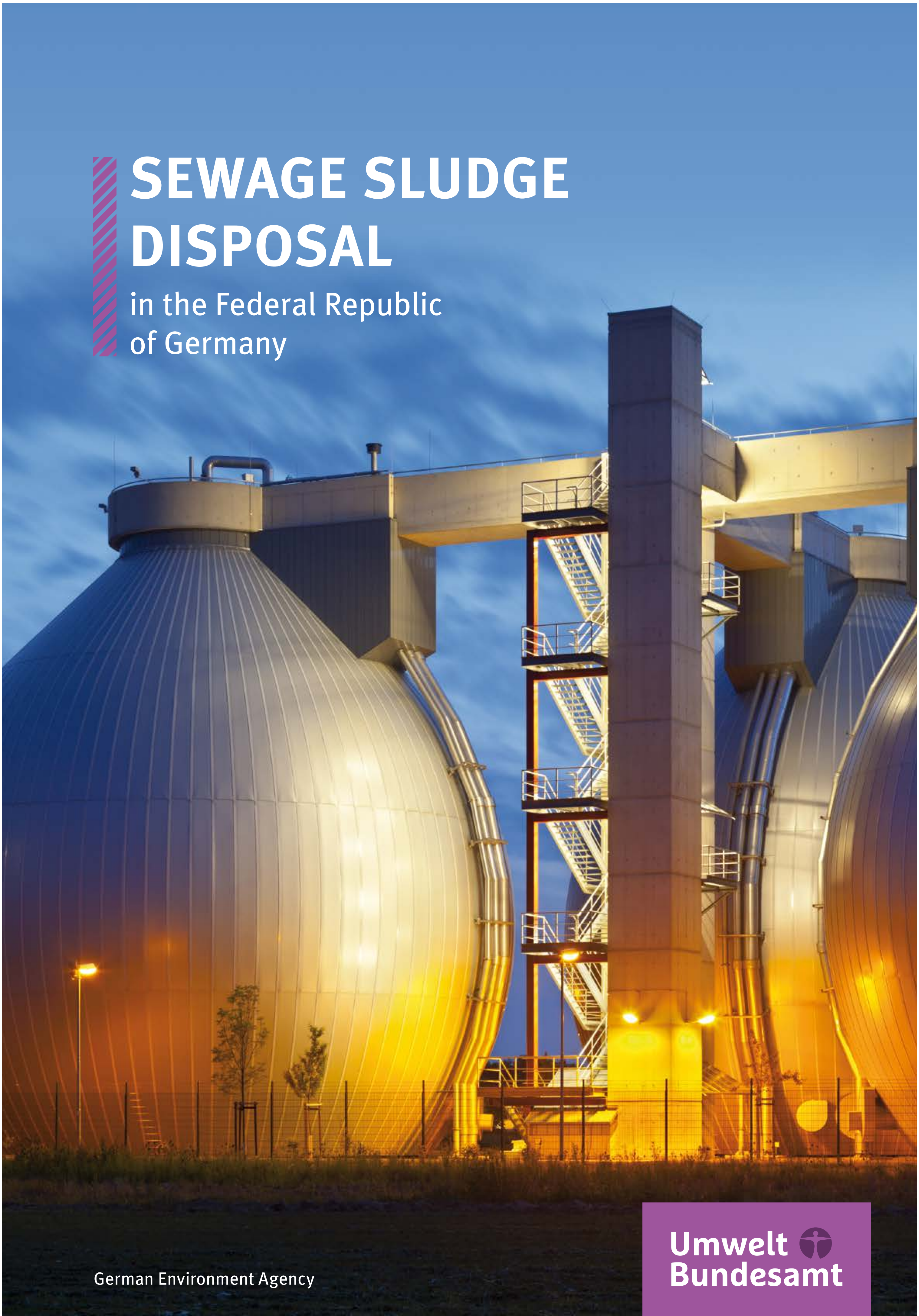
SEWAGE SLUDGE DISPOSAL

in the Federal Republic of Germany



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Introduction

In the 18th legislative period coalition agreement, the coalition partners agreed to terminate sewage sludge application for fertilising purposes and replace it with recovery of phosphorus and other nutrients from sewage sludge. The Sewage Sludge Ordinance was amended for this purpose and the amendment entered into force on 03/10/2017 as “Ordinance to Reorganise Sewage Sludge Utilisation”.

The central element of the new Sewage Sludge Ordinance is the obligation to recover phosphorus (P) from sewage sludge or sewage sludge incineration ash. Thus, after a transitional phase, sewage sludge with a minimum phosphorus content of 20 g/kg total solids (TS) must be treated using such phosphorus recovery processes that can extract at least 50 % of phosphorus from the sewage sludge total solids itself or reduce phosphorus content to less than 20 g/kg TS or recover at least 80 % of phosphorus contained in sewage sludge incineration ash. The deadline is based on suitably approved expansion capacities of wastewater treatment plants and for plants with more than 100,000 population equivalents (PE), it expires on 01/01/2029 or for plants above 50,000 PE on 01/01/2032. Until then, sewage sludge from these wastewater treatment plants may continue to be utilised as a fertiliser on soil in compliance with the criteria of waste and fertiliser legislation. Sewage sludge from smaller wastewater treatment plants (≤ 50,000 PE) may continue to be used indefinitely on soil in the future.

The vast majority of the almost 1.8 million tonnes of sewage sludge total solids (TS) produced in municipal waste water treatment plants in Germany in 2016 was incinerated. A significant increase (to around 64 %) in thermal sewage sludge treatment has been observed since the introduction of the landfill ban on untreated organic waste from 01/06/2005.

Thermal sewage sludge treatment is mostly carried out in sewage sludge mono-incineration plants, cement works, coal-fired power plants and waste incineration plants. The proportion of sewage sludge utilisation on soil – agricultural and landscape engineering use – has been decreasing for several years. While more than 45 % of sewage sludge was disposed of via this material usage pathway in 2012, it was only 35 % in 2016 [DESTATIS B]. This can be attributed to increasing quality requirements and application restrictions (fertiliser legislation).

The aim of this report is to present the current state of municipal sewage sludge disposal in the Federal Republic of Germany and to highlight the possibilities for its sustainable utilisation. The current task in the next few years is to gradually limit sewage sludge utilisation on soil and at the same time efficiently use the nutrients in sewage sludge – especially the phosphorus content – e. g. for fertilisation purposes.

01

Basics

- What is sewage sludge?
- Where does sewage sludge come from?
- Relevant legislation for sewage sludge disposal

What is sewage sludge?

The average daily drinking water consumption is about 120 litres per person in Germany. The used water enters the sewage system as wastewater and from there the connected wastewater treatment plants. In addition, there is wastewater from commercial enterprises (indirect dischargers) and rainwater (in combined sewerage). In wastewater treatment plants, the wastewater is treated mechanically, biologically or chemically in various cleaning stages, i.e. dirt and nutrients are removed to a large extent and then the wastewater is discharged into water bodies. What remains is called the sewage sludge.

Sewage sludge is produced both in municipal and industrial wastewater treatment plants. It can be dewatered, dried or otherwise treated. Raw sludge is untreated sewage sludge that is taken from wastewater treatment plants.

Only sewage sludge from municipal wastewater treatment plants or sewage sludge from industrial wastewater that is comparable to municipal wastewater in terms of material composition is suitable for recycling according to the Sewage Sludge Ordinance (see AbfKlärV p. 9 et seqq.). This may be the case if production effluents are treated together with sanitary wastewater. In the sense of the Sewage Sludge Ordinance, sewage sludge also includes sewage sludge mixtures and sewage sludge composts. Mixtures of sewage sludge with other suitable substances as per Tables 7 and 8 of Annex 2 of the Fertiliser Application Ordinance are sewage sludge mixtures pursuant to Section 2 AbfKlärV. Sewage sludge composts are composted sewage sludge mixtures [ABFKLÄRV].

Sewage sludge can be described by various physical, chemical and microbiological parameters. Parameters called sludge parameters are used for characterisation and they are shown and explained in Table 1.

In addition to the parameters mentioned here, there are other terms (e. g. sludge index or digestion time) that are used in practice to describe sewage sludge.

High ignition loss indicates a high organic content in sewage sludge. The incineration of sewage sludge also has the task of destroying organic substances including organic pollutants in the sewage sludge. For this reason, ignition loss is an important parameter that can describe combustibility of sewage sludge. Furthermore, the water content is an important guide since too high water content reduces the fuel's calorific value. Ultimately, one single parameter does not suffice to describe the sewage sludge since the parameters are always in linked to each other.

Table 1

Sludge parameters and their explanation

Parameter	Unit	Explanation
Dry substance (DS) Total solids (TS)	e. g.: kg, g, mg	The mass (total solids/substance) of dry sludge remaining after a specified drying process. Determined by subtracting water content.
Total solids content (TSR)	e. g.: kg/m³, g/l	Total solids contained in a given volume.
Dry residue (DR)	%	Measure of the solids content of the non-filtered sludge sample or the proportion of total solids in the total sludge matter. Determined by evaporating water.
Water content	%	Measure of water content in the total sludge matter. Determined by evaporating water.
Ignition residue (IR)	%	Measure of the inorganic or mineral content in the total solids of sewage sludge. Determined by incineration of dry residue.
Ignition loss (IL)	%	Proportion of organic matter in the total total solids of sewage sludge. Determined by ignition of total solids residue.
Ignition loss (IL)	%	Proportion of organic matter in the total total solids of sewage sludge. Determined by ignition of total solids residue.
pH value	-	Negative decadic logarithm of hydrogen ion activity.
Sludge type	-	Operational data. Classification of sewage sludge by its place of origin.
Sludge age	d	Operational data. Determination as the ratio of bacterial mass present in the pool to bacterial mass extracted daily in excess sludge.

Source: [KOPP; RÄBIGER]

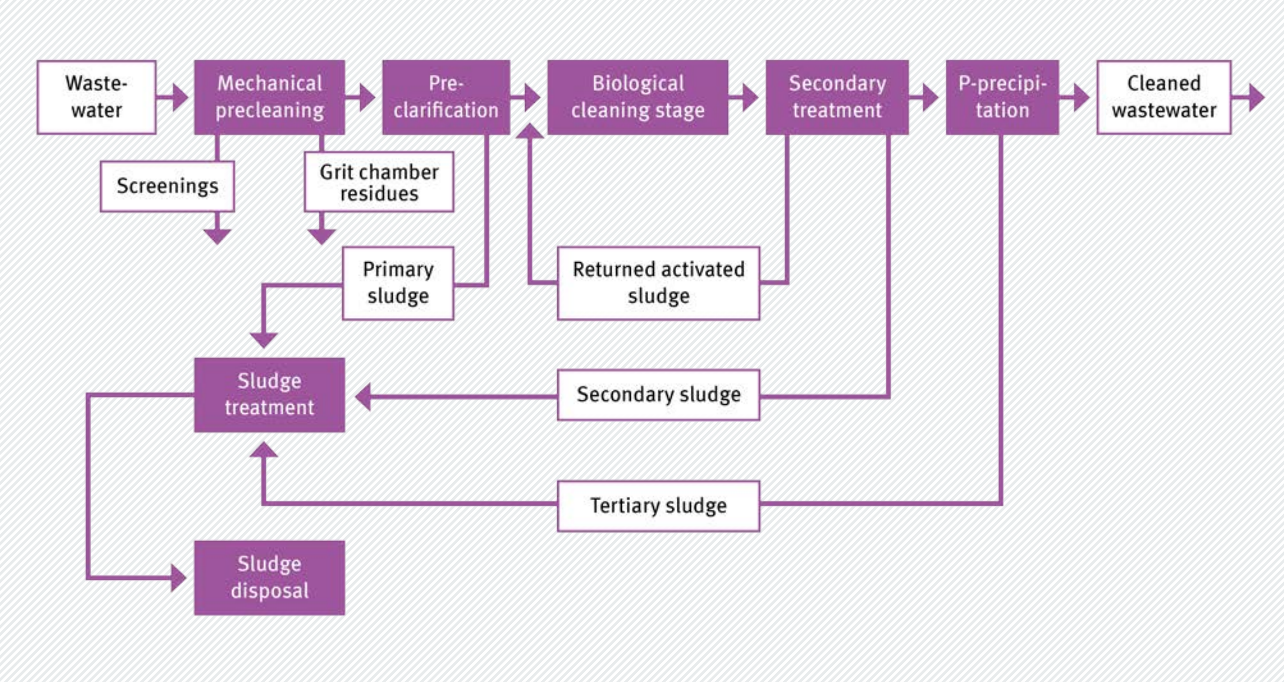
Where does sewage sludge come from?

"Sewage sludge" is an umbrella term that does not distinguish between the origin and type of sludge. Dried or dewatered sludge is equally referred to as sewage sludge in accordance with the Sewage Sludge Ordinance. The different types and composition of raw sludges have special names, depending on where they incur in the sewage treatment plant.

Figure 1 shows the sludge produced in a wastewater treatment plant depending on the cleaning stage.

Figure 1

Sludge production in the wastewater treatment plant depending on the treatment stage



Source: [UBA's ILLUSTRATION]

Primary, secondary and tertiary sludge obtained in any mixture in a wastewater treatment plant is called raw sludge. Raw sludge is untreated sludge before stabilisation (mineralisation of the organic substance using biological-chemical processes before further sewage sludge utilisation).

Primary sludge is produced in the mechanical stage (preclarification) and is thus the result of the physical processes used to separate settleable substances from the wastewater. Its colour ranges from greyish black to greyish brown to yellow. The sludge mainly contains easily recognisable components such as fecal matter, plant residues, toilet paper, etc. After being removed from the system and without any further treatment, it quickly turns into digestion with a correspondingly intense odour.

Sludge stemming from the biological stage called secondary sludge or excess sludge, is produced by microbial growth. This sludge is usually brownish and much more homogeneous than the primary sludge. After being removed from the system, the sludge turns into rot faster than primary sludge.

Sludge stemming from phosphate precipitation in municipal wastewater treatment, i.e. from the cleaning stage (precipitation of dissolved phosphorus by iron or aluminium salts, or else lime or biological phosphorus elimination) is called tertiary sludge.
In a normal treatment plant, precipitation processes are not usually carried out in a separate building but combined with preclarification or biological process in wastewater treatment. For this reason, tertiary slurries do not often occur separately but as a mixture with primary or secondary sludge.

Sludge colour depends on the relevant material reactions. Tertiary sludges clearly differ from primary and secondary sludges purely in their chemical properties. This sludge is usually stable and fails to exhibit a strong odour. Other sludge specifications are digested sludge (sludge that is undergoing or has undergone anaerobic sludge stabilisation, i.e. under air exclusion) or stabilised sludge (all kinds of sludges that have undergone a stabilisation process, be it biological or chemical) [BISCHOFSBERGER et al.

Relevant legislation for sewage sludge disposal

Legal regulations relevant to sewage sludge disposal will be presented in the following. These are essentially acts and ordinances that regulate sewage sludge incineration and its utilisation on soil.

Circular Economy Act (KrWG)

The legal basis for the disposal of waste and also sewage sludge is the Circular Economy Act (Kreislaufwirtschaftsgesetz, KrWG) of 24/02/2012, which entered into force on 01/06/2012 and was last amended on 20/07/2017. The KrWG contains regulations promoting the circular economy and ensuring an environmentally sound waste management.

The aim of the act is to sustainably improve the environment, climate protection and resource efficiency in waste management by strengthening waste avoidance and waste recycling. Therefore, the act stipulates a five-tier hierarchy consisting of avoidance – preparation for reuse – recycling – other utilisation (i.e. energy-related utilisation and backfilling) – elimination (Section 6). Germany is implementing the requirements of the EU Waste Framework Directive (2008/98/EC) [EG] by introducing the five-tier hierarchy. Based on the above ranking, priority should be given to those measures that best guarantee the protection of humans and the environment in waste production and management taking into account the precautionary and sustainability principles. The consideration of impacting on humans and the environment requires the entire life cycle of the waste to be taken into account. In addition, the following aspects must especially be taken into account: expected emissions, degree of conservation of natural resources, the energy to be used or extracted and the accumulation of pollutants in products, in waste for recovery or in products derived therefrom.

Section 11 of the KrWG requires that more detailed provisions on the use of sewage sludge should be regulated by regulations in order to ensure a proper and harmless utilisation. The new Sewage Sludge Ordinance is based on this legal basis (see AbfKlärV).

In addition, voluntary regular quality assurance can be set up to promote the circular economy and ensure the protection of humans and the environment in sewage sludge production and management in terms of Section 12(1) of the Circular Economy Act. Corresponding minimum requirements are specified in the amended AbfKlärV (see AbfKlärV) [KRWG].

Sewage Sludge Ordinance (AbfKlärV) – 2017 amendment

The Sewage Sludge Ordinance (AbfKlärV) is based on the enabling principles of KrWG and regulates sewage sludge management. In addition, the requirements of the Fertiliser Act apply to utilisation on soil (see p. 14 et seqq.). For the first time, a phosphorus recovery obligation for non-recycled sewage sludge or ash from the thermal treatment of sewage sludge has been introduced. The amended Sewage Sludge Ordinance entered into force as the "Ordinance to Reorganise Sewage Sludge Utilisation" on 03/10/2017 entirely replacing the predecessor 1992 ordinance.

Section 1 of the Ordinance regulates the application and introduction of sewage sludge, sewage sludge mixtures and sewage sludge compost on agricultural, agronomical, forestry or horticultural soil. It applies to sewage sludge, sewage sludge mixtures and sewage sludge compost produced in particular by municipal wastewater treatment plants. The ordinance also covers in-house plants that treat wastewater that is comparable to municipal wastewater. An application ban applies to raw sludge and sludge from industrial plants, industrial potato processing plants and most small wastewater treatment plants.

Section 3 of the Ordinance stipulates that sewage sludge producers are obliged to utilise the resulting sewage sludge at as high value as possible and to aim for a recovery of the entrained phosphorus into the economic cycle.

Sections 4 and 5 of the Ordinance regulate the verification obligations of sewage sludge producers. Sample testing, including sampling and sample preparation, must be performed by independent and notified verifiers. Sewage sludge producers must pay for the cost of soil and sewage sludge tests.

Section 4 AbfKlärV specifies tests on the soil on which sewage sludge will be applied before the first application and thereafter at intervals of every ten years. The soil shall be analysed for the following:

- Soil type;
- Heavy metals: lead, cadmium, chromium, copper, nickel, mercury and zinc in accordance with the Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV, Annex 2(4.1);
- pH value;
- Phosphate content;
- Polychlorinated biphenyls and benzo(a)pyrene.

