e.g. lime requirements) should be included within the site preparation procedures of the application programme. Regulations (specific or adapted from other biosolids uses in land application such as agriculture) can provide a basis for calculating the maximum rate based on trace element or contaminants loading where applicable.

For certain sites (e.g. acidic mine spoils) the convenience of adding organic matter to control acid regression can justify biosolids application rates exceptionally higher than those calculated based on nutrient or trace element maximum loads usually required for agricultural soils.

14.3 Environmental considerations

14.3.1 Climate and season

A general site assessment should be completed and take into account annual rainfall, temperature and other relevant climate data.

The timing of biosolids application should be considered in relation to the period of maximum benefit for soil development and/or vegetation uptake to mitigate the potential for nutrient losses through leaching. Reclamation sites can be more vulnerable to severe weather, heavy rains and erosion due to their existing barren state prior to, during and immediately following reclamation activities.

While it is inadvisable to apply biosolids when the soil is saturated, snow covered, frozen or during periods of heavy rainfall, since these conditions will increase the risk of run–off in most cases, application to frozen or snow–covered ground can be appropriate on a mine tailings area as winter may be the only time to get equipment onto the tailings being reclaimed. To ensure this is an appropriate practice, the risks should be taken into consideration. Risks of surface and groundwater contamination can be mitigated if the site has an existing surface water collection and treatment system.

14.3.2 Topography

Biosolids may be used as one of the ways to successfully reclaim a sloped area (slope stabilization). Nevertheless, the application of biosolids for slope stabilization should include intense consideration in order to protect the environment. Sites which are sloping or which have variation in topography can pose limitations for application of biosolids, or require further planning and management to ensure appropriate risk mitigation.

Contouring of landscapes may be employed to prevent overland flow and encourage water infiltration.

Sites with broken and irregular topography should be considered more suitable than sites where the slopes are long and uniform. Sites which slope directly towards surface water should be avoided unless the surface water is managed and treated on site. Sites where the soils have good infiltration, permeability, and internal soil drainage, such as coarse to medium textured soils can require special care to avoid the contamination of ground water. Sites that are vegetated, particularly with perennial grasses and shrubs, have reduced potential for overland flow, and an increased ability to utilize water and nutrients soon after biosolids application.

14.3.3 Protection of water sources

Protection of water sources should be considered carefully in land reclamation projects when more than the agronomic rate of biosolids is used.

Key considerations, in addition to those covered in 6.7.4, for establishing a land application area for reclamation should include:

— potential for vertical conduits to ground water due to site activities (e.g. exploration and boring);

— primary direction of surface drainage; and

— presence of existing surface and/or ground water monitoring, collection or treatment systems.

There can be specific cases where a complete hydrogeological assessment is required to protect groundwater in sensitive areas.

Special precautions should be taken in surface spreading of liquid biosolids, in particular practices like sequential applications of biosolids at rates which will not cause runoff. Liquid biosolids can often be used in aftercare operations in which vegetation (usually grass) has already been established.

14.3.4 Identification of sensitive uses and associated buffer zones

If the reclamation area is located close to a residence or residential area, factors outlined in 6.7.5 should be addressed. An assessment should also be made of impacts on native flora and wildlife in the surrounding area and possibly on the food chain. These potential adverse effects can occur both during reclamation works and as a consequence of the final intended use of the site. Attention should be paid to regulations with regard to prohibition of using biosolids in areas of special environmental interest (conservation value areas).

14.4 Operations management

14.4.1 Site preparation

Site preparation should be carried out prior to biosolids application in a reclamation context. These operations may involve considerable earth movement and the use of heavy equipment, and can have a significant impact on programme costs. Site treatment may include the following:

— removal of debris from prior activities in the site (mining, construction, other disturbance activities);

— initial major re–contouring or materials placement operations, such as subsoiling, topsoil placement, final grade preparation;

— grading operations for levelling (landscaping integration requirements, run–off control, reduction of steep slopes);

— operations to improve soil structure (scarification/ripping to remove compaction);

— erosion and surface run–off control devices or diversions to protect surface water;

— conditioning of road access and unloading/storage areas;

— creation of drainage; and

— treatment with lime to raise soil pH value.

Discontinuities in slopes, berms and piles can create topographical micro sites allowing for increased diversity. The opportunity to contour the site to minimize wind corridors and desiccation, creating aspect variation and slope discontinuities, can assist in the application logistics and subsequent vegetation establishment.

If available, surface soils from another area (overburden) should be applied to the site in conjunction with biosolids application. Overburden can introduce a seed bank, microbial diversity and organic matter to facilitate nutrient cycling. Many mines, however, do not have sufficient surface soils from another area to cover the disturbed areas, and as a result biosolids applications are made directly to the exposed soil parent material or tailings.

In the progressive reclamation of active mines, the mine reclamation, operations, or closure plan should be understood to assist in managing the logistics of biosolids stockpiles, access points and transportation.

14.4.2 Biosolids batch management and transport

Some precautions should be taken with biosolids transport to avoid unnecessary public nuisance. In many land reclamation projects, a large quantity of biosolids is used in a short period of time. A typical operation consists of one single application that can last only a few days or weeks. Therefore, 'on site' storage facilities should be used for large projects. When the biosolids supplier is a small wastewater treatment system, the storage period required can be considerable.

The storage zones should follow these minimum requirements:

— unloading and storage areas should be clearly indicated and delineated, with buffer zones to control run–off and diversion of surface water;

— storage zones should be level or near level, and preferably delineated with a berm to control ponding of water within the storage area. Where required, a drainage pump may be installed to ensure water originating within the storage area remains controlled;

— depending on biosolids type and the local climate, it would be necessary to choose the safest method of storage (bermed stockpiles, covered stockpiles, paved or unpaved surfaces, tanks, or other secure systems); and

— attention should be drawn to public health protection and safety requirements for all storage systems.

For due diligence, a site assessment should be completed before the establishment of a large or long-term stockpile area. The assessment should address the sensitivity of the surrounding environment, including the potential for phosphorous and nitrogen leaching, surface runoff and stability. Stockpiles should not be located in a floodplain.

Climate, volume, intensity, and seasonality of precipitation should be considered when assessing stockpile location and type. The potential for nitrogen and phosphorous movement from stockpiles can differ substantially with varying climate and environment. Substrate texture onto which the stockpiles are placed can affect the permeability/hydraulic conductivity of the soil and affect the potential for movement. Characteristics of the biosolids can change with storage.

When undertaking a land application programme, both the quality of the material being land applied as well as the state of the receiving environment should be considered.

See detailed sampling considerations for biosolids and the receiving soils in 7.4.3.

14.4.3 Substrate sampling

An assessment of the receiving soil/substrate quality should be made to evaluate biosolids application rates and to identify problems that could endanger the final proposed use.

Regulations can also require soil analysis prior to reclamation. Soil sampling, treatment of samples and analysis should be performed in accordance with suitable standard methods (see ISO 18400[9] for guidance about soil sampling).

Reclamation can often involve imported soils, resulting in significant and immediate differences in soil properties. Several different soils may be used in a small spatial area, all of which could be appropriate for reclamation use, and have different physicochemical properties. As a result, in disturbed sites the soil physical and chemical characteristics can vary greatly in short distances, and care should be taken to ensure that the samples are representatives of the site.

Soil should be assessed prior to initiating a land application programme for reclamation and rehabilitation and periodically thereafter to determine the following items:

— nutrient content that will be used to verify that excess nutrients are not present, or calculating successful rates for agronomic purposes in reclamation;

— organic matter content determining nutrient and organic ratios required for successful rate calculation for reclamation;

— compliance with applicable requirements regarding trace element content and other contaminants if applicable; and

— pH to determine if adjustment is needed (e.g. add alkaline material to acidic soils).

The substrate or soil at the reclamation site should be sampled using an unbiased pattern such as a rectangle or grid to obtain representative samples of the site.

Samples may be composited, in addition to using a systematic pattern, to assist in obtaining a further broad understanding of site wide analytical averages.

Samples from non–representative areas such as fence lines, waste rock storage areas, swampy areas, and near roads or buildings should be avoided.

The number of samples to be taken should depend on the area of application. Samples should be taken at a biosolids application depth, (see ISO 18400-101[11] or guidance about soil sampling).

All samples should be combined to form a composite prior to testing, whenever possible. Laboratories that are used to perform analyses should be accredited.

14.4.4 Substrate analysis

At a minimum, the following parameters should be determined for soil or substrate, if applicable:

— total and available nutrients (N, P, K). In some instances, a soil report can include NO_3–N, for example if analysis was done on a soil sample taken deeper in the soil profile at the time of planting (as a possible indication for N leaching into the ground water or N movement). Furthermore, $N0_3$–N soil test value that was taken more than a couple of weeks prior to planting should not be used;

— organic matter;

— pH;

— cation exchange capacity (CEC);

— electrical conductivity;

— carbonate content that could be used or used for neutralising the acidity of disturbed soils (e.g. mine tailings);

— structure, texture, density and porosity (physical characteristic of soil). An excess of coarse materials can make reclamation difficult, and the amount of fine material fraction < 2 mm will determine properties such as water holding capacity, nutrient retention capacity, etc.;

— trace elements (As, Cd, Co, Mo, Ni, Cu, Se, Zn, Pb, Cr, Hg); and

— any other element or compound of interest (e.g. organic compounds).