The sewage sludge producer's obligations to investigate sewage sludge are regulated in Section 5 of AbfKlärV. Sewage sludge analyses must always be carried out for each 250t of total solids (TS) (4-12 analyses/year), sewage sludge compost and sewage sludge mixtures must be analysed for each started 500t DM (maximum 12 analyses/year). The analyses shall include:

1. Arsenic, lead, cadmium, chromium, chromium (VI), copper, nickel, mercury, thallium and zinc contents;
2. Sum of organic halogen compounds as organically bound adsorbed halogens;
3. Total nitrogen content and ammonium content;
4. Phosphorus content;
5. Dry residue;
6. Organic substance;
7. Total basic active substances evaluated in terms of calcium oxide;
8. Iron content;
9. pH value.

In addition, sewage sludge, sewage sludge mixtures and sewage sludge compost must be tested for the following contents before discharge and at least every two years:

1. Polychlorinated biphenyls;
2. Polychlorinated dibenzodioxins and dibenzofurans including dioxin-like polychlorinated biphenyls;
3. Benzo(a)pyrene;
4. Polyfluorinated compounds including the individual substances perfluorooctanoic acid and perfluorooctanesulfonic acid.

According to § 7 of the Sewage Sludge Ordinance, sludge, sewage sludge mixtures or sewage sludge compost are only allowed to be applied on or introduced into the soil if the soil tests show that the BBodSchV precautionary values are not exceeded (BBodSchV No. 4.3, Annex 2). Discharge and utilisation of sewage sludge on soil is only permitted if the limiting values of the Sewage Sludge Ordinance (Appendix 1) and the Fertiliser Ordinance (DüMV, Appendix 2, Table 1.4, Column 4; or Appendix 1, Section 4.1, Column 6(2) for copper) are complied with. A summary of the limiting values can be found in Chapter 5, Table 11.

Furthermore, the requirements for disease and phytohygiene in accordance with the Fertiliser Ordinance (DüMV) must be complied with. The requirements fail to be met if salmonellae have been found in 50 g of sewage sludge, or other resistant harmful organisms are contained (DüMV, Section 5(1-3)).

The application or inclusion of sewage sludge, sewage sludge mixtures or sewage sludge compost is not permitted if soils are used on:

1. Grassland and permanent grassland;
2. Arable forage area;
3. Arable land for maize other than for grain use and for biogas production, provided that no sewage sludge has been included before sowing;

4. Arable land for sugar beet provided that beetroot leaves are to be fed and no sewage sludge has been applied or added to the land prior to sowing during the year of production;

5. Arable land for vegetables, fruits or hops;

6. Home, utility or small gardens or

7. For forestry purposes.

If arable land is used for the cultivation of field vegetables, fertilisation by sewage sludge, sewage sludge mixtures or sewage sludge compost is only permitted if a minimum interval of 24 months is observed between the last application or introduction and the next cultivation of field vegetables.

In addition, the use of sewage sludge is not allowed on:

1. water protection zones I, II and III and

2. nature reserves, national parks, national natural monuments, natural monuments, protected landscapes and protected biotopes.

The amount of sewage sludge applied must not exceed 5t DM per hectare within three years according to Section 14. Sewage sludge may be applied once on agricultural soils up to a quantity of 10 t/ha. Slightly different quantities apply to sewage sludge mixtures and sewage sludge composts (see AbfKlärV).

Sewage sludge from various wastewater treatment plants may only be mixed under certain conditions in accordance with Section 15, e. g. if they stem from the same sewage sludge producer's plants (see AbfKlärV).

The mixing of sewage sludge with dung (e. g. manure, see DüMV Appendix 2, Tables 7 and 8) is permitted. However, only so much of the mixture may be applied that the sewage sludge content does not exceed 5t DM in three years (see AbfKlärV). If sewage sludge is arranged in manure pits, the manure-sewage sludge mixture, like all other mixtures with sewage sludge, is subject to the Sewage Sludge Ordinance with all restrictions and verification obligations. It is not permitted to apply the mixture to grassland and other previously mentioned areas with an application ban on sewage sludge (see AbfKlärV).

For sewage sludge utilisation, a notification and delivery note procedure must be followed which is regulated in Sections 16-18 of the Sewage Sludge Ordinance.

Adjustments have been made in the amended regulation. The user must confirm the quantity applied in the delivery note. One copy of the delivery note should be sent to sewage sludge users, hauliers, quality markers if required (for quality-assured sewage sludge) and producers of sewage sludge mixtures or composts and the responsible authorities. The original remains with the wastewater treatment plant operator and must be kept by him for 12 years. The planned sewage sludge application must be reported in advance to the responsible authority and the sewage sludge producer.

Furthermore, the amended Sewage Sludge Ordinance pursuant to Section 12 of the KrWG introduces a system for voluntary quality assurance. This implies that quality assurance can be carried out by external quality assurance agencies. Quality assurance as regulated in Sections 20-31 facilitates the utilisation of quality assured sewage sludge, sewage sludge mixtures and sewage sludge compost (scope of investigation reduced, submission requirements for tests relaxed, sewage sludge mixing facilitated, exemption from the delivery note possible) (see Chapter 5).

Specifications for phosphorus recovery
As a central element, the amended Sewage Sludge Ordinance provides the first time comprehensive specifications for phosphorus recovery from sewage sludge or sewage sludge incineration ash or carbonaceous residues. These have to be observed by sewage treatment plant or incinerator operators where sewage sludge is incinerated after a two-stage transitional period. Phosphorus recovery obligation applies on 01/01/2029, about 12 years after the ordinance's entry into force for wastewater treatment plants with an approved expansion size of more than 100,000 population equivalents (PE). Systems with a capacity of more than 50,000 PE must also comply with the new regulations about 15 years after entry into force, i.e. on 01/01/2032. Wastewater treatment plants smaller than 50,000 PE can take technical phosphorus recovery measures voluntarily. From 2023 on, sewage sludge must be tested for its phosphorus content. In addition, the operators are required to submit a report on the planned and initiated measures to ensure

phosphorus recovery for utilisation on soil and for other sewage sludge disposal in terms of the KrWG. Figures 2 and 3 show the future phosphorus recovery obligations and possible recovery methods.

Article 5 of the new AbfKlärV regulates the requirements for phosphorus recovery from sewage sludge or the ash from sewage sludge thermal pre-treatment. According to this, sewage sludge must undergo phosphorus recovery (according to Article 5 Section 3(1)(1) AbfKlärV) if the phosphorus content in the sewage sludge is ≥ 20 g/kg total solids matter (TS) or ≥ 2 %.

Alternatively, thermal pre-treatment is possible in sewage sludge mono-incineration plants or certain sewage sludge co-incineration plants with subsequent phosphorus recovery. In this case, the sewage sludge incineration ash produced or the carbonaceous residue must be subject to phosphorus recovery or recycling. The term sewage sludge co-incineration includes processes such as mono-incineration, co-incineration (coal or gas firing) or sub-stoichiometric processes such as pyrolysis and gasification.

Plants that only treat sewage sludge with a phosphorus content of < 20 g/kg TS thermally are exempted from the recovery obligation.

Pursuant to Section 3a(1), sewage sludge phosphorus recovery processes shall be applied to treatment plants to ensure a phosphorus content reduction of at least 50 % (based on sewage sludge TS) or to below 20 g/kg TS. Sludges with phosphorus content of at least 20 g/kg TS may only be mixed. Processes ensuring at least 80 % recovery of the phosphorus contained shall be used for phosphorus recovery from sewage sludge incineration ash or carbonaceous residues (Section 3b). It is also stipulated that co-incineration of sewage sludge with a phosphorous content ≥ 20 g/kg may only be carried out in coal or gas fired combustion plants. The Ordinance also permits long-term storage of incinerator ash or carbonaceous residues in landfills (preferably in mono sections), if they are prevented from being mixed with other substances or waste or from surface runoff and if subsequent phosphorus recovery or use is guaranteed.

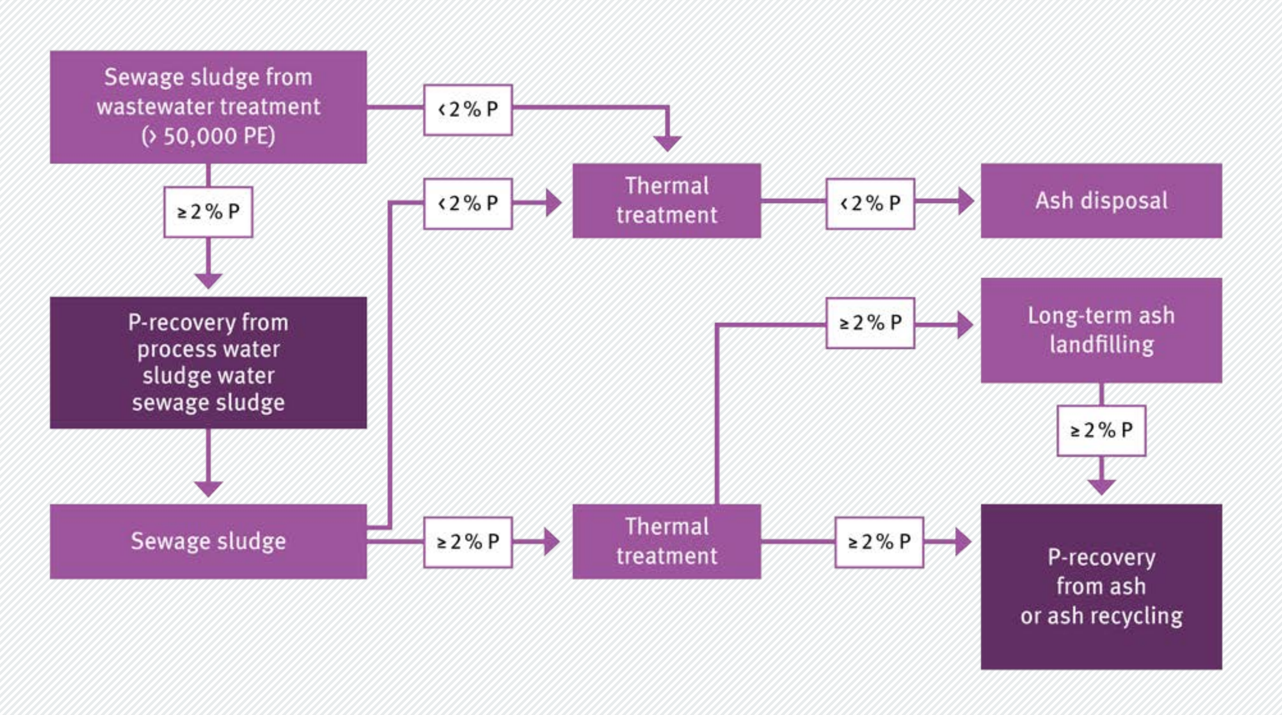
Figure 2

Future obligations for phosphorus recovery in accordance with the amended Sewage Sludge Ordinance

Wastewater treatment plants	Expansion size ≤ 50.000 EW	Expansion size › 50.000 ≤ 100.000 EW	Expansion size › 100.000 EW
Current	Utilisation on soil feasible	Utilisation on soil feasible	Utilisation on soil feasible
In 2023	Reporting obligation for planned P-recovery measures, for utilisation on soil or other disposal Obligation to investigate P-content (and basic substances)		
From 01/01/ 2029 (Transition period approx. 12 years from the entry into force-of the AbfKlärV)	Utilisation on soil feasible Exempt from P-recovery obligation (≥ 2 % P)	Utilisation on soil feasible Exempt from P-recovery obligation (≥ 2 % P)	Utilisation on soil not permitted P-recovery obligation (≥ 2 % P)
From 01/01/2032 (Transition period approx. 15 years from the entry into force of the AbfKlärV)	Utilisation on soil feasible P-recovery obligation (≥ 2 % P)	Utilisation on soil not permitted P-recovery obligation (≥ 2 % P)	Utilisation on soil not permitted P-recovery obligation (≥ 2 % P)

Figure 3

Potential future disposal and utilisation methods for sewage sludge from wastewater treatment plants over 50.000 PE (from 2032)



Source: [ABFKLÄRV]

EU Sewage Sludge Directive

The purpose of Directive 86/278/EEC of 12/06/1986 on the protection of the environment and in particular of soils when using sewage sludge in agriculture is to regulate sewage sludge landfilling in the EU to the extent that harmful substances are prevented from having an impact on soil, vegetation, humans and animals while at the same time encouraging the proper use of sludge [EEC 86]. It is stated that Member States may adopt more stringent provisions than those provided for in the Directive.

The Directive sets limiting values for heavy metals in sludges and soils and for the quantities of heavy metals that may be applied to the soil annually. The use of sewage sludge is prohibited if the concentration of one or more heavy metals exceeds the specified limits. The Directive also specifies additional parameters to be analysed and regulates the minimum intervals at which sewage sludge should be checked.

Before being used in agriculture, the sludge must be treated. However, Member States may also allow the use of untreated sludge when it is applied to or buried in the soil.

The Directive also includes some restrictions for application. For example, no sewage sludge may be applied to fruit and vegetable crops during the growing season or on pastures or forage crops before the expiry of a certain period.

The Directive also stipulates that EU Member States must submit a report on the correct national implementation of the Sewage Sludge Directive every 3 years. The quantity of sludge produced, the amount used in agriculture and the composition of the sludge must be reported (91/692/EEC) [EEC 91].

HELCOM Recommendation

HELCOM's "Recommendation 38/1 on sewage sludge handling" was adopted in March 2017. HELCOM is an intergovernmental commission set up by the Baltic Sea riparian countries that promotes recommendations for the protection of the marine environment in the Baltic Sea area. The sludge treatment recommendations include:

- Sustainable agricultural or energy-related use of sewage sludge
- Avoiding sewage sludge landfilling
- Targeted recycling of the entrained nutrients, phosphorus in particular.
- Reducing inputs of environmentally hazardous and pathogenic substances into the environment via sewage sludge utilisation
- Presentation of sewage sludge treatment measures including phosphorus recovery
- Recommendations on restrictions of application in agriculture
- Suggestions for the further development of cost-effective solutions and knowledge exchange in the region

The contracting states to the Convention will have to report regularly on the handling of sewage sludge, its quality and on phosphorus recovery in the course of the recommendations [HELCOM].

Fertiliser Legislation

Relevant fertiliser regulations are contained in the Fertiliser Act (DüngG), the Fertiliser Application Ordinance (DüV) and the Fertiliser Ordinance (DüMV). The fertiliser legislation was last revised in 2017. The main contents relating to the use of sewage sludge are briefly outlined below.

Fertiliser Act (DüngG)

The Fertiliser Act was amended on 15/05/2017 and it especially regulates the requirements for marketing and use of fertilisers, soil amendments, plant auxiliaries and culture substrates. The purpose of this law is to ensure the nutrition of crops, to maintain or improve soil fertility and to prevent or avert hazards to humans and animals caused by fertilisers and other substrates within the meaning of this Act. With regard to sewage sludge utilisation, a sewage sludge compensation fund was set up (see Section 11). The intention being to provide compensation for damage to people and property resulting from the consequences of proper agricultural utilisation of sewage sludge. Contributions to this fund are payable by the manufacturers or owners of sewage sludge provided they use agricultural utilisation as a disposal option. The obligation to pay contributions was suspended on 01/01/2007 since the financial resources of the Fund reached the maximum amount stipulated.

The Fertiliser Act also calls for ensuring a sustainable and resource-efficient use of nutrients in agricultural production. In particular, nutrient losses to the environment should be avoided as much as possible. Fertilisation may only be carried out using good professional practice which must be organised according to the requirements of the plants and to the nutrient content of the soil in terms of type, amount and time of application (see Section 3 (2)) [DÜNGG].

Fertiliser Application Ordinance (DüV)

The new Fertiliser Application Ordinance entered into force on 02/06/2017 and it specifies the requirements for good professional practice in the application of fertilisers and regulates their application on agricultural land. The Regulation includes restrictions on the application of nitrogen and phosphate fertilisers depending on location and soil conditions, regulates suspension times for fertiliser application and makes provisions for the storage of organic fertilisers.

The fertiliser requirement (Sections 3 and 4) must be determined before the application of essential amounts of nitrogen or phosphate nutrients (i.e. more than 50kg of nitrogen or 30kg of phosphate per hectare (ha) and year) using fertilisers and other substrates in the sense of this Act. The maximum fertiliser amount must not exceed the phosphate discharge for soils with a phosphate content of more than 20 mg

P2O5 per 100g soil (CAL method, other methods quoted). The anticipated P discharge may be considered within a crop rotation (maximum 3 years).

The following must be taken into account: the fertiliser's nutrient content, the crop's nutrient requirements for the yields and qualities expected under the relevant site and growth conditions, the nutrient amount available in the soil and the nutrient supply from the soil stock (for nitrogen). The available nitrogen quantities shall be determined on each plot for the time of fertilisation (at least annually) by soil analysis or by using the competent authority's advice. For phosphorus, the nutrient quantities must be determined based on representative soil samples to be taken at least once every six years for each plot of one hectare or more, usually within a crop rotation [DÜV].

Furthermore, special requirements must be observed for the application of nitrogen or phosphate containing fertilisers (Section 5). These may include a ban on application when the soil is flooded, water saturated, frozen or covered by snow. Distances and restrictions on application near surface waters and off-road terrain are also given.

Fertilisers with a significant nitrogen content including sewage sludge must not be applied to arable land from the time when the harvest of the last major fruit is completed to 31 January in the following year (exception are

catch crops, winter rape, field forage and winter barley following cereals preceding a crop). These fertilisers may also not be used on grassland, permanent grassland or on arable land with perennial field crops sown before 15th May in the period from 1st November to 31st January (Section 6).

Nutrient comparison to be carried out according to the Ordinance (Section 8) includes an assessment for nitrogen and phosphate supply and discharge in the elapsed fertilisation year. The control values for the difference between supply and discharge in the nutrient comparison will decrease in the future. According to the Ordinance, only 50 kg of nitrogen per hectare will be allowed in the 3-year average from 2020 and only 10 kg of phosphate per hectare over a 6-year average from 2023.

The Regulation requires the states (Länder) to adopt at least three additional appropriate measures from a given catalogue of 14 measures in areas of high nitrate pollution and in areas where surface waters are eutrophicated by phosphate from agriculture.

Potential further rules for the use of phosphate in polluted areas are the limitation of the permitted quantity of phosphate fertiliser for phosphate discharge (= negative phosphate balance); the ban on the application of phosphate-containing fertilisers or the extension of the retention period for the application of phosphate-containing fertilisers in eutrophicated areas from 15th November to 1st February (extension of four weeks possible). However, the control value may be reduced to 40 kg of nitrogen per hectare for areas with high nitrate pollution.

Fertiliser Ordinance (DüMV)

The Fertiliser Ordinance of 09/01/2009, last amended on 26/05/2017, regulates the marketing of fertilisers that are not designated as EC fertilisers and soil additives, culture substrates and plant auxiliaries. Sewage sludge belongs to organic or organomineral fertilisers according to the DüMV and is admitted as a main component for fertilisers. Sewage sludge incineration ash and various recycled materials from phosphorus recovery (phosphate precipitation, melt gasification) are also identified as phosphate fertilisers by the Ordinance (DüMV, Appendix 2, Table 6) [DÜMV].

In addition to the Sewage Sludge Ordinance, sewage sludge must comply with the limiting values according to Appendix 2 Table 1.4 of the DüMV. Also, sewage sludge may only be discharged if the specifications in Appendix 2, Table 7, line 7.4.3 are complied with (see Chapter 5, Table 11).

The Ordinance also regulates the requirements for disease and phytohygiene (Section 5) for sewage sludge. A specific limit is only given for salmonellae (see DüMV, cf. Chapter 2).

In the case of organic fertilisers such as sewage sludge, the content of available nitrogen in addition to total nitrogen content must also be labelled in the future (DüMV, Section 6(1)(4)).

Unrestricted discharge of sewage sludge with synthetic polymers used as flocculants for sewage sludge dewatering is only possible until 31/12/2018 according to the current Ordinance (Section 10). A decomposition rate of 20 % within 2 years (not exceeding a polymer load of maximum 45 kg of active substance per hectare over 3 years) is stipulated from 01/01/2019. In accordance with Section 9a of the Ordinance, the requirements for synthetic polymers will be reviewed by 31/12/2019 taking into account the latest scientific findings.

EU Fertiliser Legislation

Currently, the European Fertiliser Legislation is being revised which will also regulate novel fertilisers from recovery products. It is becoming apparent that the aim is to facilitate easy approval for these products. Sewage sludge is not yet provided for in the regulatory area of the Regulation. The EU Fertiliser Legislation is not expected to be adopted before 2019.

17th Federal Immission Control Ordinance (17. BImSchV)

The 17th Ordinance for the Implementation of the Federal Immission Control Act (17. BImSchV) of 02/05/2013 applies to the construction, nature and operation of incineration or co-incineration plants where waste is used. The Ordinance also applies to plants that (co-) incinerate sewage sludge.

To limit emissions, limits are set for total dust, sulphur oxides, halogens, nitrogen oxides, mercury, carbon monoxide, organic compounds and heavy metals.

The Ordinance contains requirements that must be met when building and operating the facilities. These include:

- Preventing harmful environmental impacts caused by air pollution
- Combating fire hazards
- Treatment of waste and
- Use of the resulting heat.

The essential requirements of the Ordinance are to ensure an afterburning temperature of 850 °C for two seconds (after the last combustion air supply) to reduce the organic matter content in incineration ash to below 3 % TOC or 5 % ignition loss and to oblige the operator to monitor the emission levels (mostly continuously) and transmit them to the competent authority [17. BImSchV].

Technical Instructions on Air Quality Control (TA Luft)

The Technical Instructions on Air Quality Control (TA Luft) is the first general administrative provision to the Federal Immission Control Act. It contains immission and emission requirements for air pollutants from commercial and industrial plants that require approval in accordance with the Ordinance on Installations Subject to Approval (4. BImSchV). With regard to sewage sludge treatment, TA Luft is particularly relevant for installations drying sewage sludge (cf. 5.4.8.10.2 TA Luft).

Accordingly, sewage sludge drying plants must be operated in such a way that waste gases produced during drying can be collected directly at the point of origin and fed to an exhaust gas purification device. Emission levels for ammonia, total dust, gaseous inorganic chlorine compounds, organic substances (expressed in terms of total carbon) and odorous substances (500 GE/m³ waste gas) must be observed.

Landfill Ordinance (DepV)

The Landfill Ordinance (DepV) of 27/04/2009, last amended by the new version of the AbfKlärV on 27/09/2017, regulates the construction, operation, decommissioning and aftercare of landfills. In accordance with the hazardous nature of the waste, this Ordinance specifies five landfill classes (LC) with different properties [DEPV]:

- **LC 0 – Inert waste landfill**
  (almost zero contaminated mineral waste)
- **DK I – Non-hazardous waste landfill**
  (very low contaminated mineral waste with a very low organic content)
- **LC II – Non-hazardous waste landfill**
  (low contaminated mineral waste with low organic content)
- **LC III – Hazardous waste landfill**
- **LC IV – Underground landfill**

The classification of the relevant waste in the appropriate landfill class is determined using a ‘declaration analysis’.

The different characteristics in particular relate to the structure of the basal liner and landfill cap, measuring equipment for emission monitoring, the drainage system and the leachate cleaning system up to the compulsory construction of a liner control system for DK III. Further key points of the Ordinance are regulations for the decommissioning and aftercare of the waste body.

In Germany, in principle it has been inadmissible to dispose of waste with an organic carbon content (determined as TOC – Total Organic Carbon) exceeding 1 % by mass in Class 0 and I, 3 % by mass in Class II and 6 % by mass in Class III landfills since 2005, therefore household waste and sewage sludge must be pre-treated mechanically-biologically or thermally before being landfilled. Annex 3 of the DepV describes permissible exceedances of these TOC limiting values. For example, TOC must not exceed 18 % by mass after mechanical-biological treatment. The competent authority may give its consent to disposal, even if this limit is exceeded indefinitely, when the excess is due to elemental carbon Section 23 applies to the long-term storage of ash or carbonaceous solid residues stemming from thermal sewage sludge treatment. Here an option was created to temporarily store such residues for a maximum of five years – even without written evidence of the subsequent proper and harmless recovery or community friendly disposal for subsequent phosphorus recovery purposes. The time limit can be extended on request. According to Appendix 2 of the KrWG, this storage is classified as an R 13 process meaning a recovery process. The previous utilisation option of sewage sludge incineration ash for underground stowage where the phosphorus has been irretrievably lost in the ash, is now replaced by a recovery process where phosphorus can later be recovered.

02

Composition of sewage sludge

- Heavy metals in sewage sludge
- Organic compounds in sewage sludge
- Organic compounds in sewage sludge using the EHEC example
- Pharmaceutical residues in sewage sludge
- Nanomaterials in sewage sludge
- Plastics in sewage sludge

Sewage sludge can be referred to as a multi-substance mixture. Its inhomogeneity and widely varying proportions of its constituents make it difficult to define a uniform standard composition of sewage sludge.

Sewage sludge mainly consists of organic substances. The sewage sludge (i.e. stabilised primary, secondary and tertiary sludge, which is produced as a mixture at the end of the clarification chain, see Chapter 1) contains plant nutrients such as nitrogen and phosphorus, and organic substances of concern (e. g. drug residues), heavy metals, pathogenic organisms and various anthropogenic micro- and nano-scale components.

The following Table 2 contains characteristics for characterisation of municipal sewage sludge. The data is based on a German Association for Water, Wastewater and Waste (DWA) publication [DWA 387]. Further figures provided by a study by the Austrian Federal Environment Agency [OLIVA et al.], have been added to the table for completion.

Table 2

Sewage sludge composition according to [DWA 387] and [OLIVA et al.]

Material	Unit	Value range according to DWA
pH value	–	7.7*
Total solids content (TS)	% by weight	30,5*
Ignition loss (IL)	%	45–80**
Water	% by weight (raw)	65–75
Ash	% by weight (raw)	30–50
Volatile components	% by weight (raw)	30
Volatile components	% by weight (wf)	40–65
Net calorific value (NCV)	MJ/kg (raw)	1–2/10–12***
Carbon (C) total	% by weight (waf)	33–50
Oxygen (O) total	% by weight (waf)	10–20
Hydrogen (H) total	% by weight (waf)	3–4
Nitrogen (N)	% by weight (waf)	2–6
Sulphur (S) organic	% by weight (waf)	0.5–1.5
Fluorine (F)	% by weight (raw)	approx. 0.01
Chlorine (Cl)	% by weight (raw)	0.05–0.5
Phosphorus (P)	g/kg (raw)	2–55
Antimony (Sb)	mg/kg (raw)	5–30
Arsenic (As)	mg/kg (raw)	4–30
Lead (Pb)	mg/kg (raw)	70–100
Cadmium (Cd)	mg/kg (raw)	1.5–4.5

Material	Unit	Value range according to DWA
Chromium (Cr)	mg/kg (raw)	50–80
Copper (Cu)	mg/kg (raw)	300–350
Manganese (Mn)	mg/kg (raw)	600–1,500
Nickel (Ni)	mg/kg (raw)	30–35
Selenium (Se)	mg/kg (raw)	1–5
Thallium (Th)	mg/kg (raw)	0.2–0.5
Vanadium (V)	mg/kg (raw)	10–100
Mercury (Hg)	mg/kg (raw)	0.3–2.5
Zinc (Zn)	mg/kg (raw)	100–300
Tin (Sn)	mg/kg (raw)	30–80
AOX	mg/kg DS	200–400****
PCDD/F	ng/kg TE	5–100****
PCB6	mg/kg DS	0.01–0.02****
PAH	mg/kg DS	1–50***
Molybdenum (Mo)	g/kg DS	3.9*
Cobalt (Co)	g/kg DS	6.53*
Calcium (Ca)	g/kg DS	71*
Potassium (K)	g/kg DS	2.63*
Magnesium (Mg)	g/kg DS	9.17*

Notes: raw = reference to original substance in delivery condition; waf = water and ash free; wf = water free
* Figures stem from [OLIVA et al.]; Median, according to [BOUBELA et al.]
** Figures stem from [OLIVA et al.]; according to [IWA – TU Wien]
*** Figures for dry sludge › 85 % DS
**** Figures for European sewage sludge stem from [OLIVA et al.]; according to [FÜHRACKER/BURSCH]

SOURCES: [DWA 387] AND [OLIVA ET AL.]

Heavy metals in sewage sludge

The main source of heavy metals in municipal sewage sludge is the discharge from households and industry. However, heavy metals also reach wastewater via rainwater from artificial surfaces. For example, lead, cadmium, copper and zinc enter the wastewater and thus the sewage sludge via building surfaces, pipes, brake linings or power lines [OLIVA et al.].

Table 3 shows the average concentrations of heavy metals in agriculturally used sewage sludge in Germany and their trend over recent years. It lists the heavy metals controlled by the Sewage Sludge Ordinance or the fertiliser legislation in mg/kg of total solids.

Table 3

Concentrations of seven heavy metals as well as nitrogen and phosphorus in agriculturally used sewage sludge in Germany between 1977 and 2015 [BMUB]

mg/kg DS	Pb	Cd	Cr	Cu	Ni	Hg	Zn	N total	P total
1977	220	21	630	378	131	4.8	2,140	N/A	N/A
1982	190	4.1	80	370	48	2.3	1,480	N/A	N/A
1986–1990	113	2.5	62	322	34	2.3	1,045	N/A	N/A
1998	63	1.4	49	289	27	1	835	N/A	N/A
2001	53	1.2	45	304	27	0,8	794	39,357	27,337
2002	50	1.1	45	306	27	0,7	750	38,846	22,019
2003	48	1.1	42	305	27	0,7	746	40,328	22,559
2004	44.3	1.02	40.7	306.3	25.8	0.62	756.7	42,025	23,581
2005	40.4	0.97	37.1	306.4	25.2	0.59	738.2	42,457	24,312
2006	37.2	0.96	36.7	300.4	24.9	0.59	713.5	43,943	24,531
2007	40.7	0.97	34.9	307.3	26.6	0.59	752.9	44,369	23,675
2008	38.5	0.96	33.6	297.4	25.4	0.54	744.1	44,167	23,591
2009	37.2	0.96	32.8	295.8	24.8	0.52	758.4	44,732	23,993
2010	37.5	0.96	33.2	304.7	25.2	0.53	774	45,943	23,758
2011	34.9	0.98	34	292.3	25.6	0.49	768.3	44,538	23,627
2012	33.4	1	32.6	305.3	25.1	0.5	763.5	46,046	26,727
2013	33.3	0.94	32.9	308.6	25.5	0.48	769.8	44,405	25,200
2014	32	0.87	33.8	307.3	26	0.47	799.7	45,247	25,546
2015	30.6	0.74	32.6	293.6	24.7	0.39	772.8	43,796	24,576
Modification of 1977 (=100) to 2015	-86.07	-96.49	-94.83	-22.34	-81.15	-91.83	-63.89	N/A	N/A
Modification of 2001 (=100) to 2015	-42.18	-38.54	-27.55	-3.43	-8.54	-50.99	-2.67	11.3	-10.1

Source: [BMUB]

Table 3 shows that the contemporary heavy metal concentrations of lead, cadmium, chromium, copper, nickel, mercury and zinc have decreased significantly compared to 1977 and are currently a magnitude lower than their original concentration. In each case, the most striking decrease in concentration can be observed in the period up to 2001.

It is noticeable that the phosphorus content has decreased by about 10 % since 2001, while the nitrogen content increased by about 11 % over the same period. Furthermore, it can be seen that the zinc concentration has been increasing since 2006 and is currently back to the 2001 level, which may be due to a steady increase in the use of zinc-containing materials in industry and technology (e. g. gutters and roofing).

The concentrations of the heavy metals copper and nickel have changed insignificantly over the last 15 years and fluctuate at around 300 mg (copper) and 25 mg/kg DS (nickel). The decrease of mercury and cadmium in Germany is mainly explained by a reduction in their use in different products and by the use of amalgam separators in dental practices. The European Commission's mercury strategy aims to further limit the use of mercury. The graphs showing the concentration trend of cadmium, copper, zinc, nickel, chromium, mercury and lead in agriculturally used sewage sludge are shown in Annex II.

Organic compounds in sewage sludge

The dry weight of organic materials in sewage sludge may be about 45–90 %. This consists largely of bacterial mass and is composed mainly of the elements carbon, hydrogen, oxygen, nitrogen and sulphur (see Table 2). Due to a large number of organic pollutants, sewage sludge also contains impurities. In addition to the polychlorinated dibenzodioxins and furans (PCDD/F), the most critical substances include halogen compounds and organotin compounds. Perfluorinated surfactants (PFSs), polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) are also found in sewage sludge. These organics often come from a variety of household and industrial sources, including cleaning and personal care products. Other anthropogenic (i.e. man-made) sources are chemicals used in the home such as wood preservatives, surface coatings, biocides in construction products and pharmaceuticals.

Table 4 shows the results of a study from 2006 across North Rhine-Westphalia for determining the contamination of sewage sludge with organic pollutants.

It can be said that the specified pollutants and their concentrations are mainly determined by the catchment areas or the connected households and industries [OLIVA et al.].

Table 4

Concentrations of organic compounds in sewage sludge from North Rhine-Westphalia

Substance group	Organic pollutants	Average in [mg/kg DS]	90th percentile in [mg/kg DS]
Chlorophenols	Triclosan	3.4	5.5
Organotin compounds	Dibutyltin	0.22	0.35
	Dioctyltin	0.056	0.05
	Monobutyltin	0.17	0.32
	Monooctyltin	0.031	0.043
	Tetrabutyltin	0.0067	0.0025
	Tributylzinn	0.033	0.065
Polychlorinated dibenzodioxins and furans	PCDD/F I-TEQ	14 ng TE kg DR	22 ng TE kg DR
Polybrominated diphenyl	Tetrabromodiphenylether	0.026	0.037
	Pentabromodiphenylether	0.048	0.063
	Hexabromodiphenylether	0.011	0.011
	Heptabromodiphenylether	0.013	0.0058
PAH	Decabromodiphenylether	0.57	1.06
	Benzo(a)pyrene	0.47	0.73
	Chrysene	0.64	1.11
	PAH EPA (without acenaphthylene)	6.64	9.52
Polychlorinated biphenyls	PCB6 sum	0.091	0.17
Phthalates	DEHP	27.5	57.5
	Dibutyl phthalate	0.55	1
Surfactants	LAS	1,723	4,000
	Nonylphenol	21.5	44.2

Source: [FRAGEMANN/BAROWSKI]

Pathogens and hygiene requirements

Pathogens such as bacteria, viruses, parasites and worm eggs are also eliminated from wastewater through sewage sludge. If the sludge is used in agriculture, it cannot be ruled out that pathogens may reach humans and animals via food and feed and thus endanger them [GUJER].

For some years, this potential threat has increasingly been the subject of discussion regarding the possible transfer of pathogens to humans as a result of the utilisation of sewage sludge and other organic materials on agricultural land. The EHEC epidemic in May and June 2011, triggered by the EHEC pathogen O104:H4, brought the importance of such a risk assessment to the public attention. In order to evaluate the possible risks in this context, two criteria must be fulfilled. Firstly, the survivability of the pathogens must be known and, secondly, the probability of human and animal exposure to sewage sludge must be ascertained. The greatest survivors among pathogens are bacteria that can form spores (e. g. clostridia) or parasites that can form permanent stages or spores (e. g. giardia and cryptosporidia), as well as worm eggs. Bacteria that do not form spores usually survive only a few weeks or months.

The survivability of the EHEC pathogen O104:H4 in the environment is still poorly understood. Since the epidemic strain possesses the properties of two pathogenic (disease-causing) E. coli types (EHEC and EAggEC), the risk assessment can currently only rely on the properties of these pathogenic E. coli and of apathogenic E. coli. Since EAggEC bacteria tend to flocculate the bacterial cells and form biofilms, the E. coli epidemiological strain O104:H4 could also persist as biofilms in the environment. In addition, the EHEC strain O157:H7 was able to persist for many months in various soils and can survive under a variety of experimental conditions. Therefore, it can be assumed that the epidemic strain in the soil may also survive for several months.

Experts are discussing the spread of resistant bacteria and bacterial resistance genes into the environment in connection with current hygienic questions [UBA 97]. There are indications that wastewater treatment plants may facilitate the exchange of antibiotic resistance between different bacteria since high cell densities, sufficient nutrient levels and selection pressure through micropollutants provide ideal conditions for the adaptation of bacteria through horizontal gene transfer processes. This enables the creation of new combinations of antibiotic resistance or the transfer of antibiotic resistance to bacteria that previously had no resistance. Resistant bacteria can continue to spread through the wastewater system or sewage sludge into the environment. Sewage sludge use on soil can directly transfer these resistances to the soil. In addition, EIBISCH describes that the continuous input of antibiotics into soils over extended periods of time may lead to increased concentrations. This gives antibiotic-resistant bacteria growth advantages, which means that there is the possibility of genetically transferring their resistance genes.

Since various pathogens have a high survivability, risk minimisation must ensure that humans and animals do not come into contact with them. In order to minimise possible risks, the fertiliser legislation and Sewage Sludge Ordinance regulate the requirements for the application of sewage sludge on soil.