In some cases, the trace element concentrations of the amending material (biosolids) can be significantly lower than the receiving substrate (e.g. mine tailings).

The need to analyse other parameters should depend on local conditions, history of the site or if their presence is suspected. Depending on the intended use of the restored site, it may be relevant to determine the physical characteristics of the subsoils.

14.5 Biosolids applications equipment and considerations

Mine sites requiring rehabilitation can be harmful to equipment, particularly exposed, steep, coarse textured long slopes and fine particle silt and sand in tailings. Mineral mine tailings ponds can develop clay lenses which retain water in the form of “slimes” at depth. These “slimes” can pose a hazard for application equipment. Liquefaction through retained water and silty clay sedimentation can also occur, which can result in the loss of equipment, and potential injury or death to workers at such sites.

Where appropriate, the incorporation of the biosolids into the soil substrate can increase the effectiveness of the amendment in vegetation establishment.

Several different methods including slope re–contouring and blending, gravity placement – end dumping, specialized spreaders, hydro–seeder/liquid spray applications, and conventional agricultural equipment may be used.

The application methods of biosolids for land reclamation should be similar to those used for agricultural purposes. The specific site conditions can require specific equipment (e.g. adaptation to steep slopes). The type of biosolids to be applied, particular site characteristics and the kind of application chosen (surface or injection) should determine the selection of the equipment and application technique.

Where appropriate, the incorporation of the biosolids into the soil substrate will increase the effectiveness of the amendment in vegetation establishments. Incorporation is difficult in coarse textured waste rocks dumps, however specialized harrows have been designed and used successfully. Surface application is common on waste rock dumps. Conventional reclamation equipment, such as large earthmovers or bulldozers often come equipped with rippers or similar mounted tools may be useful in incorporating biosolids at the operational scale. Significant leeway may be granted to operators in trialling new ways to successfully apply and incorporate biosolids at reclamation sites and in challenging areas. Application of this subclause presupposes awareness of applicable legal requirements which can vary depending on the country.

Whatever the final method, there are some general considerations that should be carefully evaluated.

— Timing of application. This should depend mainly on soil conditions, weather conditions and growing season.

— Safety precautions during application. The risk of exposure during application may be minimized by protective clothing and other health protection practices. Aerosol or dust production should be avoided. Soil stability should be assessed before the beginning of operations. Applying biosolids in a single pass will avoid problems of wheel slip and stability that can occur if the vehicles track over previously applied biosolids. Special safety measures should be taken when working on steep slopes.

— Equipment used for biosolids application should be designed in such a way that they provide an even biosolids distribution at the selected rate.

— Adoption of measures to minimize soil damage by compaction. For example, using large diameter wheels, low tire pressures or light equipment.

14.6 Determination of biosolids application rate

14.6.1 General

The soil in disturbed areas can often be either lacking completely, or of poor quality for vegetation establishment and growth. To promote soil development in disturbed areas, application rates higher than agronomic biosolids application rates may be used; these are typically one–time applications to meet reclamation objectives. Application rates should be selected in recognition of subsequent, future and neighbouring land use. The effects of application rates which are substantially higher than agronomic application rates on ground and surface water, vegetation and the food chain for potential consumers should also be considered.

Different methods for the determination of biosolids application rates in disturbed soils may be used. This can result in both higher and lower application rates and take into consideration agronomic soil characteristics, agronomic biosolids characteristics and characteristics of the projects' vegetation. Generally, application rates can vary for reclamation from 50 TDS (tonne dry solids) biosolids/ha through to 175 TDS biosolids/ha. The following subclauses identify several options that should be applied for rate determination based on reclamation objectives, and unique site characteristics.

14.6.2 Biosolids application rates based on agronomic nitrogen application rate

When determining a nitrogen based application rate, the vegetation's requirement for nitrogen for the growing season in which the biosolids is land–applied should be followed. This is termed the agronomic application rate, and may be most applicable to agriculture applications but can also be relevant to forestland fertilisation and some reclamation applications.

At this application rate, the vegetation is expected to utilize most of the applied available nitrogen, leaving minimal residual available nitrogen in the soil after the growing season. Minimal residual NO_3^--N reduces the potential for nitrogen movement into groundwater or surface water.

The agronomic nitrogen application rate may be determined using the calculations in 8.2.2.

14.6.3 Biosolids application rates based on maximum nutrient loads

The maximum biosolids application rate (TDS/hectare) for a specific case should be calculated as follows:

— biosolids nutrient content should be determined by specific analysis;

— biosolids nutrient content and maximum nutrient loads should be taken into account;

— biosolids application rates for each nutrient should be calculated. Nitrogen and phosphorus availability may be calculated using formulae in 8.2.2 and Annex K; and

— the lowest rate (limiting nutrient) should be the resulting maximum biosolids application rate in TDS/hectare.

NOTE These rates do not consider exploited natural environment conditions, or reclamation situations.

14.6.4 Biosolids application rates based on target carbon to nitrogen ratio (C:N)

The C:N ratio of biosolids can affect the conversion, or mineralization of nutrients (i.e. N, P, S) from an organic form to an inorganic form which is available for use by vegetation. With a C:N less than approximately 14:1, there is a propensity for nitrogen to begin to become freely available in the soil solution, enabling potential movement and leaching. Nutrient available for leaching systematically increases with decreasing C:N ratio. A C:N greater than 25:1 can begin to result in an immobilisation of N where a combination of organic complexing and micro–organism utilization removes and incorporates plant available N, resulting in less N available for plant processes.

High nutrient biosolids may be co–applied with a high C amendment (wood waste, primary pulp and paper residuals and some compost) to temporarily immobilize excess plant available N, through use of N by soil microbes for rapid decomposition of high carbon material.

After the soil achieves an ideal C:N ratio between 15:1 and 22:1, the release of N should be considered as regulated over time. This could reduce the N–NO_3 release to the environment and ground water, when plant N uptake is decreased. Nevertheless, the immobilized N in form of microbial protein can be mineralized during the decomposition of microbes' bodies.

The nutrient availability from these mixtures is not additive, when applied together, and mixtures should be evaluated together in the determination of an appropriate application rate. Application rates of these mixtures should be determined based on the mixed amendment. Qualified professionals should understand the mineralization and nutrient dynamics of these mixtures prior to calculating an application rate.

14.6.5 Biosolids application rates based on target organic matter

Most of disturbed soils or soil forming materials — especially following mine activities — are deficient in organic matter and require it to initiate and sustain nutrient cycling and pedogenesis. For reclamation of mine tailings, an application rate that provides sufficient organic matter to begin the process of soil development should be selected. The addition of organic matter to the soil forming materials can decrease the bulk density, reducing settlement and re–compaction. A lower bulk density can lead to increased porosity, infiltration and water holding capacity allowing additional water retention to support vegetation establishment. Increased organic matter can improve hydraulic conductivity if applied to soil forming materials that are prone to clogging (i.e. clay) or forming a surface crust. As the organic matter is converted to humus and litter is accumulated, the addition of organic matter may also serve to increase the cation exchange capacity (CEC) of the soil.

The agronomic nutrient application rate of biosolids on disturbed sites can result in less organic matter than is required to develop a productive soil. Calculation of a non–agronomic biosolids application rate should be based on achieving a target concentration of organic matter in the developing soil. Excess nitrogen and the potential for NO_3 leaching could be controlled by adjusting the C:N ratio.

An experienced qualified professional should complete the determination of a non–agronomic biosolids application rate. Rate trials should be established and monitored in refining application rates. Assessing vegetation development and the sustainability of that vegetation following non–agronomic biosolids applications should allow for an evaluation of the effect and efficacy of these treatments.

14.6.6 Biosolids application rates based on target pH adjustment

Acidifying effects can be seen due to the weathering of some soil forming materials, such as kaolin clay, sand, crushed sandstone and coal shale and the application of inorganic fertilizers such as ammonium sulfate.

Acid rock drainage mitigation can require the application of lime stabilized biosolids which may be added to modify the soil properties and maintain the soil pH within a range that is optimum for plant growth.

Waste lime, waste lime mud, fly ash, lime stabilized biosolids and high calcium water treatment residuals may be used as liming materials. Presence of calcium in lime stabilized biosolids can reduce aluminium toxicity and raise the soil pH, and organic matter in biosolids can bind with aluminium and prevent it from reaching toxic levels in soil.

The nutrient application rate of lime stabilized biosolids should also be considered when determining an application rate based on pH adjustment. To influence the acidity of disturbed soil, a large volume of lime stabilized biosolids may be incorporated into the soil. This can also result in excess amounts of nutrients and potential contaminants (e.g. cadmium from lime) that originate from biosolids, which could potentially leach into the ground water or runoff to surface water.