Thus, Section 5 of the Fertiliser Ordinance sets out certain disease and phytohygienic requirements that must also be complied with in a planned sewage sludge utilisation. The requirements regarding the epidemic hygiene properties are not met if salmonellae are found in 50g of sample material. Regarding phytohygienic properties, sewage sludge application is prohibited if resistant harmful organisms (particularly harmful organisms under Directive 2000/29/EC), thermoresistant viruses (particularly from the tobamovirus group) or fungal pathogens with resistant permanent organs (particularly synchytrium endobioticum, sclerotinia species, rhizoctonia solani, plasmodiophora brassicae) are found and the sewage sludge has not been subjected to a suitable cleansing treatment (see Fertiliser Ordinance (DüMV), Chapter 1).

In addition to these provisions regarding fertilisers, the Sewage Sludge Ordinance standardises restrictive regulations for the application of sewage sludge. For example, application restrictions are laid down in Section 15 of the Sewage Sludge Ordinance. Sewage sludge must not be applied to vegetable and fruit growing areas nor to permanent grassland.

In addition, there are restrictions on arable land used for the cultivation of maize or sugar beet. Furthermore, sewage sludge utilisation is prohibited in water protection zones I to III and in nature reserves (see AbfKlärV, Chapter 1). Experts assume that the existing regulations are sufficient to prevent the spread of EHEC and other pathogens into the food chain, groundwater and surface waters through soil-based sewage sludge utilisation – provided that the sewage sludge is applied as intended. However, this requires a complete monitoring of its disposal. The relevance of sewage sludge application on soil should be further investigated, particularly in view of the increasing problems in the treatment of bacterial infections through the occurrence of multi-resistant bacteria, and it should be clarified whether the current hygiene measures (the Fertiliser Ordinance's requirements, restrictions on application and insertion) will be sufficient in the future.

Pharmaceutical residues in sewage sludge

The spectrum of authorised active pharmaceutical ingredients is large. On the German market alone, around 2,300 different medicines are currently available for the human medicinal sector, of which around half are considered potentially environmentally relevant. Substances such as traditional herbal medicines, electrolytes, vitamins, peptides, amino acids as well as many naturally occurring substances in the environment such as minerals are not environmentally relevant because they are generally non-toxic or very rapidly degradable. A total of 8,120 tonnes were consumed in Germany in 2012 [IMS] of the approximately 1,200 human pharmaceutical substances with potential environmental relevance. This is an increase of more than 20 % in 10 years compared to 6,200 tonnes in 2002. Two-thirds of this quantity was accounted for by only 16 active substances whose consumption exceeded 80 tonnes. The most commonly used medicinal products for human use are antidiabetics such as metformin, anti-inflammatory and analgesics such as ibuprofen, asthma medication and psychotherapeutics [SCHWABE/PAFFRATH in EBERT].

Depending on the wastewater treatment technologies used, a greater or lesser part of the pharmaceutical residues from wastewater is concentrated in sewage sludge. If sewage sludge is used in agriculture, pharmaceutical residues may reach the fields together with the contained nutrients. There they can accumulate in the soil, reach the groundwater through seepage flow, or enter surface waters directly through surface runoff.

While there are numerous studies on pharmaceutical residues in the outflow of wastewater treatment plants and in surface waters, there are only few reliable results on the levels of pharmaceuticals in sewage sludge and their behaviour in soil. This also seems to be related to the fact that an analytical detection of the compounds, especially in the soil medium is difficult because many of these substances are firmly bound to the organic substance in soils and need to be dissolved using elaborate extraction procedures.

The elimination rate of pharmaceuticals in the wastewater treatment plants via degradation processes and sorption (meaning the absorption by or attachment to the organic components of the sewage sludge) is very varied. According to BOXALL et al., pharmaceuticals with greater molecular weight and nonpolar character such as some antibiotics, tend to be more sorbed. GOLET et al. explain the 88–92 % elimination from wastewater mainly with an enrichment in sewage sludge. They detected the antibiotics ciprofloxacin and norfloxacin from the fluoroquinolones group at levels of up to 3.5 mg/kg in sewage sludge. In soils fertilised with sewage sludge, the authors demonstrated levels of up to 0.45 mg/kg soil of the corresponding substances that are also characterised by high persistence, meaning they remain in the environment for a long time.

A study by the German Environment Agency [KONRADI] suggested the antibiotics ciprofloxacin and clarithromycin, the antiepileptic medicine carbamazepine and the hormone ethinyl estradiol as indicator substances for monitoring the impacts of pharmaceuticals on sewage sludge based on the occurrence and behaviour of pharmaceutical residues in wastewater treatment plants, the occurrence and behaviour of residues of human medicine in soils and the ecotoxicological effects of human medicine residues on soil organisms. Based on these proposals, a research project commissioned by the German Environment Agency [STENZEL et al.] determined 3 to 2 mg ciprofloxacin/kg DS, 1.1 to 8.9 mg levofloxacin/kg DS, 0.21 to 1.1 mg carbamazepine/kg DS, up to 0.16 mg clarithromycin/kg DS and up to 0.73 mg beta-estradiol/kg DS in digested sludge.

An IWW expert report on behalf of the German Environment Agency [BERGMANN et al.] compiled the literature on monitoring data of pharmaceuticals in the environment and on the antibiotics doxycycline, clarithromycin, roxithromycin and trimethoprim, of the antiepileptic medicine carbamazepine, the lipid-lowering bezafibrate, fenofibrate and gemfibrozil and the beta-blocker metroprolol, in addition to the evidence of antibiotics ciprofloxacin and norfloxacin already mentioned. The levels exceeded 100 µg/kg in sewage sludge. Oestrogens such as 17-beta-estradiol and 17-alpha-ethinylestradiol were also found in sewage sludge samples. STUMPE investigated the degradation and mineralisation of steroid hormones in the soil that reach the fields through fertilisation with sewage sludge and observed that oestrogens are stable compounds in the soil. Their laboratory tests have also shown that oestrogens in the soil are subject to vertical displacement and should therefore also be considered in the ecological risk analyses for groundwater and groundwater-influenced surface waters.

Antibiotics in the soil can be absorbed by plant roots and accumulate in the plant tissue down to the grain [GROTE et al.]. However, the quantities detected are below the health reference levels available, for example, for food of animal origin.

There are various indications of the retention and accumulation of pharmaceuticals in soils as a result of the application of sewage sludge to arable land. In general, the use of sewage sludge currently causes no known acute hazards for soils and the organisms living in and on them, nor to human health. However, there is currently insufficient knowledge of the long-term effects of pharmaceuticals in soils on soil life, the environment as a whole and on human health.

In its report on pharmaceuticals in the environment, the German Advisory Council on the Environment (SRU) points out that only a few pharmaceuticals accumulate in sewage sludge.

Due to the sink function of the sewage sludge, SRU nevertheless recommends a precautionary gradual departure from its agricultural use in order to prevent a diffuse distribution of the undesirable accompanying substances on the soil [SRU]. The SRU report on the topic of pharmaceuticals in the environment also suggested that the input of resistant bacteria is more important for the development of resistance in the environment than the input of the antibiotics themselves [SRU].

At present, the German Environment Agency is carrying out a research project on this topic, which investigates the input of resistant bacteria from wastewater or sewage sludge in soils in more detail. The aim is to gain knowledge about the effects of resistance on soils and to submit proposals for more demanding standards for sewage sludge fertilisation from smaller wastewater treatment plants.

Nanomaterials in sewage sludge

Speaking about nanomaterials, they are materials in which at least 50 % of the particles in the number size distribution have at least an outer dimension ranging from 1 to 100 nanometres (nm) [EU], which corresponds to about one-thousandth of the diameter of a human hair.

Nanomaterials can be of natural origin (e. g. fine clay particles), they can be generated in processes (e. g. combustion) or deliberately synthesised for technical purposes. These fine materials are particularly relevant as a component of consumer goods or products from the electronics industry, pharmacy, medicine, cosmetics, surface finishing or chemistry. Zinc oxide and titanium oxide nanoparticles in sunscreens and also aluminium compounds in sprays are prominent examples in the increasingly broader application.

It is generally believed that nanomaterials should not pose a risk as long as they are firmly bound into a matrix and are not released throughout the product life cycle. Nanomaterials released into the environment may interact with other substances or organisms, thereby potentially damaging the environment. Methods are currently being developed for the standardised investigation of the behaviour and impacts of nanomaterials. For example, the German Environment Agency has developed and published an OECD test guideline to investigate the impact of important environmental parameters on the stability of nanomaterial dispersions [OECD; Schwirn/VÖLKER].

Previous studies have shown that about 90 % of the nanomaterials used enter sewage sludge in the wastewater treatment plant [SCHWIRN/VÖLKER]. The extent to which these substances can be transferred from the sewage sludge into the environment depends on the choice of sewage sludge utilisation. In principle, sewage sludge incineration may cause deposition pathways via the exhaust gas or the ash. A research project initiated by the German Environment Agency verified that the nanoscale titanium dioxide particles investigated are predominantly firmly embedded in the ash matrix after the incineration of sewage sludge or household waste and emissions via the exhaust gas are negligibly small [BÖRNER et al.]. Investigations into the release behaviour of nanomaterials during further ash treatment (fracture, milling, classification, sorting, etc.) are the subject of ongoing research.

Plastics in sewage sludge

Wastewater also carries plastics to wastewater treatment plants. Particles called macroplastics (> 25 mm) are already mechanically removed in the primary treatment, for example by screens. Meso- (microparticles of plastics with the size of 5-25 mm) and microplastics (<5 mm) pass through the wastewater treatment plant and remain in the sewage sludge.

Some of the plastics in the wastewater come from the domestic sector (additives in cosmetics and detergents, called primary microplastics), the abrasion of textiles resulting from washing (as secondary microplastics) or the abrasion of other hygiene products made from plastics that are disposed of via the wastewater pathway. Cosmetic product inputs have declined sharply in recent years partly due to the voluntary recommendation of the European Industry Association 'Cosmetics Europe' to its members to abandon the use of microplastics in exfoliant cosmetics. On the other hand, there are inputs from urban areas when rainwater from streets and squares is fed into the wastewater treatment plant via the combined sewerage. In addition to macro- and mesoplastics (e. g. cigarette butts), microplastics (e. g. tyre abrasion) are also fed to the wastewater treatment plant.

Wastewater treatment plants are optimised for particle separation. Preliminary investigations show that the majority of solids (and thus also plastics) are retained in the wastewater treatment plants. These retained substances can then be found either in the screenings or in sewage sludge.

The agricultural utilisation of sewage sludge also causes a corresponding input of plastics into the soil. There is currently insufficient knowledge about the long-term impacts of plastic particles on soil life and the environment as a whole.

The plastics are destroyed if sewage sludge is subjected to thermal utilisation or disposal. In this respect, wastewater treatment plants can contribute to the removal of plastics from the environment.

Nevertheless, it can be stated that there is currently no valid data on the occurrence of plastics in sewage sludge. One major reason is the lack of research methodology. In 2017, the Federal Ministry of Education and Research initiated a research focus programme on plastics in the environment, which investigates wastewater treatment plants in several projects.

03

Sludge treatment

Sludge treatment refers to all processes that improve the usability or the transportability and storability of sewage sludge. Sludge treatment processes include thickening, hygienisation, stabilisation, dewatering, drying and incineration [GUJER; BRANDT]. Incineration or thermal treatment is discussed separately in Chapter 4.

Thickening

The purpose of thickening is to remove as much water as possible from the sludge and thus to reduce its volume. Thickeners are very similar to sedimentation tanks in terms of shape and function. Gravity makes the particles sink to the bottom of the sludge and settle. In addition, a raking mechanism (agitator) accelerates the flocculation of particles making them settle faster. The sludge is drawn off at the bottom of the thickener and the excess water (free water) is removed at the surface [GUJER; DWA 379].

Hygienisation

The purpose of hygienisation is to reduce pathogenic organisms (such as bacteria, viruses, protozoa or worm eggs) in the sewage sludge in order to minimise the contamination risk to humans, animals and the environment when used on soil. Regarding the requirements for disease and phytohygiene, Section 5 of the Fertiliser Ordinance must be complied with. A starting material is considered to be of concern if salmonellae are found or so-called resistant harmful organisms are contained in 50g of sample and no hygienisation treatment has taken place. The application is then subject to certain conditions (see Chapter 1, Fertiliser Ordinance (DüMV)). Table 5 provides an overview of different sewage sludge hygienisation processes discussed in the amendment of the Sewage Sludge Ordinance.

Table 5

Chemical/physical/thermal stabilisation processes for the hygienisation of sewage sludge

Process type	Process	Description
Reaching the treatment temperature through external heating	Sludge pasteurisation	The sludge is heated to over 70°C during a 60-minute exposure time to heat.
	Thermal conditioning	Conditioning takes place at a pressure of at least 15 bar, a temperature of at least 80°C and at an exposure time of at least 45 minutes in the sludge reaction container.
Reaching the treatment temperature through self-heating/chemical reaction heat	Aerobic thermophilic sludge stabilisation (ATS)	Active air/oxygen supply triggers exothermic microbial degradation and metabolic processes that result in heating and a pH increase to about 8 in sewage sludge. ATS installations operated semi-continuously must be built in at least two stages. Only a minimum temperature of 55°C and an exposure time of at least 22 hours in the second container can ensure a sufficient reduction of the harmful organisms.
	Sludge composting in stacks or reactors	Microbial aerobic decomposition composts the sludge. The required heat is provided by only these degradation processes. Structural materials such as straw, sawdust etc. are added to the sludge. The initial water contents of the mix of 40–60 % are ideal conditions for a perfect composting process.
	Addition of unslaked quicklime	The addition of CaO to dewatered sewage sludge heats the mixture to at least 55°C due to exothermic reactions of the calcium oxide with the water present, provided that there is sufficient thermal insulation of the reactor. The initial pH of the lime-sewage sludge mixture must be at least 12.8 and the treatment time must last at least 3 hours at a minimum temperature of 55°C.
Shifting the pH value	Addition of hydrated lime during sludge conditioning	The addition of Ca(OH)2 (e. g. as milk of lime) to liquid sludge can lead to an increase in the pH. In addition, this also reduces harmful organisms. This requires the addition of at least 0.2 kg of $Ca(OH)_2$/kg of DM and the initial pH value of the lime-sludge mixture must be at least 12.8. The mixture must be stored for at least three months prior to usage.
Long-term storage processes that ensure a reduction of harmful organisms	Treatment in plant beds	Reeds or bulrush absorb the organics contained in the liquid sludge and mineralise them. The result is an earth-like substrate that contains the organic components taken from the sewage sludge and the decomposed root mass. The reed plants contribute to the ventilation of the subsoil. In addition, their high evaporation capacity favours sewage sludge dewatering. The procedure should take place in modular treatment beds that are fed staggered in time. This ensures minimum treatment times and no-feed times.
Drying process	High temperature drying	The drying medium (air, water, etc.) is heated to a temperature above 100°C thus drying the sewage sludge.

Source: [BMU]

Sewage sludge disintegration

Sewage sludge disintegration processes aim to break up the structures and microorganisms contained in the raw sludge, thus enabling an accelerated and on-going degradation. External forces (physical, chemical, biological) alter the sludge properties and make the ingredients of the cells more accessible to the degradation processes of digestion. The aims of sewage sludge disintegration also include the targeted transfer of sewage sludge components such as phosphorus into the free water, to achieve a higher biogas yield, to reduce the sludge mass, to prevent the formation of foam or bulking sludge or to improve sludge dewatering. The processes used include mechanical (e. g. high pressure, ultrasound), chemical/biochemical (e. g. acids, alkalis, oxidants, enzymes) and thermal (heating) processes or combinations of processes such as thermal pressure hydrolysis.

Biological sludge stabilisation

The purpose of biological sludge stabilisation is to reduce rapidly degrading organic substances since these can cause odour problems. Biological sludge stabilisation can be divided into anaerobic (digestion), aerobic (composting) and alternating anaerobic/aerobic (humification) processes. These usually occur in the psychro, meso or thermophilic temperature range.

Anaerobic sludge treatment in Germany usually takes place on larger wastewater treatment plants in, as they are called, digestion towers. Meanwhile, the high-load digestion process is also an applied option, which is particularly relevant for smaller wastewater treatment plants. The aim of sewage sludge digestion is to stabilise sewage sludge, meaning the reduction of biological activity and odour development. It is also important to achieve a better dewaterability of sewage sludge through digestion. Another advantage of anaerobic treatment is that one part of the organic components produces a gas that can be used as an energy source. Further stabilisation methods are the composting and the humification of sewage sludge.

The fact that digestion enables an improved downstream dewaterability whereby the sludge’s calorific value can be increased with less technical effort is favourable for subsequent thermal treatment.

Dewatering

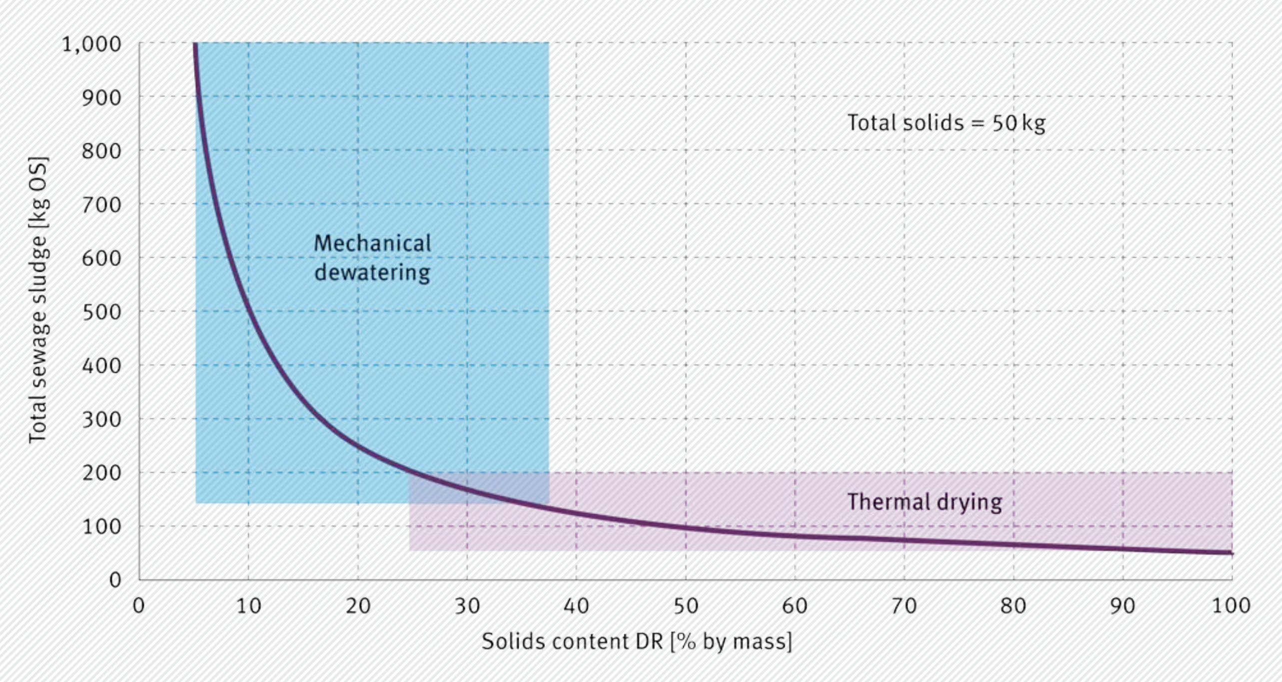
Mechanical dewatering is used to reduce the amount of sludge mixture by reducing the water content. Dewatering is particularly necessary if the sewage sludge has to be transported for further treatment or disposal. On the one hand, the amount of sewage sludge to be transported is reduced, on the other hand, spadeable sewage sludge is much easier to handle than liquid sludge. At the same time, dewatering increases the calorific value, which increases the efficiency of a subsequent thermal treatment.

The mechanical dewatering of the sewage sludge in decanters, centrifuges, belt or chamber filter presses achieves a solids content, measured as dry residue (DR), between 20 and 45 %. The success of mechanical dewatering depends largely on the processes selected, the type and properties of the sludge, and potential conditioning. Figure 4 shows the mass reduction through dewatering and drying.

In upstream sludge conditioning, the dewaterability of the sludge is improved with the help of additives (flocculants and flocking aids). A distinction is made between inorganic flocculants (e. g. iron and aluminium salts, lime, coal) and organic flocculants (organic polymers). Iron and aluminium salts are often used in the wastewater treatment process as precipitants for the removal of phosphate. The addition of inorganic precipitants significantly increases the non-combustible part of the dewatered sludge (ash content). Biological precipitation processes have a lower ash content than inorganic processes. Therefore, organic conditioning agents are usually used prior to thermal treatment of sewage sludge.

Figure 4

Mass reduction by dewatering and drying



Source: [LEHRMANN 2013]

Sewage sludge drying

Dry sewage sludge has some advantages over wet sludge that comes directly from the wastewater treatment process. The following reasons speak for the dewatering and subsequent drying of sewage sludge:

- reduction of sewage sludge quantity
- better storage and transportability
- better transporting and dosing
- inhibition of microbiological processes and reduction of hygienic concern
- increasing the calorific value

Mechanical dewatering is only a first step in the drying process. Various drying methods are used in order to increase the dry residue content in sewage sludge to more than 50%. As far as drying is concerned, a distinction is made between partial drying in which the dried sludge contains up to approximately 85 % DR and full drying with up to approximately 95 % DR.

Sewage sludge that is partially dried has passed through the adhesion phase, meaning it has a DR content exceeding 50 to 55 %.

Increasing the calorific value is most important for later thermal treatment. The dry substance content achieved through mechanical dewatering is frequently insufficient for autothermic incineration; or further drying before incineration may also be necessary due to technical reasons. Drying at the site of the incineration plant (waste incineration plants, power plants, etc.) is energetically and economically feasible in this case, for example using waste heat recovery. In principle, the drying of sewage sludge is a very energy consuming process. The remaining water in the sewage sludge must be evaporated with the help of thermal energy. The chosen degree of dryness depends on the subsequent use of the sewage sludge.

Dewatering and drying of the raw sludge to a DR content of 35 % is generally sufficient for an autothermic incineration (without additional firing) in, so-called, sewage sludge mono-incineration plants (incineration plants for pure sewage sludge incineration).

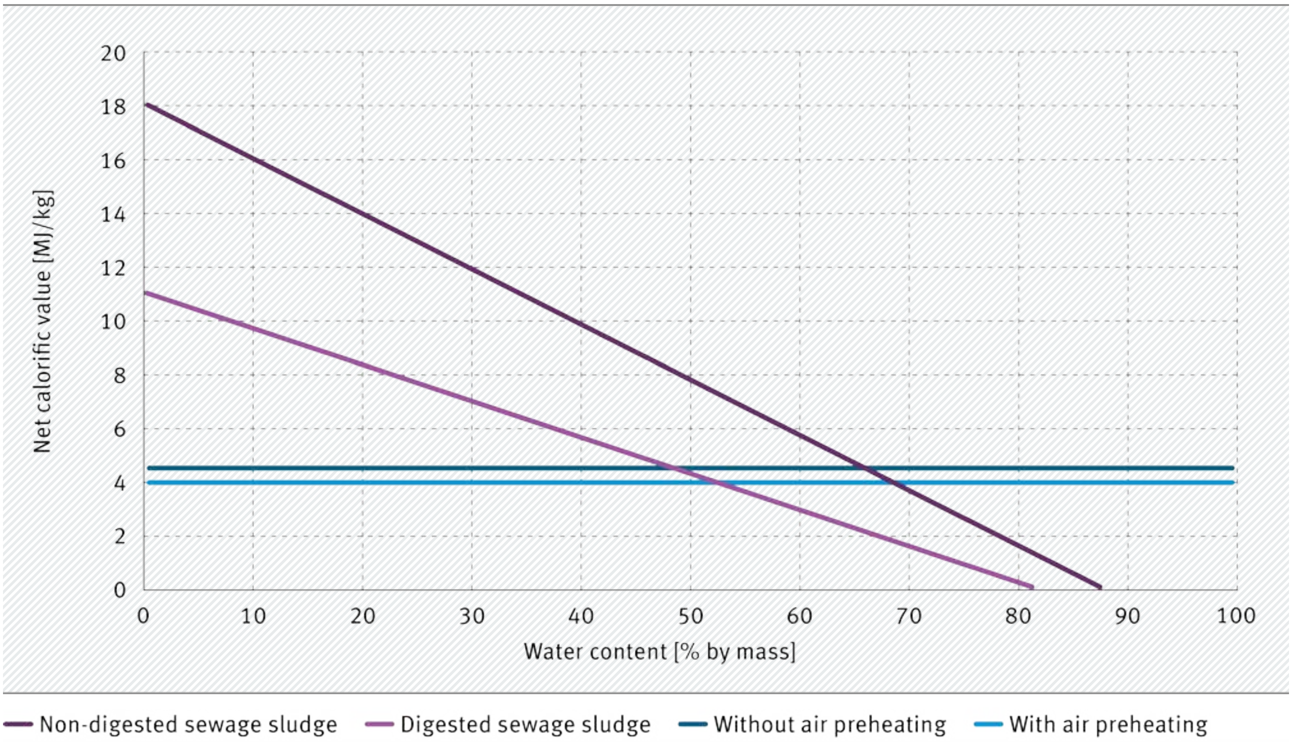
Digested sludge must be dried to at least 45 to 55 % DR for autothermic incineration, since digestion produces a lower residual organic mass for incineration, which ultimately causes a lower calorific value. Figure 5 shows the relationship between the calorific value achievable through drying and the water content of the sewage sludge. Waste incineration plants co-incinerate both dewatered and partially dried or fully-dried sewage sludge. Co-incineration in coal-fired power plants usually uses dewatered sewage sludge with a solids content between 20 and 35 % DR. The power plants concerned carry out an integrated drying of the sewage sludge in coal mills. It is also possible to directly use fully dried sludge in power plants. The use of sewage sludge in cement works requires, in addition to the dewatering process, a complete drying due to process reasons.

Sewage sludge only combusts in an autothermic manner at a net calorific value (NCV) of about 4,500 to 5,000 kJ/kg. This roughly corresponds to a water content of 50 % digested sludge with 50 % ash content. If incineration plants use hot exhaust air from the boiler to preheat the combustion air, autothermic incineration can be achieved from as low as 4,000 kJ/kg. Depending on the ash content, drying can increase the calorific value of the digested sewage sludge to 10,000 to 12,000 kJ/kg. The calorific value of dried sewage sludge is thus at the same level as that of air-dried wood or lignite. Due to the higher organic content, this may even be 18,000 kJ/kg in the case of completely dried, non-digested sewage sludge. There is a series of suitable methods to heat the dryers. Table 6 provides an overview of the heating media used and the drying systems or process conditions used for this purpose.

The selection of the 'correct' drying method depends on many influences and boundary conditions. The expected properties of the end product as well as economic and, not least, ecological considerations should be taken into account in addition to the integration into the entire process.

Figure 5

Relationship between the achievable calorific value and the water content of the sewage sludge



Source: [UBA's EVALUATION, LEHRMANN 2013]

Table 6

Used heating media, temperature and pressure ranges and the associated drying units

Heating medium	Examples of drying systems	Pressure (bar a)	Temperatures (°C)
Flue gas	Drum dryer	~ 1	≤ 850
CHP exhaust	Fluidised bed dryer	~ 1	≤ 350
Air	Drum dryer	~ 1	≤ 450
	Belt dryer	~ 1	≤ 160
Steam	Thin-layer dryer	5–11	150–180
	Disc dryer	5–11	150–180
	Fluidised bed dryer	≤ 20	≤ 200
Pressurised water	Thin-layer dryer	5–11	150–180
	Disc dryer	5–11	150–180
	Fluidised bed dryer	≤ 20	≤ 200
Thermal oil	Thin-layer dryer	3–4	≤ 200
	Disc dryer	3–4	≤ 200
	Fluidised bed dryer	≤ 20	≤ 250
Radiation	Solar dryer	~ 1	< 50
	Infrared dryer	~ 1	< 50

SOURCE: [DWA 379]

Drying processes can basically be differentiated into direct and indirect processes as well as into radiation-based processes (solar drying, infrared drying).

In direct dryers, also called convection dryers, the sewage sludge to be dried comes into direct contact with the heating medium (usually steam, air or flue gas). Drying produces vapours that are a mixture of water vapour, air and the gaseous components expelled from the sludge. The vapours must then be subjected to cleaning. In order to avoid odour nuisance and hazards to local residents, dust particles are first filtered out of the gases (dedusting) before they are treated by technical or biological exhaust gas cleaning processes.

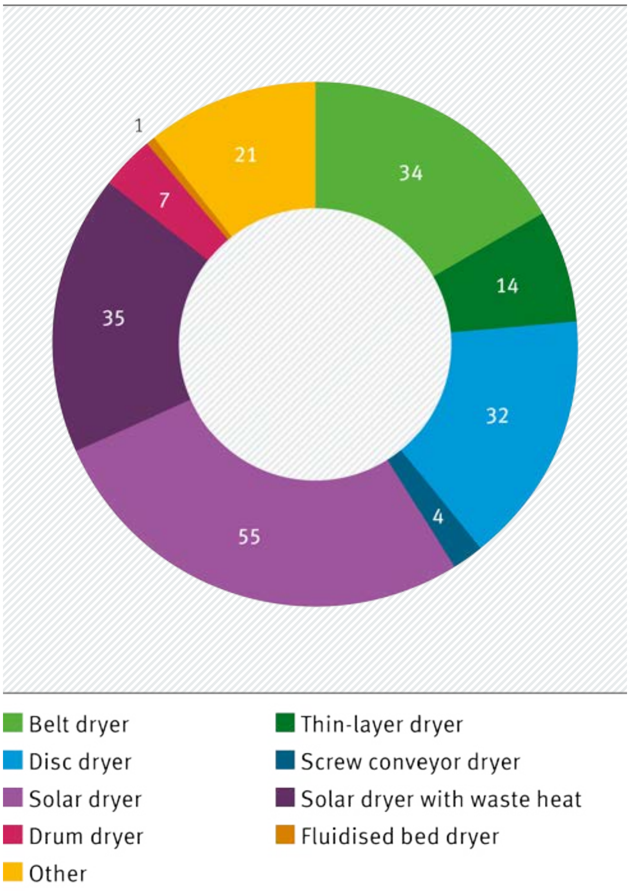
In indirect dryer systems, also called contact dryers, the required heat is provided by a steam generator or a thermal oil installation in which synthetic oil acts as a heating medium. Heat transfer in contact dryers occurs between a hot dryer surface and the sludge. The heating medium and sewage sludge are separated. The advantage of this technique is that the heating medium and gases do not mix. This facilitates the subsequent purification of the two substance flows. Contact dryers usually reach solids contents of 65 to 80 % DR. The water evaporated through drying is only contaminated with air leakage and small amounts of volatile gases. The water vapour from the effluent gasses can be almost completely condensed. The remaining gases can be deodorised during the boiler firing.

Solar drying processes have spread in recent years. They use solar energy for sewage sludge drying. The sludge is heated and dried by the sun in a glazed building similar to a greenhouse. For the optimal progression of the water evaporation and thus the drying of the sewage sludge, the sewage sludge has to be well ventilated and turned over several times [FELBER/FISCHER]. Waste heat from power plants or waste incineration plants can be used to support this process, for example by using underfloor heating or radiators [LEHRMANN 2010].

In Germany, a total of 203 drying systems are currently installed at 175 sites handling municipal sewage sludge. Figure 6 provides an overview of the drying methods used. Based on the number, solar dryers with and without waste heat recovery make up the largest share of all installed drying systems with almost 44 %. However, these installations cumulatively produce only 9 % of the sewage sludge dried in Germany. Other very commonly used drying processes are belt, thin-layer and disc dryers. Sewage sludge drying based on the fluidised bed principle is operated at just one location, the same as paddle drying although they achieve very high throughputs with 16,000 and 17,500 t/DS per year respectively.

Figure 6

Number of sewage sludge dryers divided by the type of dryer



Source: [UBA's EVALUATION 2018]

Table 7 shows a list of the installed drying plants as well as the summed throughputs according to the applied drying technology. In 2004, a total of 74 drying installations were operating in Germany, treating a total of almost 360,000 tonnes of sewage sludge dry substance (DS). By 2012, that number had doubled to 143, with the overall throughput not rising to the same extent due to the increased installation of solar dryers. Since 2012, the number of solar dryers has essentially only increased by installations that use waste heat (especially from power plants) to support the solar drying process, which enables comparatively higher throughputs with the same space requirement. In the years up to 2018, the drying capacity of the belt drying system increased predominantly, which currently accounts for almost a quarter of the total capacity of approximately 560,000t DS per year (a). In contrast, the number of installations and the capacity of drum and fluidised bed dryers decreased significantly in recent years, primarily due economic reasons.

In addition to the drying process used, the drying installations also differ in their capacity ranges used and in the average throughput which is shown in Figure 7.

A detailed overview including technical details of all drying installations in Germany can be found in Table 25 in Annex III.

Table 7

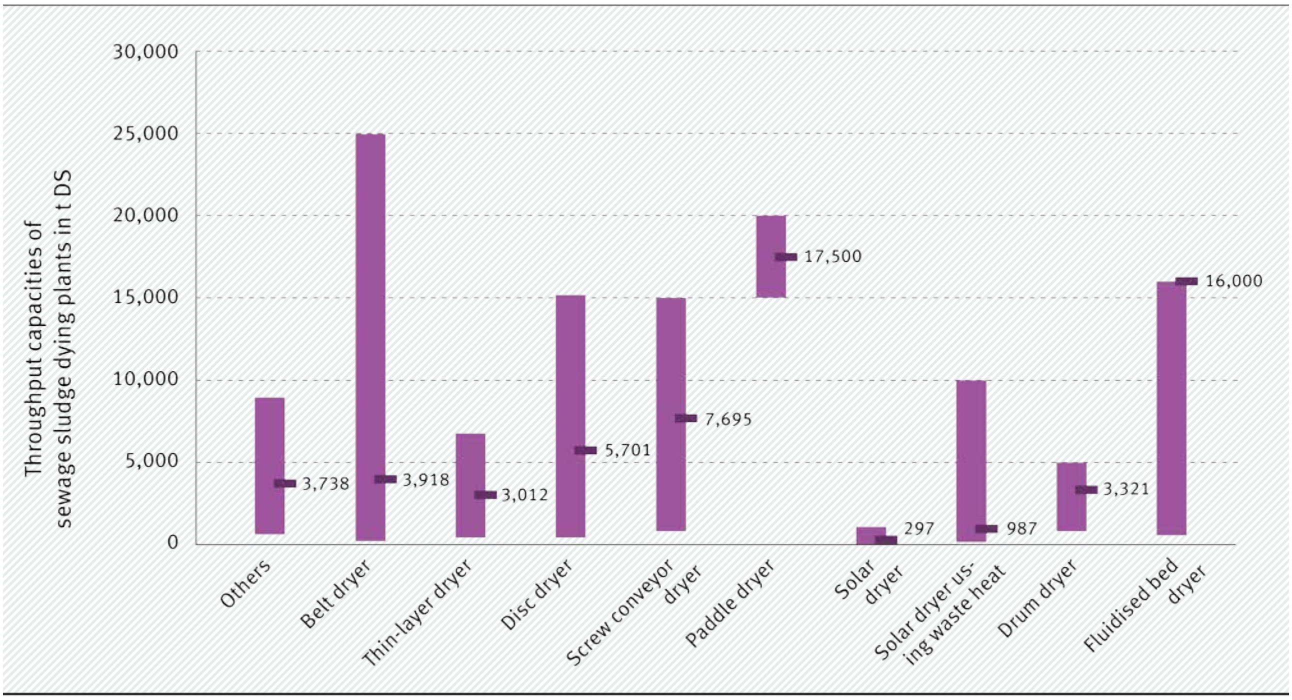
Installed drying systems and throughputs trend

	2004		2012		2018	
	Number [-]	Throughput [t DS/a]	Number [-]	Throughput [t DS/a]	Number [-]	Throughput [t DS/a]
Belt dryer	16	29,086	20	45,001	34	133,206
Thin-layer dryer	7	38,092	7	40,982	14	42,162
Disc dryer	14	183,087	14	179,587	32	182,420
Screw conveyor dryer	–	–	1	30,000	4	30,780
Solar dryer	10	9,440	55	19,521	55	16,333
Solar dryer using waste heat	–	–	20	23,178	35	34,554
Drum dryer	18	83,460	16	65,400	7	23,250
Fluidised bed dryer	6	13,590	6	22,500	1	16,000
Others	3	300	4	25,500	21	78,500
Total	74	357,055	143	451,669	203	557,205

Source: [UBA's EVALUATION in 2018]

Figure 7

Capacity ranges of dryer types and average sewage sludge throughput [t TS/a]



Source: [UBA's EVALUATION in 2018]

04

Thermal sewage sludge treatment

- Sewage sludge mono-incineration
- Sewage sludge co-incineration

The term 'thermal treatment' of sewage sludge generally includes incineration in mono-incineration plants (including gasification plants) as well as co-incineration in coal fired power plants, cement plants and waste incineration plants. In addition, alternative thermal treatment options (e. g. pyrolysis) have been tested for several years.