The amount of lime stabilized biosolids that should be added for pH adjustment should be related to the volume of soil that biosolids needs to be added to, soil buffering capacity and the targeted soil pH level. The soil pH may be adjusted to help with macronutrient availability, prevent micronutrient toxicity in plants and reduce the mobility of trace elements.

Reclamation application rates should be determined based on a beneficial use objective, and the means to achieve that objective should be clearly defined. Application rates should be calculated based on nutrient application rate, organic matter goal, pH adjustment, or C:N ratio. The resultant soil/substrate concentration of nutrients and trace elements should be determined and considered in relation to the rehabilitation goals and initial site conditions.

14.7 Revegetation

Reclamation activities with biosolids may involve the use of vegetation to achieve a specific reclamation outcome. Phytoremediation may be combined with biosolids application in reclamation to obtain the optimum results, and allow the plants to absorb the remainder of the contamination from the soil. Phytoremediation is the natural ability of certain plants that bio accumulate, degrade or absorb contaminants. With phytoremediation, vegetation shall be removed or used for recovery in the appropriate conditions.

The revegetation or phytoremediation outcomes can be diverse, ranging from the creation of new wildlife habitat through increased and specialized vegetation establishment and growth to the development of productive agricultural land, through the re-creation of natural forested or grassland ecosystems. If the site is to be used for agricultural production, it is necessary to make sure that there is no risk to the food chain.

Timing of biosolids application should be considered in conjunction with the establishment of vegetation. Sometimes, a suitable "rest period" after biosolids application can be observed. Sequential operations (e.g. 1st seeding and 2nd planting) may also be performed. As mines are often located in environments of extreme climate, attention should be given to the actual growing season, which can be short and related to adequate moisture and temperature. See Annex R for more information on revegetation.

14.8 Environmental post application monitoring

14.8.1 General

The aftercare programme should include field inspections, soil and water monitoring, maintenance operations, general management practices of the site and if appropriate, the quality of vegetation and the impact on the biocenosis. In particular cases, special requirements can be necessary. For example, the analysis for certain trace elements can be required to validate the use of the vegetation for animal consumption, and biosolids monitoring if used as fertilizer in site aftercare. Monitoring of fauna species may also be an indicator of holistic environmental health, particularly the return of species formerly located in the area of disturbance. Monitoring policies and procedures should be established with the goals of:

— ensuring representative sampling;

— confirming biosolids quality;

— protecting the environment; and

— protecting human health.

Monitoring programmes should be proactive, statistically significant and sufficiently comprehensive to allow for the detection of indicators prior to adverse impacts, and the identification of benefits (positive impacts) that result from the beneficial use of biosolids.

The restored site should be monitored and there should be aftercare of the restored site due to the fragility in the first developing stages of the system that is intended to be established.

The following two main objectives in a post–application management programme should be followed:

— appraisal of the system development in the disturbed site (i.e. vegetation quality and growth responses, soil development) and, if necessary, adoption of appropriate measures for its improvement. This can include, for example, field inspections, biomass estimations, fertilizer application, weed control to prevent desirable species from being swamped, replacement of dead plants and new plantations; and

— verification that the reclamation process does not cause adverse environmental effects and, if necessary, adopting appropriate measures to reduce such effects. The actions should be, for example, water analysis, management of erosion control and soil analysis for potential toxic elements and nutrient content. This will confirm that the biosolids applications were carried out as intended.

The aftercare programme should include field inspections, soil and water monitoring, maintenance operations and general management practices of natural systems. In particular cases, special requirements can be necessary. For example, the analysis for certain trace elements can be required if the vegetation is used for animal consumption, and biosolids monitoring if used as fertilizer in site aftercare.

14.8.2 Soil monitoring

Pre- and post-biosolids application soil analysis should include total trace elements and available nutrients, pH, CEC, organic matter concentration and other parameters if applicable. Representative samples should be collected from the rooting zone or zone of incorporation. In the case of surface application, sampling should be done a couple of days after application and from the root zone, and in the case of incorporation, sampling also should be done in the root zone. Application rates used may warrant further sampling to assess the depth and extent of N and other parameter movement where potential contamination is a concern. This may be completed by taking replicate soil samples at depth.

Obtaining representative soil samples from replaced soil from other sources (overburden), tailings, and forestry roads and landings is relatively simple compared to sampling waste rock dumps, where there is a high coarse fragment content and a lack of substantial amounts of fines. Pre–application analysis of the developing soil can provide insight into the fertility and trace element content of the fine particles (and of the coarse parent material). As there can be very little soil parent material on these sites post–application soil sampling can result in nutrient and trace element concentrations similar to that of the residuals applied. Care should be taken when scaling these concentrations up to an area basis by multiplying the concentrations by the percentage of fines in the zone of incorporation. The usefulness of post–application soil sampling in these situations can be limited, and if completed, the results should be carefully interpreted.

Sampling should occur post–application for additions of biosolids designed to modify the pH of the soil to confirm that the pH is within the desired range and significant changes have not occurred.

When using the deep–row technique (burying biosolids in deep–rows covered by a soil, used mainly in forestry), soil sampling post–application should be taken immediately below the row to assess nutrient or trace element movement.

14.8.3 Water monitoring

Surface and ground water monitoring should identify if there are any existing water quality concerns prior to land application and provide a benchmark for the water quality.

If there is surface run–off from steep slopes and biosolids is suspected to have entered into a stream, evidence of movement should be confirmed by sampling both upstream and downstream of the application area (see ISO 5667-6)[12]. Post–application samples should be compared with an appropriate control, or historical data that can allow for quantification of any water quality changes. As surface water chemistry can change through the seasons, sampling should occur throughout the year to capture this variation.

Mining can involve explosives, and most explosives are N based and may also contain potential contaminants. Explosive residue can be found on waste rock and in settling dust following detonation. In the development of a surface water monitoring plan, current and future mining activities should be considered.

Groundwater sampling may be conducted through wells in situations where excess constituents from the biosolids are suspected to be moving down through the developing soil profile. The hydrogeological layout and water movement through the disturbed site should be understood prior to initiating a groundwater sampling programme. A groundwater monitoring programme may already be in place and if needed, additional, biosolids–specific analyses may be added to the existing routine monitoring.

14.8.4 Foliage monitoring

Monitoring of foliage quality should be conducted on reclamation programmes where vegetation is to be established on soil parent material with little to no initial organic matter. Non–agronomic application rates can require the development of a post–application vegetation sampling programme. Foliage monitoring may not be necessary in cases where the goal of the reclamation is either restoration of natural vegetation or the sole purpose of the growing crop is for use on–site (e.g. dust control) or non–food or non–feed crops (biofuel). Imbalances in nutrient ratios can occur on disturbed sites such as incorrect copper: molybdenum (Cu:Mo) ratio in vegetation which can result in molybdenosis in ruminant animals.

The use of biosolids can significantly improve nutrient imbalances (Cu:Mo is such an example), or exacerbate/create more challenging conditions, therefore the prescription and use of biosolids in reclamation should include care and understanding. Application rates that produce excess soil NO_3^- can result in luxury consumption of N by vegetation and transfer of trace elements which can result in health impacts for grazing animals and some tree species. As with soil analysis, foliar nutrient analysis should be conducted at the same time in the vegetation's development to facilitate appropriate comparisons and the analysis should include plant essential nutrients and trace elements. The uptake of trace elements can vary significantly.

In sites where native plant species are to be used, plant sensitivity to specific nutrients or trace elements should be considered. For example, some common Acacia, Banksia and Grevillea species are sensitive to high P levels.

14.9 Quality assurance

See 7.4.5 for information regarding quality assurance.

15 Nuisance and risk management for biosolids use for land reclamation

Public acceptance is a crucial part in developing any strategy for biosolids use. Stakeholder engagement and public participation in the basic scheme for deciding on current and future biosolids outlets should be considered from the beginning, since this constitutes a key factor for the integration of the adopted scheme in the local or regional context.

A general agreement should be reached in the final application programme.

See 7.2 for information regarding community consultation.

16 Biosolids treatment

16.1 Biosolids quality criteria

The relative importance of biosolids quality criteria can vary according to the utilization option. Improving the quality of biosolids can offer increased flexibility in end use options. In land reclamation programmes, improved quality can enable increased application rates or extend the lifetime of an application site, based on reduced concentrations of key nutrients or trace elements in the biosolids.

16.2 Pathogens

Exposure to pathogens at reclamation sites is often low in comparison to other forms of beneficial use as these sites are usually not linked to the human food chain. Sites are often fenced, secured and have restricted access and with a minimal amount of animal grazing in comparison to other sites. However, the same quality criteria of biosolids that is used in agricultural programmes should apply to biosolids that is used in reclamation programmes, biosolids should still be incorporated, and vegetation should be established rapidly following application, to further create barriers to pathogen transmission. Pathogen hazard should be managed to protect workers in progressive reclamation projects or active sites with a biosolids reclamation activity component, as well as public or private parties who might frequent the final reclaimed areas.