Sewage sludge mono-incineration

Sewage sludge mono-incineration plants operate at temperatures between 850 and 950°C. Temperatures below 850°C can lead to odour emissions, while at temperatures above 950°C there is a risk of sintering the ash. The temperature level that occurs during incineration depends on the energy content, the amount of sewage sludge introduced and the amount of combustion air.

The 17th Federal Immission Control Ordinance (17. BImSchV, see Chapter 1) stipulates a secondary incineration at minimum 850°C and sufficient retention time of the exhaust gases in the secondary incineration chamber of at least 2 seconds in order to achieve the complete incineration of the flue gases. In Germany, there are currently about 22 sewage sludge mono-incineration plants and one sewage sludge mono-gasification plant with a total capacity of around 670,000t of sewage sludge per year and 7 industrial sewage sludge mono-incineration plants, which together can burn 980,000t DS per year [KRÜGER; Krüger et al.]. The utilisation rate of the approved installation capacities is just under 75 % for municipal sewage sludge and up to 80 % for industrial sewage sludge. Depending on the type, raw or digested sludge can be fed into the installation. This can then be dewatered, semi-dried or dried. More detailed information can be found in Table 22.

Firing systems

Sewage sludge mono-incineration mainly uses the following firing systems:

- Fluidised bed furnace
- Multiple-hearth furnace
- Multiple-hearth fluidised-bed furnace
- Grate firing

With 19 installations, stationary fluidised bed technology accounts for the dominant share of the 23 large-scale thermal sewage sludge treatment plants installed in the municipal area (including gasification). Alternative conversion technologies (grate firing, fluidised bed incinerator or multiple-hearth furnace) have not yet been widely used, but have been in operation for some decades, with the exception of grate firing.

Table 8 summarises the special features of the individual incineration furnaces.

The four mentioned firing systems operate according to different process technologies. The furnace structure, firing management, operation of the incineration plant, the resulting downstream purification facilities and transport of the various material flows have a considerable influence on the quantity and quality of the resulting emissions. In recent years, the stationary fluidised bed has prevailed as the most suitable for sewage sludge incineration type. Current considerations on new plant installations point to the trend of scaling down the proven mono-incineration concepts to the requirements of the decentralised sector.

Table 8

Comparing the firing systems

	Fluidised bed furnace	Multiple-hearth furnace	Multiple-hearth fluidised-bed furnace	Grate firing
Special features	No mechanical moving parts and low wear; suitable for all drying conditions	No separate pre-drying required, complex furnace structure with moving parts, cooled hollow shaft	No separate pre-drying required, movable hollow shaft, low fluidised bed volume	Mechanical moving parts in the firebox, high throughput
Operating behaviour	Fast start up and shut down through short heating and cooling times, intermittent operation possible	Long heating times; continuous operation necessary	Medium heating and cooling times	Long heating times; insensitive to partial load operation
Incineration	Little excess air required, complete burn-out only above the fluidised bed	Burn-out difficult to control, insensitive to fluctuations in feed quantities and coarse materials	Little excess air required, good burn-out control, incineration is largely completed within the fluidised bed, less sensitive to quality variations of the sludge than fluidised bed furnaces	More excess air required, burn-out more difficult to control, sensitive to high calorific fuels
Ash content in the exhaust gas	High	Low	High	Low
Ash discharge	Through exhaust flow and sand extraction	Directly from the bottom hearth	Through exhaust flow and sand extraction	Through exhaust flow and grate exhaust
Residues	Ash, fluidised bed materials	Ash	Ash, fluidised bed materials	Ash, grate ash

Emissions from sewage sludge incineration plants

The incineration of sewage sludge in mono-incineration plants and co-incineration plants is subject to the 17th Federal Immission Control Ordinance (17. BImSchV) which contains a number of emission limiting values that limit emissions according to the state of the art. In order to reduce emissions and thus also comply with the limiting values, all sewage sludge mono-incineration plants have installed elaborate emission control systems.

The regulation regulates dust, nitrogen oxides and mercury emissions. Dust occurs in every incineration process and in every type of incineration plant. All installations are equipped with one or more filtering dust collectors, which effectively reduces dust emissions. The average dust content in the purified exhaust gas is only between 0.2 and 2.5 mg/m^3. The emission limiting value of the current regulation is 5 mg/m^3 (daily average).

The formation of nitrogen oxides (NOx) in sewage sludge mono-incineration plants is mainly from two sources. On the one hand, the sewage sludge itself contains nitrogen compounds which can form NOx as a result of oxidation. On the other hand, input is made via the combustion air in the form of oxygen and nitrogen, which together react to NOx at high temperatures (air synthesis). The average emission value is about 80 mg/m^3 but values up to 180 mg/m^3 have also been measured. The limiting value for nitrogen oxides is 200 mg/m^3 (daily average) for installations in the power range of up to 50 megawatts (MW) of rated thermal input.

Dinitrogen monoxide (N2O) – commonly known as laughing gas – is an important greenhouse gas which has around a 300 times stronger impact on the climate than CO2. It can be produced in the thermal treatment of nitrogen-rich residues – such as sewage sludge – under unfavourable process conditions (e. g. high excess air and too low combustion temperatures in fluidised bed firing).

In addition to the two air pollutants mentioned above, mercury is of particular environmental relevance. For the period from 2015 to 2017, the DWA determined the average mercury concentrations in municipal and industrial sewage sludge as well as in the exhaust gas of mono-incineration plants.

The evaluation was based on measurement data from several sewage sludge incineration plants which together represent 40 % of the total incineration capacity used. Based on the input, about 98.5 % of the mercury is retained by the exhaust gas treatment installations of the mono-incineration plants [SIX]. The mercury concentration falls on average about tenfold below the limit stipulated by the 17. BImSchV (daily average 0.03 mg Hg/m^3). Based on this data, the total mercury load in 2016 amounts to approximately 15 kg from all sewage sludge mono-incineration plants in Germany. Compared to German coal-fired power plants which emit more than 5 tonnes of mercury per year, mercury emissions from sewage sludge incineration are almost negligible.

Other processes

The SynGas process is a sewage sludge gasification process which was developed several years ago at two sites (Balingen and Mannheim) based on the the fluidised bed principle in a trial operation. In the first process stage, fully dried sewage sludge is transformed to a flammable lean gas at 850–880°C which, in addition to nitrogen, is mainly composed of hydrogen, methane, carbon monoxide or dioxide and long-chain hydrocarbons (tars). In the second process stage, the hydrocarbons are decomposed by partial oxidation to methane, carbon monoxide and hydrogen. The resulting synthesis gas is then cleaned and incinerated in a combined heat and power plant and thus serves the coupled generation of electricity and heat. Currently, the construction of another gasification plant in Koblenz with an annual throughput of 4,000t DS is being planned.

Developments of alternative sewage sludge treatment processes

According to experts, chemical-physical processes such as wet oxidation, hydrolysis, hydrothermal carbonation (HTC) or hydrothermal oxidation (supercritical water oxidation) may be further alternatives to the thermal treatment process. At present, a number of other sewage sludge gasification and pyrolysis processes are being developed. Examples include the Pyreg process, Pyrobuster or the sewage sludge reforming process. The alternative treatment processes listed here are mostly still in the developmental stage or have so far only been tested on a large scale in very small numbers

Co-incineration of sewage sludge

In addition to thermal treatment in sewage sludge mono-incinerators, sewage sludge can also be co-incinerated in existing power plants.

This co-incineration of sewage sludge takes place mainly in coal-fired power plants, waste incineration plants and cement works. For the cement industry, an advantage over sewage sludge mono-incineration is that it can save fuel and raw materials. If the sewage sludge has at least one partially dried condition, the co-incineration additionally contributes to saving (fossil) fuels.

Co-incineration in coal-fired power plants

In recent years, the co-incineration of sewage sludge in power plants has taken an increasing share of sewage sludge disposal. Currently, 401,000t TS/a of the co-incineration capacity is used for municipal sewage sludge. Sewage sludge can be co-incinerated in both lignite and hard coal fired power plants. Pulverised-fuel or circulating fluidised bed are the main operating furnace systems.

Generally, only stabilised (i.e. digested) sewage sludge is burned. The use of raw sludge would cause great difficulties in handling and storage and is not suitable due to its high water content and especially due to its poor dewaterability and gas and odour generation. Technically, both the incineration of dried sewage sludge and that of simply dewatered sewage sludge is possible. Currently, dewatered sewage sludge having a dry substance content of about 25 to 35 % DR is burnt in most co-incinerating power plants. Some power plants only use fully dried sewage sludge, in others it is mixed with dewatered sewage sludge and added back to the incineration process.

When using dewatered sewage sludge, integrated drying of the sewage sludge generally takes place prior to incineration. In power plants using PF (pulverised fuel) firing, the sewage sludge is usually introduced in the process via the coal mill and dried and crushed together with the coal. The drying capacity of the coal mills is often the limiting factor, limiting the use of dewatered sewage sludge to a low percentage. This is especially true for hard coal-fired power plants where only limited drying capacity is available due to the low water content of hard coal. Table 9 provides an overview of co-incineration in coal-fired power plants.

Compared to coal, sewage sludge has a relatively high proportion of mineral components of about 40 to 50 %. Correspondingly high is the ash content, which must be separated after incineration, and correspondingly low is the calorific value related to the total solids content. The calorific value of sewage sludge is 9 to 12 MJ/kg in the fully dried condition. Lignite has a comparable as-delivered calorific value, meaning at about 50 % water content. Hard coal is extracted with a water content of 7 to 11 % and has a calorific value of 27 to 30 MJ/kg in this condition.

Dewatered sewage sludge has no positive calorific value in the as-delivered condition – i.e. at a water content of 65 to 75 %. If the sewage sludge is dried by waste heat from a coal-fired power plant in the low-temperature range, sewage sludge can be burned with an energy gain. Waste heat that would otherwise be released through the cooling tower can also be used to dry sewage sludge to produce high-quality energy in the form of electricity and steam when burned. Sewage sludge can thus substitute the fossil fuel coal to a small extent in the power plant which is why the discussions also talk of an energy-related utilisation of sewage sludge.

As already indicated, sewage sludge is a sink for a number of pollutants. When sewage sludge is co-incinerated in coal-fired power plants, the additional input of heavy metals – particularly highly volatile substances such as mercury – becomes noticeable in the emission values. This is one of the reasons why the sewage sludge amount co-incinerated in power plants remains limited to a small percentage. When using larger amounts of sewage sludge, additional exhaust gas purification devices must be retrofitted. Regardless of the amount of sewage sludge, the 17. BImSchV must be complied with when sewage sludge is co-incinerated in coal-fired power plants. Another reason for limiting the co-incinerated sewage sludge quantity is the quality of the fly ash which is usually used as a building material and must comply with the relevant building material standards.

Table 9

Co-incineration in coal-fired power plants

	Fuel properties	Firing type	Sewage sludge co-incineration
Hard coal-fired power plant	Hard coal, water content: 7–11 %, calorific value: 27–30 MJ/kg	PF firing, slag-tap cyclone, circulating fluidised bed	Use of dewatered sewage sludge is limited by the
Lignite-fired power plant	Lignite, water content: 46–60 %, calorific value: 8.5–12.5 MJ/kg	PF firing, circulating fluidised bed	Use is limited by the pollutant content (heavy metals) of sewage sludge

In most coal-fired power plants, the proven sewage sludge content was up to 5 % of the fuel mass. Experience has shown that the co-incineration of this quantity can be managed without significant problems. The current utilisation rate of the approved co-incineration capacity in coal-fired power plants is just under 50 %.

Co-incineration in waste incineration plants

Municipal sewage sludge is disposed of in different degrees of drying in a number of waste incineration plants, the procedural principle of which is mostly based on grate firing technology. The admixture rate should not exceed 20 % and the moist sludge should be well mixed with the rest of the material to avoid lumping, which is often achieved by so-called strewers in the

waste bunker or through centrifugal devices for feeding the combustion chamber. If dried sewage sludge is co-incinerated, there is a risk that the sludge will fall through the grate without being sufficiently burned out. When co-incineration takes place in waste incineration plants, it should be noted that the sewage sludge significantly affects the dust content of the exhaust gas and therefore the flue gas cleaning facilities must be designed for the required increased separation performance.

The amount of sewage sludge disposed of in waste incineration plants has been at nearly constant levels in recent years and amounted to approximately 42,300t TS in 2016.

Co-incineration in cement works

Cement production is a very energy intensive process and it has been using surrogate fuels from waste for decades. Here, dried sewage sludge can replace fossil fuels. In addition, the mineral content in sewage sludge can substitute the mineral raw materials such as sand or iron ore required in cement production.

The co-incineration of sewage sludge in cement works is thus advantageous in two respects. On the one hand, valuable raw materials and fuels can be saved and, on the other hand, the co-incineration of sewage sludge, which is considered to be largely climate-neutral, also contributes to CO2 reduction. In addition to dried sewage sludge, mechanically dewatered sewage sludge is also used to a small extent. In this case, only a very small contribution to meeting the energy demand can be expected; the substitution of raw materials is much more important.

The heavy metal limit values of waste incineration also apply to the co-incineration of sewage sludge in cement works since the amendment of the 17th Federal Immission Control Ordinance (17. BImSchV) of 02/05/2013. Heavy metal input limits for sewage sludge are also particularly important to limit the heavy metals content.

Table 10 shows the amount of sewage sludge incinerated in cement works between 2004 and 2016.

The co-incineration of sewage sludge in cement works has been documented in the environmental data of the German Cement Works Association (VDZ) since 2003. Significant increases were observed particularly between 2004 and 2006 and in 2013 and 2016, with 463,000 tonnes of sewage sludge (with an average water content of 27 % by weight) in 2016 (corresponding to approximately 125,000t DM). One of the main reasons for the first rapid increase is the landfill ban for all untreated waste by the Technical Instructions on Municipal Waste (TASi) at the time. Drivers for the second increase between 2013 and 2016 are particularly climate and resource protection activities.

The coal-fired power plants currently have the largest share in the co-incineration of municipal sewage sludge with about 401,000t TS/a, which accounts for about 23 % of the total volume. The proportion of sewage sludge incinerated in cement works is around 7 %, that of waste incinerators around 3 %.

Advantages and disadvantages of sewage sludge co-incineration

The co-incineration of partially or fully dried sewage sludge can save fossil fuels and therefore costs as well. The reduction of fossil fuels resulting from their substitution with sewage sludge contributes to a reduction of CO2 since the combustible components of sewage sludge are largely of biogenic origin. At the same time, the cement industry uses sewage sludge ash as a substitute for raw materials, which enables further cost reductions and helps conserve resources.

Table 10

Sewage sludge amount incinerated in cement works between 2004 and 2016

Year	Usage [kt/a]	Calorific value [MJ/kg]
2004	48	4
2005	157	3
2006	238	4
2007	254	4
2008	267	4
2009	263	4
2010	276	4
2011	304	4
2012	310	4
2013	316	3
2014	348	3
2015	382	3
2016	463	3

Source: [VDZ A-M]

However, one disadvantage of co-incineration is that the phosphorus contained in sewage sludge is usually removed from circulation because phosphorus is either firmly bound in the cement or is strongly diluted in the slag and distributed in other incineration residues. In the future, the co-incineration of phosphorus-rich sewage sludge will be further restricted in line with the requirements of the Sewage Sludge Ordinance for mandatory phosphorus recovery for sewage treatment plants> 50,000 PE. For sewage sludge whose phosphorus has already been recovered or only has a low proportion of phosphorus (e. g. industrial sewage sludge), co-incineration in coal-fired and cement works or waste incineration plants will continue to offer a suitable disposal pathway.

The recovery of phosphorus and the resulting importance for future sewage sludge disposal will be discussed in more detail in Chapter 6 “Phosphorus recovery”.

A detailed list of all installations in Germany that incinerate or co-incinerate sewage sludge can be found in Annex I.

05

Agricultural use of sewage sludge

- Nutrients in sewage sludge
- Pollutants in sewage sludge
- Advantages and disadvantages of agricultural sewage sludge utilisation

The application of sewage sludge as a fertiliser has a long tradition in agriculture. Soil-related uses recycle nutrients such as phosphorus and nitrogen and can meet some of the nutrient needs of agricultural crops. Sewage sludge can also improve the humus balance. Sewage sludge utilisation on soil is regulated by the fertiliser legislation and additionally by the Sewage Sludge Ordinance. This makes sewage sludge one of the most frequently and regularly controlled secondary raw material fertilisers. At the same time, however, sewage sludge also constitutes a sink for undesirable wastewater components from households, industry and diffuse sources, whose environmental relevance and impact are somewhat poorly understood. An associated potential pollution of soil, plants or ground and surface water is difficult to assess. For this reason, the use of sewage sludge as a fertiliser has been controversial for some time. Due to the new legal regulations (update of the fertiliser legislation, amendment of the Sewage Sludge Ordinance, effective since 03/10/2017), sewage sludge utilisation on soil is being increasingly restricted. The use of sewage sludge from large sewage treatment plants (more than 50,000 PE) will be completely eliminated in the medium term. In addition, the Sewage Sludge Ordinance is now also valid for the use in landscaping measures (see Chapter 6 and Annex II).

The amount of sewage sludge that may be used in agriculture for fertilisation purposes is limited. According to the Sewage Sludge Ordinance, up to 5t of sewage sludge TS per hectare may be applied within three years. In principle, only sewage sludge originating from municipal wastewater treatment plants may be used. The application of sewage sludge is generally prohibited to safely prevent the transmission of pathogens in organic farming, in the forest, in gardens, on grassland and arable land, in fruit and vegetable cultivation as well as in water conservation and nature reserves.

There are restrictions for field vegetable cultivation (see AbfKlärV, Chapter 1). The application of sewage sludge, sewage sludge mixtures and composts is only permitted after prior soil and sewage sludge/mixture/compost tests that must be carried out by a notified testing body in accordance with a prescribed scheme (see Sewage Sludge Ordinance, Chapter 1).

The amended Sewage Sludge Ordinance introduced a voluntary regular quality assurance system in accordance with Section 12 of the Circular Economy Act. This quality assurance carried out by external quality assurance advocates aims to promote the circular economy, to ensure the protection of people and the environment and to increase confidence in agricultural sewage sludge utilisation. Although the responsibility remains with the sewage sludge producer, the quality assurance of sewage sludge, sewage sludge mixtures and composts also brings reliefs such as a reduced testing scope, a relaxed submission obligation for the tests, a facilitated mixing of sewage sludge and the possible exemption from the delivery note (see Sewage Sludge Ordinance, Chapter 1). However, although sewage sludge contains the substances to be investigated under the ordinances, there are also constant discoveries of new degradation products from medicines and other novel substances such as nanomaterials and microplastics. These enter the sewage sludge through pathways such as human excretions and the use of household products. It is not really possible to develop specific detection methods for all these substances and to evaluate them according to their environmental impact. It is particularly difficult to characterise and assess the combination effect of these substances and their degradation products. Toxicologists and analysts can only estimate the potential hazards of such substances – they will have already reached the environment by the time a real evaluation has been performed.

Nutrients in sewage sludge

Sewage sludge has different levels of nutrients (such as nitrogen, phosphorus or potassium), depending on the degree of dewatering and origin. For example, 100 tonnes of wet sludge containing 5 % dry substance (DS) contains on average about 190 kg of nitrogen (N), of which 55 kg are ammonium-N, 195 kg of phosphate (P2O5) and 30 kg of potassium (K2O) (see Table 3) [LFL].

The nutrient availability in sewage sludge is influenced by many factors. Thus, the binding form of the phosphorus contained in sewage sludge depends, amongst other things, on the type of phosphorus precipitation in the sewage treatment plant. Depending on the precipitation method (chemical or biological), 60 to 80 % are in inorganic form, of which around 1–38 % are water-soluble [KRATZ/SCHNUG]. The actual plant availability of phosphorus is influenced by several factors such as pH value, soil and fertiliser buffering, levels of iron and aluminium in the sewage sludge or the plants themselves. An unfavourable phosphorus to iron ratio can significantly decrease the plant availability [ABD EL-SAMIE]. Therefore, biological P-precipitation during the wastewater treatment process is preferable to a chemical P-precipitation for sewage sludge that is to be utilised on soil.

The fertiliser legislation amended in 2017 tightened the regulations governing the application of fertilisers containing nitrogen and phosphate such as sewage sludge. This aims to reduce environmental pollution through fertilisation and increase fertilisation efficiency. According to the applicable fertiliser legislation, phosphate may only be applied to soils containing more than 20 mg P2O5 per 100 g soil (according to the CAL method) depending on the requirement (maximum up to the expected phosphate removal). Fertiliser requirements for nitrogen and phosphorus must be established by means of compulsory fertiliser requirements in accordance with precisely defined specifications. To establish the requirements the expected yields and qualities, the nutrient levels available in the soil, the site-specific plant population and the nutrient replenishment must be taken into account. The minimum efficiency in the year of application is 30 % of total nitrogen for liquid sewage sludge and 25 % of total nitrogen for solid sewage sludge (see Fertiliser Application Ordinance, Chapter 1).

According to the Sewage Sludge Ordinance, a maximum of 5t of sewage sludge (DS)/ha may be applied in three years. This amount corresponds, for example, to 100 m^3 of sewage sludge with 5 % TS (see Sewage Sludge Ordinance, Chapter 1).

For nitrogen, fertilisation efficiency in the year of application depends essentially on the ammonia nitrogen content. This proportion is completely accessible to plants, which must be taken into account in fertiliser planning. Due to its high loss potential for ammonia emissions (> 20 % loss of the applied nitrogen), liquid sewage sludge should, if possible, be applied with low emissions or incorporated immediately after application to untilled farmland. The effectiveness of the organically bound nitrogen is about 10 % in the year of application with about 3 % subsequent delivery in the following years. According to the amended Fertiliser Application Ordinance (DüV), the amount of nitrogen applied via sewage sludge must be fully included in the operational upper limit of 170 kg nitrogen per hectare per year. Likewise, when comparing nutrients, the total nitrogen content must be taken into account, without subtracting the application losses.

Pollutants in sewage sludge

The heavy metal contamination in sewage sludge has generally settled at a low level over the past 15 to 20 years. In contrast, organic pollutants have recently become the focus of attention. However, the spectrum of substances for which sewage sludge must be examined is limited.

The updating of the fertiliser legislation and the amendment to the Sewage Sludge Ordinance also entail a change in the investigation scope of sewage sludge. Thus, the heavy metals chromium (VI) (Cr (VI)), arsenic (As), thallium (Tl) and iron (Fe) have been added.

Table 11

Old and new limit values according to the Sewage Sludge Ordinance (KlärV) and Fertiliser Ordinance (DüMV)

The values marked in bold currently apply to sewage sludge.

Parameter	KlärV (old)	KlärV (new)	DüMV	Unit
Pb	900	–	**150**	mg/kg DS
Cd	From 2 % P2O5 (WM)	–	**50 mg/kg P_2O_5**	mg/kg DS
Cr	900	**only measured**	–	mg/kg DS
Cr(VI)	–	–	**2**	mg/kg DS
Cu	800	–	**900**	mg/kg DS
Ni	200	–	**80**	mg/kg DS
Hg	8	–	**1.0**	mg/kg DS
Zn	500	**4,000**	–	mg/kg DS
As	–	–	**40**	mg/kg DS
Tl	–	–	**1.0**	mg/kg DS
Fe	–	**only measured**	–	mg/kg DS
PCB	0.2	**0.1**	–	mg/kg DS
PCDD(/F)* incl. dlPCB	100	–	**30**	ng/kg DS
AOX	500	**400**	–	mg/kg DS
B(a)P	–	**1**	–	mg/kg DS
PFT	–	–	**0.1**	mg/kg DS

* According to the Fertiliser Ordinance, furans are not included in the limit value but should also be measured according to the Sewage Sludge Ordinance

Regarding organic substances, benzo(a)pyrene (B(a)P) and perfluorinated tensides (PFT) have also been included in the scope of investigation to represent polycyclic aromatic hydrocarbons (PAH). The limits for polychlorinated biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) and adsorbable organically bound halogens (AOX) have been lowered. The new scope of investigation for heavy metals and organic pollutants is shown in Table 11.

For example, PFTs have only recently been recognised as relevant sludge components. Since this substance group is used in many ways because of its properties, its distribution in the environment will also increase. PFTs are used to produce impregnations and polymers (including Teflon® and Gore-Tex®) and are classified as indicating health concerns. The transition to the fertiliser regulation has already introduced a sewage sludge limit (0.1 mg/kg DS).

Many PAHs have carcinogenic, toxic properties. Therefore, the amended Sewage Sludge Ordinance first specified a limit value for sewage sludge for B(a)P (1 mg/kg DS), which is often used as a guiding parameter for PAHs.

As before, there are no limit values for pollutants such as uranium, nanomaterials or medical residues such as antibiotics or hormones since these are sometimes difficult to detect analytically or no agreement can be reached on specific limits and hazard potentials.

Advantages and disadvantages of sewage sludge utilisation on soil

Before discussing the importance of phosphorus, the new legislation on phosphorus recovery and its state of the art, the advantages and disadvantages of sewage sludge utilisation on soil are briefly presented in Table 12. The problem when dealing with or disposing of sewage sludge lies in its importance as a pollutant sink and nutrient supplier.

Table 12

Advantages and disadvantages of sewage sludge utilisation on soil

Advantages	Disadvantages
Sewage sludge is thoroughly tested for pollutants, Sewage Sludge Ordinance and DüMV provide limits for heavy metals and organic pollutants	In addition to the controlled substances, sewage sludge may contain a number of unknown or unregulated pollutants (e. g. nanomaterials, microplastics, antibiotic residues, tributyltin (TBT), total petroleum hydrocarbons (TPH), various pathogens)
High content of organic matter (favourable for the formation of humus)	Possible risk of entry and accumulation of pollutants in soils
Replenishment of necessary nutrients	Risk of over-fertilisation and nutrient leaching
Favourable phosphorus fertiliser, no import dependency	Direct plant availability of the phosphate depends essentially on the form in which the precipitation took place. Phosphorus recycling via phosphorus recovery is also possible
Soil investigation before sewage sludge application (this is carried out at the behest of and at the expense of the wastewater treatment plant operator)	Impact of sewage sludge on soil, for example, via the entry of antibiotic-resistant microorganisms or non-regulated pollutants is unclear

06

Phosphorus recovery

- Phosphorus recovery potentials and processes
- Germany on the road to economical phosphorus recycling
- Utilisation of sewage sludge incineration ashes

Phosphorus (P) is an element that is found in nature only in bound form, usually in the form of phosphate (P04) in the earth's crust. Phosphate is a non-renewable raw material, mined for the most part as phosphate rock extracted from the available ores. Phosphate rock reserves are marine sedimentary, magmatic or formed as guano deposits, with the sedimentary deposits being predominate. The long-term supply of rock phosphate depends on the availability of deposits and whether they can be used economically and technically. With an annual extraction of 58 million tonnes of P2O5 (amount mined worldwide in 2017), the current economically extractable phosphate deposits can cover global demand in agriculture (> 40 million tonnes) for more than 320 years [BGR 2013].

However, information regarding the static range (availability at constant consumption) varies widely. On the one hand, the global demand for phosphate is steadily increasing [FAO] and on the other, new reserves of phosphate are being opened up whose minable possibilities increase with its demand. The U.S. Geological Survey assumes an annual increase in global phosphate fertiliser demand of more than 2 % (equivalent to over 5 million t/a), with approximately 90 % of this additional demand being caused by Asia and America [USGS; FAO]. The growth of the world population and people's pursuit of a higher standard of living in developing countries play the biggest role. In particular, the associated increase in meat consumption will increase phosphate consumption worldwide, as livestock consume significantly more phosphorus in the form of feed during rearing than they provide when slaughtered.

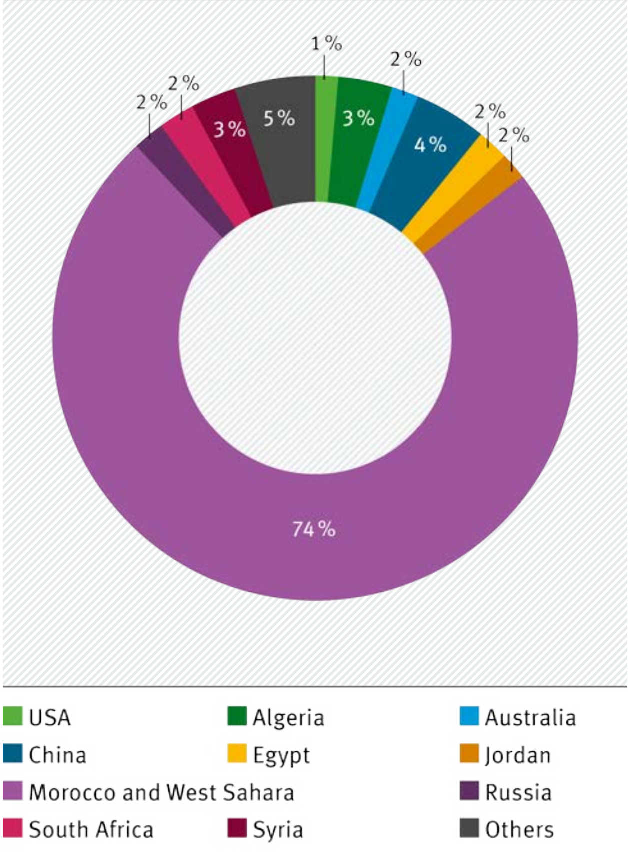
In addition, only part of this phosphorus is used, the remainder being lost through the thermal treatment of animal by-products (residues that are not suitable or intended for human consumption) and the disposal of the resulting ash (Category I). The highest increases in phosphate fertiliser demand are forecast for up to 6.3 % in Asia, the lowest at 0.1 % for Western Europe [FAO].

The decreasing quality of the mined raw phosphates which mainly come from sedimentary deposits is also problematic due to the increasing contamination with toxic heavy metals (especially cadmium with up to 147 mg/kg phosphorus) [SCHEIDIG] and radionuclides (especially uranium with up to 687 mg/kg phosphorus) [RÖMER et al.] and the associated risks for humans and the environment. According to a current study, the so-called “phosphorus peak”, meaning the time at which the phosphorus supply can no longer meet the increased demand, is expected to occur between 2051 and 2092 [CORDELL et al.].

Figure 8 shows that about 95 % of the deposits are under the control of only ten countries and over 80 % of the economically mineable phosphate deposits on Earth are present in Africa. The fact that Morocco, which is the second most important provider of raw phosphate for the EU after Russia, owes its abundance of phosphorus to the annexation of the Western Sahara not recognised by the United Nations, already has great potential for conflict and can be considered of concern with regard to the security of supply in Germany and the EU. By far the largest raw phosphate mining country is China, which accounted for more than half of the world’s 261 million tonnes of raw phosphates mined in 2016. Although the US has increased its annual phosphate production to about 28 million tonnes in 2016, it must import additional raw phosphate to meet its own phosphorus needs. Since China also heavily regulates its phosphorus exports, more than 80 % of the world’s traded raw phosphate is covered by the countries in North Africa and the Middle East. Europe’s only phosphate mine is in Finland, whose reserves of 2,300 million tonnes account for less than 1 % of the global reserves [GTK]. Global resources (but by no means all of them are sufficiently minable) are estimated at more than 300 trillion tonnes [USGS].

Figure 8

Global distribution of the explored raw phosphate reserves for 2016



Source: [USGS]

Germany is completely dependent on the import of raw phosphates and the mineral fertilisers produced from them. Phosphorus therefore represents a strategic resource, particularly as a plant nutrient, of which 231,100t P2O5 were used in the form of mineral phosphate fertilisers in Germany in the economic year 2016/2017 [DESTATIS A]. In 2014, the European Commission [EC] added phosphate rock to the list of critical raw materials.

Phosphorus recovery potential and methods

In view of the situation described above, in particular the Earth's growing population and the consequent demand for phosphorus (FAO), the future use of secondary sources of phosphorus will play a greater role than before in security of supply, human health and conservation of natural resources. That is why for several years, politics and science have been working on the development of suitable recovery techniques. As early as 2004-2011, as part of an initiative of the Federal Government for the Protection of Resources, the Federal Ministry of Education and Research (BMBF) and the then Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) promoted the development of processes as well as the large-scale implementation of technologies for the recovery of phosphorus. At this time, the material flows considered were municipal sewage sludge, municipal wastewater, excess manure, animal meal and other phosphorus-containing, organic materials. Table 13 below shows the recycling potential of some of the material flows in Germany.

The decision of the Federal Government (coalition agreement, 2013) to stop the use of sewage sludge for fertiliser purposes and instead to recover phosphorus and other nutrients, highlighted the material flows of wastewater or sewage sludge and sewage sludge incineration ashes as a focus for technical developments [COALITION AGREEMENT, 2013]. In various research projects, precipitation, crystallisation, adsorption, wet-chemical digestion, thermochemical and metallurgical processes for recovering phosphorus from sewage sludge, sludge water and sewage sludge ash were developed with the aim of recovering the phosphorus contained and the so-called recyclates produced in the process to make it recyclable.

The recovery of phosphorus in accordance with fertiliser regulations and of sufficient quality, both wet-chemical method, e. g. with the magnesium ammonium phosphate (MAP or struvite) recovered by precipitation, and thermal processes, are considered particularly promising.

The wet-chemical processes usually allow a recovery of 5–30 % of the phosphorus contained in the wastewater treatment plant feed, since in most cases only the part of the phosphorus which is available in the sludge water is recovered. These methods are often relatively simple and inexpensive to implement and provide a low-pollutant recyclate, not least because of its generally good plant availability as NP fertiliser (nitrogen (N) phosphorus (P) fertiliser) or suitability as a raw material for fertiliser production. However, the remaining organic content, depending on the degree of subsequent purification of the recyclate

Table 13

Theoretical phosphorus recycling potential of different material flows in Germany

Material Flow	Estimated recoverable amount P in t/a
Municipal wastewater (inflow)	61,600*
Industrial wastewater (inflow)	15,000
Municipal sewage sludge	50,000
Sewage sludge ash	50,000
Manure	444,000
Digestate	125,000
Animal by-products (category 1-3, excluding animal fats)	40,000**
Geschätzter Verbrauch an P in Deutschland	**124,000***

* LAGA, 2015, ** NIEMANN – STN, 2017

Source: [LAGA 12; LAGA 15; NIEMANN; OWN COMPOSITION]

[MAP or struvite, CaP (calcium phosphate), CSH (calcium silicate hydrate)], is relatively high, which also increases the risk of unwanted residues in the recyclate.

Thermal or pyrometallurgical processes are technically more complex in comparison to wet-chemical precipitation processes and thus often considerably more expensive to implement and operate. However, many methods allow high recovery of up to more than 90 % of the phosphorus contained in the wastewater treatment plant feed. Also advantageous is the destruction of organic pollutants in the sludge during incineration.

Plant availability of the recycled materials obtained is very different depending on the process. Mono-incineration (possibly incineration with other residue-free substances) of the sewage sludge is essential for an efficient thermal or pyrometallurgical recovery of phosphorus from sewage sludge or sewage sludge ash, as with this method the phosphorus is in relatively high concentrations and has a manageable amount of contaminations e. g. heavy metals.

If incineration of the accumulated sewage sludge in Germany (close to 1.8 million t TS/a) was completely based on mono-incineration with downstream phosphorus recovery, then theoretically around 50,000 t of phosphorus per year could be recovered from the resulting ash. This corresponds to a good 40 % of the current agricultural consumption of mineral phosphorus. Since sewage sludge incineration ash is legally authorised as a fertiliser, it could be used directly for fertilising purposes provided the limit values were complied with under the Fertiliser Ordinance. The proportion of ash with higher pollutant levels would have to be fed to a phosphorus recovery system.

Gasification, pyrolysis or carbonation (HTC) processes have also been developed over a number of years and tested on a large scale, with the aim of recycling the phosphorus contained in sewage sludge. So far, neither the extent of phosphorus recovery required under the Sewage Sludge Ordinance, nor the recovery of recyclate that can be used for fertilisation purposes (from a legal and material point of view) can be assessed accurately.

Table 14 gives an overview of worldwide phosphorus recovery processes. Many of these were developed in Germany. However, very few have so far been implemented as pilot plants or on an industrial scale. Most of the processes have been operated on a laboratory or pilot plant scale and not all produce a recyclable or fertiliser approved recyclate.