16.3 Vector attraction

Vector attraction should be managed in biosolids–based reclamation, as the site either remains an active industrial site, with workers constantly in close proximity to biosolids reclamation areas, or it is closed, rendering it more likely to be frequented by wildlife which can inadvertently, or through attraction to improved vegetation, become vectors.

16.4 Odour

If the site to be reclaimed is close to urban settlements or even within in an urban/semi–urban zone, potential nuisance that reclamation operations can cause should be taken into account, particularly those regarding potential odour production. See 6.8.3 for more information on odour management.

16.5 Fencing and signage

Biosolids should be stored in areas where the public access can be restricted or controlled.

See Clause 9 for information on fencing and signage.

16.6 Record keeping

See Clause 13 for information on record keeping.

Annex A
(informative)

Soil carbon dynamics

A.1 Biosolids for soil carbon storage

The application of organic amendments including biosolids and composts to land can help restore soil quality and boost soil organic carbon stocks[13]. Applying biosolids during reclamation can help reduce reclamation costs, aid pedogenesis and increase on–site carbon sequestration potential.

Organic carbon is stabilized and retained in the soil via (bio)chemical transformation and physicochemical protection[14]. Soil organic carbon amendments from biosolids consist of two fractions with differing degrees of biodegradability: a labile fraction (50 % – 70 %) that is quickly mineralized; and a stable fraction (30 % – 50 %) less available or resistant to soil microbe turnover that may remain in the soil for > 1 year after biosolids application.

A.2 Estimation of soil carbon storage from biosolids amendment

Carbonaceous amendments such as biosolids when applied to soil undergo microbial decomposition and partial organic C remineralization. First–order single [see Formula (A.1)] and double [see Formula (A.2)] exponential decay formulae can be used to calculate C decomposition rates experimentally:

$$N = N_0 \, e^{-kt} \tag{A.1}$$

$$N = (RN_0 \, e^{-k1t}) + ((1-R) \, N_0 \, e^{-k2t}) \tag{A.2}$$

where

N_0	is the initial amount of carbon recovered at day 0 (g C kg^{-1} soil);
N	is the concentration of residual carbon in the soil at that time (g C kg^{-1} soil);
t	is incubation period (d);
R	is the rapid decomposable carbon fraction;
k, $k1$, and $k2$	are the first–order decay rate constants[15].

The carbon half–life (time taken to reduce carbon concentration to half the initial value) is calculated from the rate constants.

Two approaches are used to derive the C storage resulting from biosolids application. Firstly, the total carbon storage per hectare (T_C) for various treatments is calculated using the soil carbon contents measured at various intervals [see Formula (A.3)]. From these values, the net carbon storage resulting from biosolids application will be calculated as the difference between the control and biosolids–amended soils.

$$T_C = D\rho S_C 10^3 \tag{A.3}$$

where

T_C is total soil carbon storage (Mg ha^{-1});

D is the soil depth (m);

ρ is the bulk density (Mg m^{-3});

S_C is soil carbon (%).

Secondly, the net carbon storage (N_C) is also estimated from residual carbon inputs from biosolids application (B_C) and root biomass carbon (R_C) production [see Formula (A.4)]:

$$N_C = B_C + R_C \tag{A.4}$$

B_C is estimated using the decay equation developed for the incubation experiment [see Formulae (A.1) and (A.2)]. Since incubation experiments are often conducted under controlled conditions, a decay equation developed for biosolids decomposition under field conditions [see Formula (A.5)]; Reference [90] can be also used to estimate B_C.

$$B_C = ((0{,}339 - (55 - V_s/55))\ B_s\ \mathrm{e}^{-0{,}020\,5t}) + ((1 - (0{,}339 - (55 - V_s/55)))\ B_s\ \mathrm{e}^{-0{,}000\,301t}) \tag{A.5}$$

where

B_C is the remaining biosolids carbon;

V_s is the volatile solids in biosolids;

B_s is the carbon input from biosolids application;

t is the time (d).

Laboratory methods related to measuring carbon storage in soils are reasonably standardized. Bulk density is most often measured using a coring device to remove an undisturbed soil sample with a known volume. Total carbon content (equivalent to soil organic carbon in non–calcareous soils) is often measured using the dry combustion method (calcareous soils require pre–acidification to correct for inorganic carbonates). In soils potentially contaminated by coal, complex chemi–thermal[16][17] or thermal techniques[18] have been used to quantify the newly deposited and fossil organic carbon fractions.

Annex B
(informative)

Benefits of biosolids land application

B.1 General

The land application of biosolids can be beneficial in many ways. Some of the major advantages of biosolids land application include increasing soil organic matter (which leads to several other soil biological-physical–chemical improvements), improving soil pH (through lime stabilized biosolids), recovery of nutrients, carbon sequestration in soil and possible reduction of greenhouse gas emissions.

B.2 Effects of biosolids on increased soil organic matter

The major component of biosolids is organic matter which constitutes an average of 50 % to 60 % of the dry solid content. This organic matter originates from the suspended solids contained in the effluent discharged to the wastewater treatment plants and microbial activities. Organic matter improves the physical conditions of soil by improving soil structure, stability, permeability, cation exchange capacity, water holding capacity, bulk density, aeration and drainage and reduces soil erosion. The high organic carbon content also provides an energy source for stimulating functioning microbial communities, modulating nutrient uptake and acting as a pH buffer.

B.3 Soil biological activity

Soils contain many living organisms, ranging from microscopic bacteria and fungi to macro fauna such as earthworms. All play a significant part in maintaining the natural processes which are vital for soil fertility.

Biosolids land application influences the size and activity of soil microbial biomass, which is widely recognized as an important agent in soil organic matter turnover, due to addition of carbon and nitrogen as well as other nutrients[19][20]. Soil respiration is positively influenced by biosolids and compost supply[21]. Research has shown that over a decade after a single biosolids application higher microbial activity was found in comparison with mineral fertilizer application[22].

B.4 Soil porosity and bulk density

Bulk density and soil porosity are part of the most important properties of soil which regulate water movement, storage of air and water available to plants. A valuable outcome of the application of biosolids is maintaining or improving soil tilth[2)] [23][24].

B.5 Soil water infiltration rate

Water infiltration rate is a measurement of the rate at which soil is able to absorb rainfall or irrigation. The infiltration rate is directly related to soil structure, with particular reference to pore space. Limited water infiltration rate leads rapidly to water runoff and soil erosion. The positive impact of biosolids land application on soil hydrologic characteristics due to increase of porosity and aggregate stability have been documented in numerous biosolids land application sites worldwide[25][26].

2) Soil tilth is the suitability of soil for supporting plant growth.

B.6 Aggregate stability and soil erosion

The structural stability of soils is a physical characteristic that influences their behaviour during processes of degradation. This is one of the main factors controlling topsoil hydrology, crusting and erosion. Organic matter that is the major constituent of biosolids plays a crucial role in soil aggregation by increasing organic carbon[27], which increases the macro porosity of the soil.

Increased biological activity in biosolids–amended soil[28] also enhances aggregate stability, which is often used as an indicator of soil quality[29][30]. Soil biological activity fosters aggregate formation through the production of numerous binding agents (root exudates, microbial gums, polysaccharides) and fungal hyphae in the rhizosphere[31]. Organic matter sequestered within aggregates is protected from further mineralization[32] by physically separating soil microorganisms and their enzymes from the substrate[33].

B.7 Cation exchange capacity

Cations are positively charged ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}). The capacity of the soil to hold onto these cations is called the cation exchange capacity (CEC). These cations are held by the negatively charged clay and organic matter particles in the soil through electrostatic forces (negative soil particles attract the positive cations). The cations attracted to soil particles are easily exchangeable with other cations and as a result, they are plant available. CEC is therefore an indication of soil fertility for plant growth. If CEC is high, nutrients may be leached away prior to plant uptake and lost, but if it is too low then nutrients are not available for plant growth. Soils with the right level of cation exchange will release nutrients at a rate that plants require for growth.

Regular biosolids land application progressively increases the soil organic matter content and the overall soil CEC, providing a reservoir of nutrients to replenish those removed by plant uptake[34][35].

Biosolids application may also ensure slow release of nutrients in the years subsequent to the first application. Research has indicated that after land application of biosolids, 15 % – 25 % of the available nutrients are released in the first year, with sustained long-term nutrient release over subsequent years[36].

Due to this increase of CEC, biosolids amended soils require a lower frequency of fertilizer application.

B.8 Effects of land application of lime stabilized biosolids on soil pH

Acidification of soils is a natural phenomenon. To increase productivity, farming practices inadvertently induce soil acidity, accelerated acidification in soils occurs due to the use of ammonium fertilizers and spreading of animal manure. In general, soil is too acidic if the pH < 4,5 (at 0 cm – 10 cm depth) or pH < 4,0 (at 10 cm – 45 cm depth). The effects of soil acidification are not immediately obvious apart from declining crop and pasture yields due to aluminium and manganese toxicity and calcium deficiency. Soil pH levels should be maintained at optimum levels for minimization of metal uptake in plants, as well as migration of nutrients and contaminants into groundwater and surface waters.

In order to prevent acidic condition, the addition of lime may be used to buffer acidic soils, or alternatively lime amended biosolids which have a high neutralising value and readily exchangeable calcium can be applied, thereby providing an attractive resource.

Lime amended biosolids should only be applied at a rate estimated to raise soil pH to ensure satisfactory crop growth rather than at an application rate based on the nitrogen content of the lime amended biosolids product.

B.9 Effects of land application of biosolids on overall nutrient recovery and nutrient cycle

Biosolids contain organic matter, macronutrients and micronutrients required for plant growth, and are typically land applied for their fertilizer and nutrient value. For more information, see Annex C.

Mineralization is an important soil process as it releases nitrogen, phosphorus, sulfur and other nutrients from biosolids and other organic matter in soil, in a form that can be taken up by plants. Biosolids undergo stabilization during treatment which promotes the development of organo–nutrient complexes through microbial ingestion resulting in the development of biological mass[37]. This results in prolonged release of several nutrients dependent on the mineralization rates of organic nutrients[38], and improved moisture retention as compared to fertilisation with untreated animal manure or traditional chemical fertilizers[39]. For example, the nitrogen mineralization rate (release of plant available nitrogen) is inversely related to the stability of the residual: manures are observed to have the highest mineralization rate, followed by biosolids and composts[40]. Factors influencing mineralization rates include pH, moisture, aeration and temperature[41].

The release of plant available nutrients from biosolids is related to the:

— local environmental conditions such as soil texture and climate;

— concentration of nutrients in the biosolids;

— properties of nutrients (organic or inorganic forms);

— extent to which the biosolids have been stabilized;

— form of the biosolids (liquid vs dewatered); and

— choice of flocculant for phosphorous removal during treatment.

B.10 Effects of land application of biosolids on soil carbon sequestration and greenhouse gas emissions

Global warming is a critical environmental issue and the carbon cycle plays a major role both in the cause and mitigation of the global climate change. Through links to the carbon and nitrogen cycles, soils play a key role in regulating global climate via greenhouse gas (GHG) emissions and terrestrial carbon storage/sequestration. Promoting soil carbon sequestration is considered an effective strategy for reducing GHG emissions, including atmospheric carbon dioxide (CO_2). Soil carbon sequestration is an important option not only to mitigate climate change but also to enhance soil fertility and the productivity of agroecosystems. Recognizing the potential environmental and economic benefits from improved soil management practises, there is considerable international interest in developing policies and implementing strategies to help mitigate the loss of soil carbon stocks and/or bolster soil carbon sequestration potential.

However, soil–based GHG emissions mitigation activities in general are still in their infancy and face substantial future challenges, not least of which is the accurate measurement of emissions reductions over climate–relevant timescales (decades to centuries).

Land application of biosolids may still have some positive impact on GHG emissions due to the avoided use of mineral fertilizers, such as nitrogen and phosphorus.

Annex C
(informative)

Average concentrations of organic matter and plant macronutrients in biosolids

See Table C.1 and Reference [42].

Table C.1 — Average concentrations of organic matter and plant macronutrients in biosolids

Origin	Industrial		Municipal			
Type	**Dairy** **% (mass fraction)**	**Paper mill** **% (mass fraction)**	**Liquid biosolids[a]** **% (mass fraction)**	**Digested biosolids** **% (mass fraction)**	**Lime treated biosolids** **% (mass fraction)**	**Composted biosolids** **% (mass fraction)**
Organic matter	60–80	60–80	60–70	40–50	40–50	50–60
Nitrogen (N)	3–8	0,5–2,5	6–7	3–5	3,5–4	2–3
Phosphorus (P_2O_5)	2,5–8	0,15–1,5	4–7	3–6	4–4,5	3–5
Potassium (K_2O)	0,1–0,3	0,05–0,15	0,6–0,8	0,3–0,7	0,4–0,5	1–1,5
Sulfur (SO_3)	–	0,15–0,9 +	2–2,5	1,5–2	1,5–2	2–3
Calcium (CaO)	3–10	10–30	3–7	2–5	20–30	5–15
Magnesium (MgO)	0,5–1	0,3–0,5	0,5–0,9	0,6–1,2	0,5–1,5	0,6–1

[a] Liquid biosolids is referring to biologically treated sludge (not digested) from some small wastewater treatment plants.

Annex D
(informative)

Comparative pathogen and indicator limits for Group 1 biosolids

See Table D.1 and References [43], [44], [45], [46], [47], [48] and [49].

Table D.1 — Comparative pathogen and indicator limits for use of biosolids

Indicator/Pathogens	(Group 1)	Agriculture (consumed raw, salad plants and root crops)	Agriculture (crops consumed cooked or processed)	Landscaping and recreational use	Forestry and non-recreational landscaping	Reference source
Faecal coliform	< 100 MPN/g	< 1 000 MPN/g	< 1 000 MPN/g	< 1 000 MPN/g	< 1 000 MPN/g	USEPA, Part 503
Salmonella	Not detected/ 50 g	Not detected/ 50 g	< 1/50 g	Not detected/ 50 g	< 1/25 g	Aus (WA, SA, NSW) NZ
E. coli	< 100 MPN/g	< 100 MPN/g	< 100 MPN or /g	< 100 MPN/g	< 100 MPN/g	NZ
Campylobacter	< 1/25 g	< 1/25 g	< 1/25 g	< 1/25 g	< 1/25 g	NZ
Enteric virus	< 1PFU/4 g	< 1PFU/4 g	< 1 PFU/ 4 g	< 1 PFU/ 4 g	< 1 PFU/4 g	NZ
Total virus	< 1PFU/50 g	< 1PFU/50 g		< 1 PFU/50 g	< 1 PFU/50 g	AUS (SA, NSW)
Helminth ova	< 1/4 g	< 1/4 g	< 1/4 g	< 1/4 g	< 1/4 g	NZ, Aus (NSW, SA)

Key

MPN – most probable number

PFU – plaque forming unit

Annex E
(informative)

Source of trace elements in wastewater and biosolids and examples of trace elements standards in biosolids and in soil after biosolids application

The source of trace elements in wastewater, and therefore in treated wastewater and sludge, can be trace elements presence in fresh water and additions originating from domestic, industrial and agricultural water use. Trace elements are widely used in industries such as metal coating, battery production, animal hides processing, chemical industry, textile industry, and electronic industry. Corrosion of water pipes is another source of trace elements.

In addition, road runoff (storm water) can contribute, when it is conducted in a combined sewer system.

Even though sewage treatment plants are not designed for trace elements removal, higher and more efficient removal takes place as treatment level increases. Most elements are absorbed into the organic and inorganic matter, or become insoluble due to high pH, and hardness of the sewage water. Treatment processes therefore remove the trace elements from the liquid phase (treated wastewater) to the solid phase (biosolids). As a consequence, the removal of trace elements from the treated wastewater results in an accumulation of these elements in the biosolids. See Table E.1 and Table E.2.

Table E.1 — Maximum permissible concentration of trace elements in biosolids–treated soil (mg kg^{-1}DS)[53]

	As	Cd	Co	Cr	Cu	Hg	Mo	Ni	Pb	Se	Zn
Directive 86/278/EEC[50]		1–3		100–150 [d]	50–140	1–1,5		30–75	50–300		150–300
Australia[62][63]											
National Guidelines, (Grade C1 – Unrestricted)	20	1		100–400	100–200	1		60	150–300	3	200–250
New South Wales (A)	20	3		100	100	1		60	150	5	200
South Australia (A)	20	1		1[g]	100	1		60	200		200
Tasmania (A)	30	3		100	100	1		60	150	5	200
Victoria (C1)	20	1		400	100	1		60	300	3	200

a For soil pH ≥ 5, except for Cu and Ni are for pH range 6–7; above pH 7, Zn = 300 mg kg^{-1} DS (DoE, 1996).

b Approximate values calculated from the cumulative pollutant loading rate from Final Part 503 Rule (US, EPA 1993).

c Reduction to 200 mg kg^{-1} DS proposed as precautionary measures.

d EC (1990) – proposed but not adopted.

e Provisional Value (DoE, 1989).

f German limits (BMUB, Sewage Sludge Ordinance, 2017).

g Chromium VI.

h For pH < 6.

i In soils where 5 < pH < 6, it is permitted to use lime–sterilized sludge.

j Depend on the soil pH.

Table E.1 *(continued)*

	As	Cd	Co	Cr	Cu	Hg	Mo	Ni	Pb	Se	Zn
Western Australia (C1)	20	1		1[g]	100	1		60	200	3	200
Austria											
Lower Austria		1,5		100	60	1		50	100		200
Upper Austria		1		100	100	1		60	100		300/150[h]
Burgenland		2		100	100	1,5		60	100		300
Voralberg		2		100	100	1		60	100		300
Steiermark		2	30	100	100	1	10	60	100		300
Carinthia											
pH < 5,5		0,5		50	40	0,2		30	50		100
5,5 < pH < 6,5		1		75	50	0,5		50	70		150
pH > 6,5		1,5		100	100	1		70	100		200
Belgium											
Flanders	15	0,9		46	49	1,3		18	56		170
Wallon	15	2		100	50	1		50	100		200
Bulgaria											
6 ≤ pH ≤ 7,4		2		200	100	1		60	80		250
pH > 7,4		3		200	140	1		75	100		300
Canada (British Columbia)		3–20[j]		60	150	10		150	25		450
Canada (Ontario)[51]	14	1,6	20	120	100	0,5	4	32	60	1,6	220
Cyprus		1–3		100–150	50–140	1–15		30–75	50–300		150–300
Denmark		0,5		30	40	0,5		15	40		100
Estonia[i]		3		100	50	1,5		50	100		300
Finland		0,5		200	100	0,2		60	60		150
France		2		150	100	1		50	100		300
Germany[f]											
Clay		1,5		100	60	1		70	100		200
Loam/silt		1		60	40	0,5		50	70		150
Sand		0,4		30	20	0,1		15	40		60
Greece		3		—	140	1,5		75	300		300
Hungary	22	1	50	75/1[g]	75	0,5	7	40	100		200
Ireland		1		—	50	1		30	50		150

a For soil pH ≥ 5, except for Cu and Ni are for pH range 6–7; above pH 7, Zn = 300 mg kg^{-1} DS (DoE, 1996).

b Approximate values calculated from the cumulative pollutant loading rate from Final Part 503 Rule (US, EPA 1993).

c Reduction to 200 mg kg^{-1} DS proposed as precautionary measures.

d EC (1990) – proposed but not adopted.

e Provisional Value (DoE, 1989).

f German limits (BMUB, Sewage Sludge Ordinance, 2017).

g Chromium VI.

h For pH < 6.

i In soils where 5 < pH < 6, it is permitted to use lime-sterilized sludge.

j Depend on the soil pH.

Table E.1 *(continued)*

	As	Cd	Co	Cr	Cu	Hg	Mo	Ni	Pb	Se	Zn
Italy	20	1,5		200	100	1		75	100	10	300
Latvia		0,5–0,9		40–90	15–70	0,1–0,5		15–70	20–40		50–100
Lithuania		1,5		80	80	1		60	80		260
Luxembourg		1–3		100–200	50–140	1–1,5		30–75	50–300		150–300
Malta											
5 ≤ pH ≤ 6		0,5		30	20	0,1		15	70		60
6 ≤ pH ≤ 7		1		60	50	0,5		50	70		150
pH > 7		0,8		100	100	1		70	100		200
Netherland		0,8		10	36	0,3		30	35		140
Portugal											
pH < 5,5		1		50	50	1		30	50		150
5,5 < pH < 7		3		200	100	1,5		75	300		300
pH > 7		4		300	200	2		110	450		450
Poland											
Light soil		1		50	25	0,8		20	40		80
Medium soil		2		75	50	1,2		35	60		120
Heavy soil		3		100	75	1,5		50	80		180
Romania		3		100	100	1		50	50		300
Slovakia		1		60	50	0,5		50	70		150
Slovenia		1		100	60	0,8		50	85		200
Spain											
pH < 7		1		100	50	1		30	50		150
pH > 7		3		150	210	1,5		112	300		450
Sweden		0,4		60	40	0,3		30	40		100
UK[a]		3		400[e]	135	1		75	300[c]		20
USA[b]		20		1 450	775	9		230	190		1 500

[a] For soil pH ≥ 5, except for Cu and Ni are for pH range 6–7; above pH 7, Zn = 300 mg kg^{-1} DS (DoE, 1996).

[b] Approximate values calculated from the cumulative pollutant loading rate from Final Part 503 Rule (US, EPA 1993).

[c] Reduction to 200 mg kg^{-1} DS proposed as precautionary measures.

[d] EC (1990) – proposed but not adopted.

[e] Provisional Value (DoE, 1989).

[f] German limits (BMUB, Sewage Sludge Ordinance, 2017).

[g] Chromium VI.

[h] For pH < 6.

[i] In soils where 5 < pH < 6, it is permitted to use lime–sterilized sludge.

[j] Depend on the soil pH.

Table E.2 — Maximum level of trace elements (mg kg $^{-1}$ of DS) in biosolids and biosolids derived products used for agricultural purposes[53]

	As	Cd	Co	Cr	Cu	Hg	Mo	Ni	Pb	Se	Zn
Directive 86/278/EEC		20–40		–	1 000–1 750	16–25		300–400	750–1 200		2 500–4 000
Australia[62] [63]											
National Guidelines (Grade C2)	60	20	—	500–3 000	2 500	15	—	270	420	50	2 500
New South Wales (C)	20	20	—	500	2 000	15	—	270	420	50	2 500
South Australia (C)	—	20	—	1[b]	2 500	–	—	—	—	—	2 500
Tasmania (B)	20	20	—	500	1 000	15	—	270	420	50	2 500
Victoria (C2)	60	10	—	3 000	2 000	5	—	270	500	50	2 500
Western Australia (C2)	60	20	—	1[b]	2 500	15	—	270	420	50	2 500
Austria											
Lower Austria		2	10	50	300	2		25	100		1 500
Upper Austria		10		500	500	10		100	400		2 000
Burgenland		10		500	500	10		100	500		2 000
Voralberg		4		300	500	4		100	150		1 800
Steiermark	20	10	100	500	500	10	20	100	500		2 000
Carinthia		2,5		100	300	2,5		80	150		1 800
Belgium											
Flanders	150	6		250	375	5		100	300		900
Wallon		10		500	600	10		100	500		2 000
Bulgaria		30		500	1 600	16		350	800		3 000
Canada (Federal Fertilizers Act)	75	20	150			5	20	180	500	14	1 850
Canada (British Columbia)[58]											
Biosolids Class A	75	20	150	1 060	2 200	5	20	180	500	14	1 850
Biosolids Class B	75	20	150	1 060	2 200	15	20	180	500	14	1 850
Compost Class A	13	3	34	100	400	2	5	62	150	2	500
Compost Class B	75	20	150	1 060	2 200	15	20	180	500	14	1 850
Biosolids Growing Medium	13	1,5	34	100	150	0,8	5	62	150	2	150

a Fertilizer regulation *(BMEL, 2012); **(BMUB, Sewage Sludge Ordinance, 2017).

b Chromium VI.

Table E.2 *(continued)*

	As	Cd	Co	Cr	Cu	Hg	Mo	Ni	Pb	Se	Zn
Canada (Ontario) values for non-aqueous biosolids (>1 % dry matter)[51]											
Group 1	13	3	34	210	100	0,8	5	62	150	2	500
Group 2	170	34	340	2 800	1 700	11	94	420	1 100	34	4 200
Canada (Québec)											
Group 1	13	3	34	21	400	0,8	5	62	15	2	70
Group 2	41	10	150	1 060	1 500	4	20	180	300	14	1 850
Cyprus		20–40		–	1 000–1 750	16–25		300–400	750–1 000		2 500–4 000
Czech Republic	30	5		200	500	4		100	200		2 500
Denmark	25	0,8		100	1 000	0,8		30	120		400
Estonia		15		1 200	800	16		400	900		2 900
Finland		3		300	600	2		100	150		1 500
France		10		1 000	1 000	10		200	800		3 000
Germany[a]	40*	1,5*		2*	900**	1,0*		80*	150*		4 000**
Greece		20–40		500	1 000–1 750	16–25		300–400	750–1 200		2 500–4 000
Hungary	25	10	50	1 000/1[b]	1 000	10	20	200	750		2 500
Ireland		20			1 000	16		300	750		2 500
Israel		20		400	600	5		90	200		2 500
Italy		20			1 000	10		300	750		2 500
Japan	50	5		500		2		300	100		
Latvia		20		2 000	1 000	16		300	750		2 500
Luxembourg		20–40		1 000–1 750	1 000–1 750	16–25		300–400	750–1 200		2 500–4 000
Malta		5		800	800	5		200	500		2 000
Netherland	1,5	1,25		75	75	0,75		30	100		300
Poland		10		500	800	5		100	500		2 500
Portugal		20		1 000	1 000	16		300	750		2 500
Romania		10		500	500	5		100	300		2 000
Slovakia	20	10		1 000	1 000	10		300	750		2 500
Slovenia		0,5		40	30	0,2		30	40		100
Spain		20		1 000	1 000	16		300	750		2 500
Spain		40		1 750	1 750	25		400	1 200		4 000
Sweden		2		100	600	2,5		50	100		800
USA											
Group 1 (Class A)	41	39			1 500	17	(1)	420	300	100	2 800

[a] Fertilizer regulation *(BMEL, 2012); **(BMUB, Sewage Sludge Ordinance, 2017).

[b] Chromium VI.

Table E.2 *(continued)*

	As	Cd	Co	Cr	Cu	Hg	Mo	Ni	Pb	Se	Zn
Group 2 (Class B)	75	85			4 300	57	75	420	840	100	7 500

[a] Fertilizer regulation *(BMEL, 2012); **(BMUB, Sewage Sludge Ordinance, 2017).

[b] Chromium VI.

Annex F
(informative)

Standards for maximum concentration of organic compounds in biosolids

See Table F.1 and Reference [53].

Table F.1 — Standards for maximum concentration of organic compounds in biosolids (mg kg^{-1} DS except PCDD/F ng TEQ kg^{-1} DS)

	Absorbed organic halogens (AOX)	Bis (2–ethylhexyl) phthalate (DEHP)	Linear alkylbenzene sulfonic (LAS)	Nonylphenol and nonylphenol ethoxylates (NP/NPE)	Polycyclic aromatic hydrocarbons (PAH)	Polychlorinated biphenyl (PCB)	Polychlorinated dibenzodioxins and furans (PCDD/F)
Austria							
Lower Austria	500					0,2[c]	100
Upper Austria	500					0,2[c]	100
Voralberg						0,2[c]	100
Carinthia	500					1	50
Czech Republic	500					0,6	
Denmark		50	1 300	10	3 [a]		
France					Fluoranthene = 4 Benzo(b)fluoranthene = 2,5 Benzo(a)pyrene = 1,5	0,8[b]	
Germany (BMU 2017)					Benzo(a)pyrene = 1	0,1	30
Sweden				50	3[a]	0,4[b]	–

[a] Sum of 9 congeners: acenapthene, fluorene, phenanthrene, fluoranthene, pyrene, benzo (b+j+k) fluoranthene, benzo(a)pyrene, benzo(ghi)perylene, indeno (1, 2, 3–c,d) pyrene.

[b] Sum of 7 congeners: PCB 28, 52, 101, 118, 138, 153, 180.

[c] Sum of 6 congeners: PCB 28, 52, 101, 138, 153, 180.

Annex G
(informative)

Organic compounds

Sewage biosolids can contain trace amounts of a wide variety of organic compounds from common household sources such as pharmaceuticals and personal care products (PPCPs) including: soaps, shampoos, detergents and healthcare products. There is a body of scientific literature that supports the regulated land application of sewage biosolids as a sustainable and beneficial use of this resource rich material.

Some examples of research include:

— monitoring of pharmaceuticals and personal care products in runoff from fields applied with sewage biosolids found presence in exceptionally low or non–detectable levels[54][55];

— multi–organism bioassays that investigated potential eco–terrestrial and aquatic impacts from the land application of sewage biosolids found that the majority of the aquatic and terrestrial organisms were not negatively impacted when exposed to soils amended with biosolids at regulated application rates. Experiments with plants (corn, canola, mustard, soy, and wheat) showed no negative impact, and confirmed previous observations by other researchers that plants grow better in amended soils, presumably due to the nutrients provided by the biosolids[56];

— a Canadian study found that when best management practices were followed, the concentration of triclosan and trichlocarban (common anti–microbial ingredients in soaps, hand sanitizers and toothpastes) in edible portions of plants grown in sewage biosolids amended soils represented a negligible exposure pathway to humans[57]; and

— in a 2015 literature review by McCarthy et al. it was stated, in general, the currently available evidence suggests that the risk posed by organic contaminants in the biosolids land application context can be considered low for the general public, especially compared to the risks posed in different contexts; e.g. human exposure of PBDEs (commonly used flame–retardant) is more likely to occur from a domestic source than from agricultural products grown in biosolids–amended soil containing PBDEs[56].

Annex H
(informative)

Setbacks (buffer zones) in different regions

Table H.1 — Setbacks (buffer zones) and animal grazing in different regions

Location	**Building setback** (m)	**Surface water body setback** (m)	**Road setback** (m)	**Well setback** (m)	**Water table depth** (m) **or special provisions**	**Animal grazing enclosures** (days)
Australia (National Guidelines)[63] [64]						
New South Wales	50–100	50–250	5			25–50
South Australia	100	400	5			
Tasmania	50–100	50–100	5–10			25–50
Victoria	25–50	25–250	5			10–50
Western Australia	100	50–400	5			50
Canada (British Columbia– only for Group 2 biosolids)[58]	30	30	10–20[a]		Minimum 1 m	60
Canada (Ontario)[52]	Separation distances are dependent on odour level of the biosolids	20		Municipal– 100 m Drilled – 15 m Other– 90 m[b]	0,3 to 0,9 depending on application method	
Canada (Alberta) **Surface Application**	Area zoned residential – 500 Occupied dwelling – 60 Public building perimeter – 10 Public Building – 60 School yard boundary (in-session) – 200 School yard boundary (not in session) – 20 Cemeteries, playgrounds, parks, campgrounds – 200	30	n/a	20	"Sites with a seasonal water table within 1 m of the soil surface, and areas underlain by a shallow potable aquifer, should be avoided."	

[a] 10 m for minor roads and 20 m for major roads.

[b] Specifically for Group 2 biosolids.

Table H.1 *(continued)*

Location	**Building setback** (m)	**Surface water body setback** (m)	**Road setback** (m)	**Well setback** (m)	**Water table depth** (m) **or special provisions**	**Animal grazing enclosures** (days)
Canada (Alberta) **Subsurface injection**	Area zoned residential – 165 Occupied dwelling – 20 Public building perimeter – 3 Public Building – 20 School yard boundary (in–session) – 66 School yard boundary (not in session) – 7 Cemeteries, playgrounds, parks, campgrounds – 66	10	n/a	20	Sites with a seasonal water table within 1 m of the soil surface, and areas underlain by a shallow potable aquifer, should be avoided.	
Israel[61]		> 50 > 100 surface water source used for drinking water		> 20	Shall not be used in field within a protection hydrologic area (defined as a circular area surrounding a freshwater drilling, whose diameter is set according to the depth of the drilling and the soil's characteristics) and shall not be used at soil with the slope > 12 %.	
USA		10				

[a] 10 m for minor roads and 20 m for major roads.

[b] Specifically for Group 2 biosolids.

Annex I
(informative)

Biosolids quality based on treatment method

Table I.1 — Biosolids quality based on treatment methods

Type of biosolids according to treatment process	Description	Example typical conditions	Organic Matter	Nutrients	Pathogens	Product odour potential
Secondary	Wastewater solids that have been screened and biologically treated (secondary treated)	Screened and biologically treated	High	Moderate	High	High
Mesophilic digestion	Raw or secondary treated sludge that has undergone low temperature anaerobic digestion	Digestion held at 35–38 °C for 20 days	High	Moderate	High	High
Thermophilic digestion	Raw or secondary treated sludge that has undergone high temperature anaerobic digestion or high temperature treatments	Digestion held at > 55 °C for 10 days or thermal hydrolysis at 165 °C for 20 min or wet air oxidation at 250–300 °C for between 15 and 150 min	High to moderate	Moderate	Pasteurized	Moderate
Alkaline treatment	Sludge that has been treated to high pH by chemical addition	Lime treated to pH > 12 for 2 h	High	Moderate	Pasteurized	Low
Composting	Mix of sludge with green waste with sufficient time for aerobic biological reactions to break down to a humus like material. Grade A is treated to strongly reduce pathogens Grade B may contain some pathogens	Temperature reaching at least 55 °C for 3 days (static pile) or 15 days (windrow) followed by a curing period (depending on the process this could take up to 6 months)	Very high	Moderate	Pasteurized	Low
Heat drying	Removal of water from the sludge to produce a dry product	Thermal drying to produce a product with 90 %–98 % dry solids	Low	Very high	Low	Low

Annex J
(informative)

Determination of plant available phosphate

Plant available phosphate (PAP) is the phosphorus that is released by organic matter decomposition and chemical reactions within the soil. The quantity of PAP available from biosolids can be estimated using the following:

$$Ppa_1 = T_P \times 2{,}29 \times k \tag{J.1}$$

where

- Ppa_1 is the plant available phosphate in the year of application;
- T_P is the total phosphorus in the biosolids;
- 2,29 is the conversion factor from P to P_2O_5;
- k is the decomposition factor in the year of application.

Over time organic matter decomposition and soil chemical reactions will continue to transform biosolids phosphorus into plant available phosphate. The rate of this transformation is again influenced by:

— the treatment process used to generate the biosolids;

— the climatic conditions in the application area (temperature, moisture); and

— soil health (soil microbiological activity).

$$Ppa_{OT} = T_P \times 2{,}29 \times k \tag{J.2}$$

where

- Ppa_{OT} is the plant available phosphate over time;
- T_P is the total phosphorus in the biosolids;
- 2,29 is the conversion factor from P to P_2O_5;
- k is the decomposition factor after the year of application.

The total phosphorus available from a biosolids application should therefore be calculated as the result of $Ppa_1 + Ppa_{OT}$.

Annex K
(informative)

Determination of maximum biosolids application rates based on trace elements

K.1 General

To determine a maximum permitted biosolids application rate based on the trace element concentrations in the biosolids it is necessary to consider the trace element concentration in the biosolids and the receiving soil and the maximum limits in both.

K.2 Trace element concentration in biosolids

The average trace element concentration in the biosolids is a monthly average concentration of the trace elements [e.g. arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), molybdenum (Mo), nickel (Ni), selenium (Se) and zinc (Zn)]. The concentration of each trace element shall not exceed the concentration limit and also each of the samples in the month shall not exceed the ceiling concentration limits. The ceiling concentrations are the maximum concentration limits for the trace elements in biosolids and should not be exceeded on any sample.

Examples of average concentration limits and ceiling concentration limits are given in Tables K.1 and K.2.

Table K.1 — Trace element average concentration limits in biosolids applied to land

Element	Chemical symbol	Trace element average concentration limits for biosolids applied to land (mg kg^{-1}DS)	
		Reference [50]	Reference [51]
Arsenic	As	41	170
Cadmium	Cd	39	34
Cobalt	Co	.....	340
Chromium	Cr	1 200	2 800
Copper	Cu	1 500	1 700
Lead	Pb	300	1 100
Mercury	Hg	17	11
Molybdenum	Mo	.....	94
Nickel	Ni	420	420
Selenium	Se	36	34
Zinc	Zn	2 800	4 200

Table K.2 — Trace element ceiling concentration limits in biosolids applied to land

Element	Chemical symbol	Ceiling concentration limits for biosolids applied to land (mg kg^{-1} on DS)		
		Reference [59]	Reference [50]	Reference [61]
Arsenic	As	75	—	—
Cadmium	Cd	85	20–40	20
Chromium	Cr	3 000	—	400

Table K.2 *(continued)*

Element	Chemical symbol	Ceiling concentration limits for biosolids applied to land (mg kg^{-1} on DS)		
		Reference [59]	Reference [50]	Reference [61]
Copper	Cu	4 300	1 000–1 750	600
Lead	Pb	840	750–1 200	200
Mercury	Hg	57	16–25	5
Molybdenum	Mo	75	—	—
Nickel	Ni	420	300–400	90
Selenium	Se	100	—	—
Zinc	Zn	7 500	2 500–4 000	2 500

K.3 Cumulative trace element loading rate limits in biosolids (maximum mass applied — dry mass basis)

Bulk biosolids can be land applied if the concentration of one or more of the trace elements exceeds the values in Table K.1, but none of the ceiling concentrations (Table K.2) are exceeded. In this case the cumulative loading rate for each trace element shall not exceed the cumulative loading rate presented in Table K.3.

A cumulative trace element loading rate is the maximum amount (mass on a dry weight basis) of a trace element that can be applied to a site during its entire life by all bulk applications. No additional biosolids can be applied to a site after the maximum trace element loading rate is reached at that site for any of the trace elements regulated.

To ensure that the cumulative loading rate does not exceed any of the values in Table K.3, actual loadings of each trace element should be tracked on a site, or biosolids application history of the site should be known.

To calculate trace element loadings applied to a site, Formula (K.1) can be used. however, Formula (K.1) calculates trace element loading for each application of biosolids to a site. Once the trace element loading for each application of biosolids has been determined, trace element loadings can be summed to determine the actual measured cumulative trace element loading rate of a site during its entire life.

$$L_{TE} = C \times R_A \times 0{,}001 \quad (K.1)$$

where

L_{TE} is the trace elements loading (kg/ha);

C is the concentration of the trace elements in the biosolids (mg kg^{-1}DS);

R_A is the application rate to a site (metric ton/ha);

0,001 is the conversion factor.

Table K.3 — Cumulative trace element loading rate limits for biosolids applied to land

Element	Chemical symbol	Cumulative trace element loading rate limits for biosolids applied to land (kg/ha)
		Reference [40]
Arsenic	As	41
Cadmium	Cd	39
Chromium	Cr	3 000

Table K.3 *(continued)*

Element	Chemical symbol	Cumulative trace element loading rate limits for biosolids applied to land (kg/ha)
		Reference [40]
Copper	Cu	1 500
Lead	Pb	300
Mercury	Hg	17
Nickel	Ni	420
Selenium	Se	100
Zinc	Zn	2 800

K.4 Maximum trace element loading over 365 days

Annual trace element loading rate is the maximum amount of a trace elements that can be applied to a unit area of land during a 365–day period. To calculate trace elements loadings during a given 365–day period applied to a site, Formula (K.2) can be used. The annual biosolids application rate should not result in exceedances of the jurisdictionally regulated maximum trace element loading.

Table K4 shows examples of maximum annual trace element loading rates.

$$R_{ATEL} = C \times R_{ABA} \times 0{,}001 \quad (K.2)$$

where

R_{ATEL} is the annual trace element loading rate (kg/ha)/365 days;

C is the trace element concentration (mg kg^{-1});

R_{ABA} is the annual biosolids application rate (metric ton/ha)/365 days;

0,001 is the conversion factor.

Table K.4 — Annual trace element loading rate limit for biosolids

Element	Chemical symbol	Annual trace element loading rate limit for biosolids applied to land (kg/ha per 365–day period)		
		Reference [59]	Reference [50] based on 10–year average	Reference [61]
Arsenic	As	2,0	—	—
Cadmium	Cd	1,9	0,15	0,30
Chromium	Cr	—	—	6
Copper	Cu	75	—	9
Lead	Pb	15	15	3
Mercury	Hg	0,85	0,10	0,075
Nickel	Ni	21	3,0	1,35
Selenium	Se	5,0	—	—
Zinc	Zn	140	30	37,5

K.5 Annual trace element loading rate (ATELR)

To calculate the annual trace element loading rate analyse the biosolids and determine the dry mass concentration for the listed trace elements and determine the ATELR using Formula (K.3):

$$R_{\text{ABA}} = \frac{R_{\text{ATEL}}}{C \times 0{,}001} \tag{K.3}$$

where

C is the the concentration of the trace elements in the biosolids (mg kg^{-1} DS);

0,001 is the conversion factor converting mg/kg units to metric tons;

R_{ATEL} is the value for that specific trace elements (kg/ha per 365–day period).

K.6 Annual biosolids application rate (ABAR)

The annual biosolids application rate (ABAR) is the maximum amount of biosolids in metric tons (dry mass) that can be applied to a hectare of land in a 365–day period. It is limited by the most limiting of nitrogen, phosphorus and trace elements. The ABAR shall be calculated for nitrogen as per 8.2.2; phosphorus as per Annex J and for each of the trace elements (ATELR) as per this annex. The ABAR for the biosolids is the lowest ABAR calculated for nitrogen, phosphorus or trace elements. Application of this subclause presupposes awareness of applicable legal requirements which can vary depending on the country.

K.7 Limit values for concentration of trace elements in soils (Soil end point concentration method)

The application rate (using biosolids below the ceiling limits for trace elements concentration) should take in account the maximum allowable soil trace elements concentrations for agricultural land. Soil samples from the application site shall be analysed to determine trace element concentrations before biosolids application. The results of the soil and biosolids analyses are used to calculate the maximum application rate based on trace elements loading. Application of biosolids should be managed so that the maximum allowable soil trace elements concentrations listed in Table K.3 are not exceeded. The trace elements limited application rate (TELAR) should be calculated using Formula (K.4).

Table K.5 — Maximum allowable soil trace element concentrations for agricultural land after biosolids application

Element	**Chemical symbol**	**Maximum allowable soil trace element concentrations for agricultural land after biosolids application (mg kg $^{-1}$DS soil) with a pH 6 to 7**
		Reference [50]
Cadmium	Cd	1 to 3
Copper	Cu	50 to 140
Lead	Pb	50 to 300
Mercury	Hg	1 to 1,5
Nickel	Ni	30 to 75
Zinc	Zn	150 to 300
Analytical method		Strong acid digestion. The reference method of analysis shall be that of atomic absorption and the limit of detection of each metal should be no greater than 10 % of the appropriate limit value.

NOTE These values can be exceeded if the soil has a pH consistently higher than 7, but not by more than 50 %.

$$R_{TELA} = \frac{(C_{MASTE} - C_{AST}) \times m_S}{C} \quad \text{(K.4)}$$

where

R_{TELA}	is the trace elements limited application rate (metric tons/ha);
C_{MASTE}	is the maximum allowable soil trace elements concentration (mg kg^{-1}DS);
C_{AST}	is the actual soil trace elements concentration (mg kg^{-1}DS) from soil analysis;
C	is the concentration of the trace elements in the biosolids (mg kg^{-1}DS);
m_S	is the incorporated soil mass per hectare (dry metric tons/ha); calculated using the soil bulk density, the incorporation depth and the soil area (1 ha).