Table 14

Overview of methods developed for phosphorus recovery from wastewater, sewage sludge and sewage sludge ash

Aqueous phase / sludge water / Process water	Sewage sludge / sludge	Sewage sludge ash
Adsorption process	Air Prex / MAP-process	AshDec (SUSAN)
Air Prex/ MAP-process	Aqua Reci	BioCon
CSIR fluidised bed reactor	ATZ-iron bath reactor	Bioleaching
DHV Crystallactor	CAMBI	Ecophos
Ebara	Elophos	Iron bath reactor (ATZ)
Ekobalans	ExtraPhos (Budenheim process)	Eberhard-process
Kurita fixed bed	FIX-Phos	EPHOS
Magnetic separator	Gifhorn process	EuPhoRe
MAP crystallisation Treviso	KEMIKOND	Inocre
Post-precipitation/flocculation	Kemira-KREPRO	Kubota
NuReBas process	KREPRO	LEACHPHOS
NuReSys	Leachphos/Zar	Mephrec (KRN)
Ostara PEARL™	LOPROX	PARFORCE
Phosiedi	MEPHREC	PASCH
Phosnix	NuReSys	PhosRec (Koop slate)
PHOSPHAQ	Peco	RECOPHOS (AT)
PHOSTRIP	Phostrip	RecoPhos (DE)/Seraplant
PRISA	POPROX process	Rhenania
P-RoC (Prophos)	PRISA	SEPHOS
RECYPHOS	PROXNAN	SESAL(-Phos)
REPHOS	Seaborne	TetraPhos
RIM NUT ion exchanger	SESAL-Phos	Thermphos
Struvia	Stuttgart process	
Sydney Water Board Reactor	Unitika-Phosnix	
	Pyrolysis/HTC process	

Source: [Own Composition]]

Germany on the road to economical phosphorus recycling

The international research and development picture reflects the increased interest in recovery techniques that allow the phosphorus contained in various "waste streams" to be recovered and made available for recycling. Germany is among the leaders in terms of research and development in this field. However, states such as Canada, Japan and the USA are leading the way in large-scale implementation. Various processes have been implemented on a large scale and have been operating successfully for several years (e. g. Ostara PEARL).

A large number of different technical processes for the recovery of phosphorus from sewage sludge, sludge water and sewage sludge ash are also available in Germany. Most, however, are still in the experimental stage. A number of procedures are currently being worked on intensively for implementation on a large-scale. Table 15 gives an overview of the current state of implementation of technical phosphorus recovery in Germany.

Over the next few years, it will be necessary to improve the technical, legal and economic conditions that enable new procedures to become established in the circular economy system. An important first step has been taken with the adoption of the amended Sewage Sludge Ordinance on 03.10.2017 (see AbfKlärV, Chapter 1).

In Switzerland, a law came into effect in 2016, which stipulates phosphorus recovery from waste water and animal meal. The goal is to turn Switzerland from a phosphor importing country into a phosphorus exporter. A transitional period until 2026 will be granted for the recovery; concretising specifications will be regulated as an aid to enforcement. In Switzerland, sewage sludge fertilisation has not been permitted since 2006. However, large-scale installations for the recovery of phosphorus from sewage sludge have not yet been implemented.

Table 15 summarises the already-implemented or specifically planned installations for phosphorus recovery in Germany with some important parameters. A prerequisite for the success of large-scale implementation of a recovery process is the usability of the recovered phosphorus. The process will only be economically operated in the long term if a marketable, i.e. qualitative and quantitatively satisfactory, and legally approved recyclate, is recovered. The processes presented here produce recyclates which may be used as fertilisers or which give basic materials for fertilisers or phosphoric acid.

Pollutants from the recyclates of phosphorus recovery are often less than those from conventional mineral fertilisers. Recovered phosphate fertiliser contains significantly less cadmium and uranium than fertilisers made from sedimentary rock phosphates [RÖMER et al.]. Pollutant removal currently does not occur in conventional fertiliser production.

The required nutrient availability, i.e. sufficient fertilising effect, is provided in most of the recycled materials obtained from the processes implemented. Comparative studies on the plant availability of various phosphorus-containing recyclates from phosphorus recovery with commercially available mineral fertilisers have shown that high iron contents, caused by the use of iron salts as precipitants, have a negative effect on plant availability. Recyclates from sewage treatment plants using the Bio-P process have proven to provide good plant availability. Frequently, recyclates from precipitation processes have better plant availability than recyclates from sewage sludge ash. The fertiliser efficiency of the recycled material is also dependent on a whole range of parameters such as soil type, plant, type of P precipitation in wastewater treatment, etc.

Recyclates produced from sewage sludge ash are free from organic residues and therefore, unlike some recyclates from precipitation processes, no longer contain residues of organic contaminants. The content of heavy metals in the recyclates is highly dependent on the respective recovery process and the sewage sludge used.

Table 15

Implemented or specifically planned large-scale plants in Germany (as of 2018)

Operator/Location	Process	Input	Output	Start of operation/ level
Seaborne EPM AG/ KA Gifhorn	Seaborne (MAP precipitation)	120 m^3/d Fermentation sub-strate	MAP/struvite	2007 Demonstration plant, temporary operation
Remondis Aqua/ Altentreptow	REPHOS MAP precipitation	Dairy wastewater (80 mg P/l)	MAP/struvite	2007
Berliner Wasser-betriebe/ Ber-lin-Waßmannsdorf	AirPrex Trading name: “Berliner Pflanze“, MAP pre-cipitation	Digested sludge	MAP/struvite	2011
Neuwerk-Möncheng-ladbach	Airprex	Digested sludge	MAP/struvite	2009
Braunschweig-Steinhof	Airprex, MAP precip-itation	Digested sludge	MAP/struvite	2015
Uelzen	Airprex, MAP precip-itation	Digested sludge	MAP/struvite	2014
Salzgitter	Airprex, MAP precip-itation	Digested sludge	MAP/struvite	2012
Lingen	Elophos (MAP pro-cess)	Digested sludge	MAP/struvite	2017
Hildesheim	FIX-Phos	Digested sludge	CaP	2012
Mainz-Mombach	Budenheim Extra-Phos	Digested sludge	CaP	2017
Offenburg	Stuttgart process / MAP precipitation	Digested sludge	MAP/struvite	2011
Neuburg	P-Roc	Digested sludge	P-containing CSH	
SUN-Nürnberg	Mephrec	Sewage sludge (25 % TS), 60,000 t/a (or sewage sludge ash)	P slag	2016
Remondis-Hamburg	Tetra-Phos/ wet-chemical	Sewage sludge ash	P acid (H_3PO_4)	2015 experimental phase/2018 large-scale implementation

Source: [OWN COMPOSITION]

Table 16

Comparison of wet-chemical and thermal or downstream thermal processes

	Wet-chemical	Thermal or downstream thermal process
Advantages	Cost-effectiveness realised	High recovery rate of › 90 % (legal requirements are met)
	Easy to retrofit and relatively easy to operate	Simultaneous recycling and energy-related use of sewage sludge
	In most cases good plant availability of the recovery products	Complete destruction of organic pollutants
	Operational advantages (spontaneous struvite formation is prevented, improved sludge dewatering)	Flexible use (mostly suitable for all sewage sludge and other substances)
Disadvantages	Recovery rate currently ‹ 50 % (below legal requirements)	High investment costs
	Only suitable for Bio-P installations	Elaborate procedure (technical staff required)

Today, the cost of most phosphorus-containing recyclates exceeds the market price for mineral phosphorus fertiliser many times over. Only the wet-chemical precipitation methods can currently be operated economically since they entail procedural advantages for wastewater treatment plant operation. Spontaneous precipitation of struvite is prevented by the use of Airprex, for example, and reduction of phosphorus content increases the sludge dewatering. Also, the REPHOS process implemented by Remondis Aqua for dairy wastewater has proven itself todate.

Installations in which thermal or downstream thermal treatment processes have been implemented as large-scale industrial practice, are currently not yet in operation but some are close to it (see e. g. TetraPhos). Theoretically, it can be assumed that phosphorus recovery processes that are not economically viable at the moment, will in the medium term achieve this cost-effectiveness in the world market for phosphorus – as forecast today. The prerequisite for this must always be that the recovered phosphorus-containing recyclates have corresponding qualities (e. g. nutrient availability, no pollutants) as well as legal approval (e. g. as a fertiliser) and that there is a market for them.

A brief comparison of the advantages and disadvantages of the wet-chemical and thermal recovery processes is shown in Table 16.

The promotion of technical phosphorus recovery can be achieved by legal requirements such as recently, by amending the Sewage Sludge Ordinance with an obligation for phosphorus recovery. In addition, other policy instruments have been discussed in the past. The introduction of an admixture quota in the field of phosphorus recovery is not currently required. Nevertheless, to advance development and achieve high levels of phosphorus recovery, in its report "Assessment of options for the sustainable use of secondary phosphorus reserves", the States (Länder) Working Group on Waste (LAGA) proposes various measures such as a voluntary commitment by producers or the establishment of a fund [LAGA15]. In addition, large-scale implementation of phosphorus recovery is regularly promoted (e. g. ERDF Baden-Württemberg, Environmental Innovation Programme (UIP)). Flanking should facilitate the transfer of recyclates from phosphorus recovery into product status (e. g. waste end, fertiliser legislation, requirements according to REACH).

The advantages and disadvantages of the currently available sewage sludge utilisation pathways are summarised in Table 17.

Table 17

Pros and cons of current sewage sludge utilisation pathways

Recovery pathway	Advantages	Disadvantages
Direct utilisation on soil (agriculture, landscaping)	Use of phosphorus, all contained nutrients and the humous-forming organics Utilisation pathway that (at least until now) involves the lowest cost	Sewage sludge involves hygiene risks for humans and the environment Sewage sludge contains many pollutants that are not legally regulated. These are not removed from circulation but rather enriched. The possibility will be abolished in the medium term for plants › 50,000 PE
Mono-incineration with downstream phosphorus recovery	Destruction of all organic pollutants and pathogens in sewage sludge Long-term disposal planning in line with legal requirements for wastewater treatment plant operators Energy production Phosphorus recovery from ash in line with legal requirements Possible thermal treatment in conjunction with phosphorus recovery from ash conserves resources and opens up new markets	Phosphorus recovery from ash is currently still technically complex and rarely tested on a large scale Possible additional burden due to transport Generates the highest costs as a utilisation pathway
Incineration with upstream phosphorus recovery	Destruction of all organic pollutants and pathogens in sewage sludge Energy production Conserving resources through fuel saving and additive replacement Thermal treatment in conjunction with previous phosphorus recovery from sewage sludge conserves resources Cost-effective disposal route by mono-incineration	In future only sewage sludge with low or reduced phosphorus content is suitable as no use or recovery of the phosphorus is possible, which does not meet the legal requirements Currently established upstream recovery process for sewage sludge mostly provides phosphorus recovery rates below the statutory requirements Possible additional burden due to transport

Utilisation of sewage sludge incineration ash

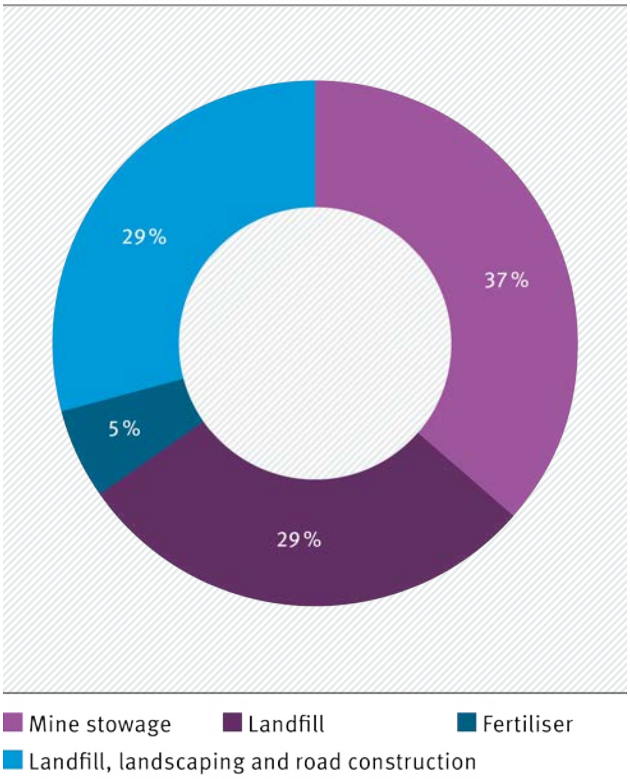
In the meantime, legislation has made it possible to separately landfill sewage sludge ash and carbonaceous residues. According to the Sewage Sludge Ordinance, the possibility of long-term storage (with an obligation for later phosphorus recovery) is given if mixing with other waste and the loss of phosphorus are excluded. In 2013, the amendment to the Landfill Ordinance already paved the way for this (see DepV, AbfKlärV).

Most of the current ways of using sewage sludge incineration ash or carbonaceous residues rule out the possibility of recovering the ashes and thus the phosphorus. According to the amendment to the Sewage Sludge Ordinance, these recycling paths will only be possible in future if the original phosphorus content in the sewage sludge is less than 20 g/kg total solids (see AbfKlärV)

Figure 9 shows that the majority of ashes have previously been recovered from landfills or have been used for mine stowage. Only a small proportion of 5 % was used as fertiliser on agricultural land which complies with the requirements of the Fertiliser Ordinance [KRÜGER/ADAM].

Figure 9

Disposal routes of the sewage sludge ashes from sewage sludge mono-incinerators for 2014 from 24 installations



Source: [KRÜGER/ADAM]

07

Sewage sludge generation, disposal and utilisation

In Germany, about 1.77 Mt TS sewage sludge were disposed of in 2016. Around two-thirds of this is currently thermally treated in the form of co- or mono-incineration. Only 24 % of the total sewage sludge volume is used directly in agriculture. Further recycling paths can be found in landscaping and other recycling (e. g. composting or recultivation measures), which together account for around 12 % of the total sewage sludge disposal. Landfilling untreated sewage sludge has not been used in Germany since 2009.

In line with the prevailing regional or local circumstances, sewage sludge disposal practised in the individual states (Länder) sometimes deviates significantly from these German mean values. Table 18 and Figure 10 provide an overview of the disposal routes used in the states (Länder).

States such as Baden-Württemberg and North Rhine-Westphalia burn more than 80 % of the sewage sludge generated in their state. Up to now, most of the agricultural utilisation of sewage sludge has been practised in the states of Mecklenburg-Western Pomerania, Lower Saxony, Rhineland-Palatinate and Schleswig-Holstein. It is striking that the two city states of Berlin and Hamburg only use thermal disposal, while the state-free Hanseatic city of Bremen uses more than a quarter of its sewage sludge volume for agricultural purposes.

Table 18

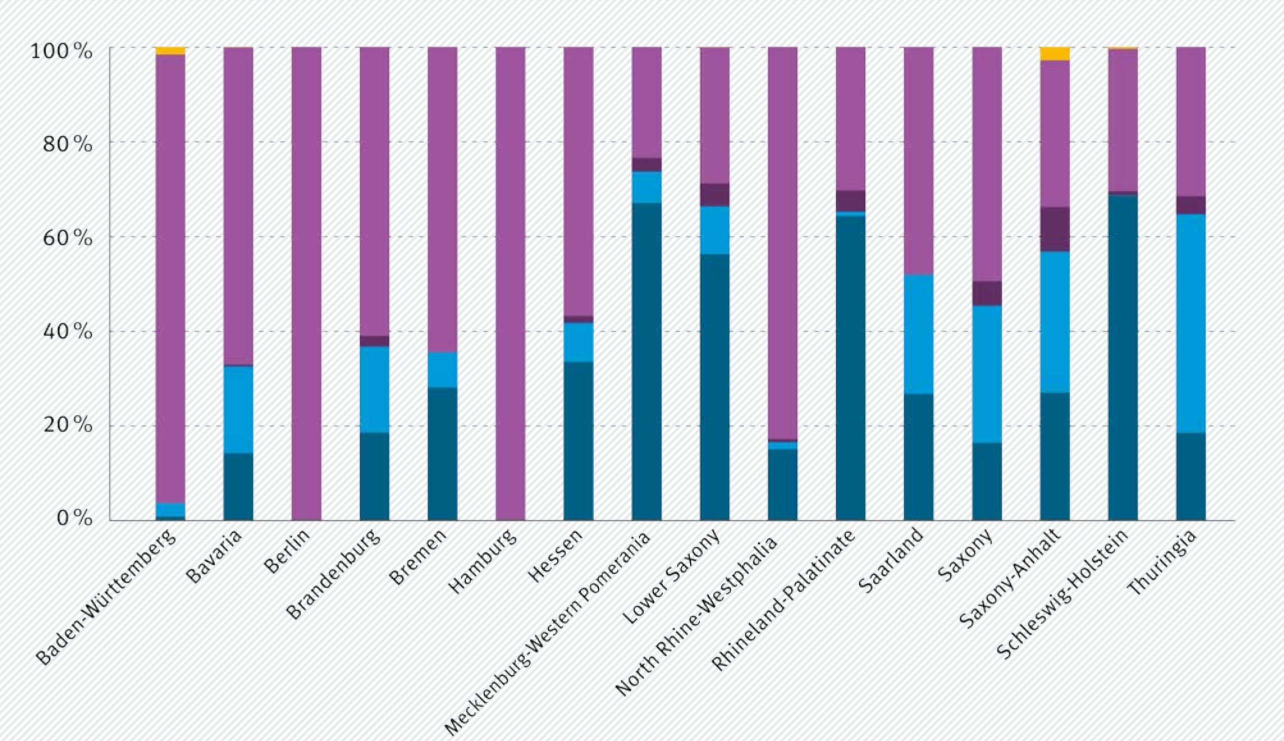
Sewage sludge disposal quantities and pathways by state (Land) in 2016

State	Sewage sludge disposal total [t TS/a]	Agricultural use [t TS/a]	Landscaping measures [t TS/a]	Other material use [t TS/a]	Thermal treatment [t TS/a]	Other direct disposal [t TS/a]
Baden-Württemberg	223,523	2,032	6,206	36	211,452	3,797
Bavaria	290,306	41,387	53,167	1,136	194,304	312
Berlin	50,871	–	–	–	50,871	–
Brandenburg	74,015	13,772	13,413	1,696	45,134	–
Bremen	20,031	5,635	1,478	–	12,918	–
Hamburg	50,619	–	–	–	50,619	–
Hesse	156,282	52,369	12,868	2,369	88,676	–
Mecklenburg-Western Pomerania	34,508	23,109	2,286	1,009	8,104	–
Lower Saxony	143,951	80,999	14,410	6,968	41,424	150
North Rhine-Westphalia	383,341	57,884	5,502	2,818	317,137	–
Rhineland-Palatinate	86,162	55,343	808	3,862	26,149	–
Saarland	19,022	5,089	4,781	–	9,152	–
Saxony	70,108	11,530	20,266	3,649	34,663	–
Saxony-Anhalt	57,775	15,625	17,179	5,414	17,889	1,668
Schleswig-Holstein	75,622	51,821	30	693	22,712	366
Thuringia	37,036	6,888	17,045	1,414	11,689	–
Total	**1,773,172**	**423,483**	**169,439**	**31,064**	**1,142,893**	**6,293**

Source: [DESTATIS B]

Figure 10

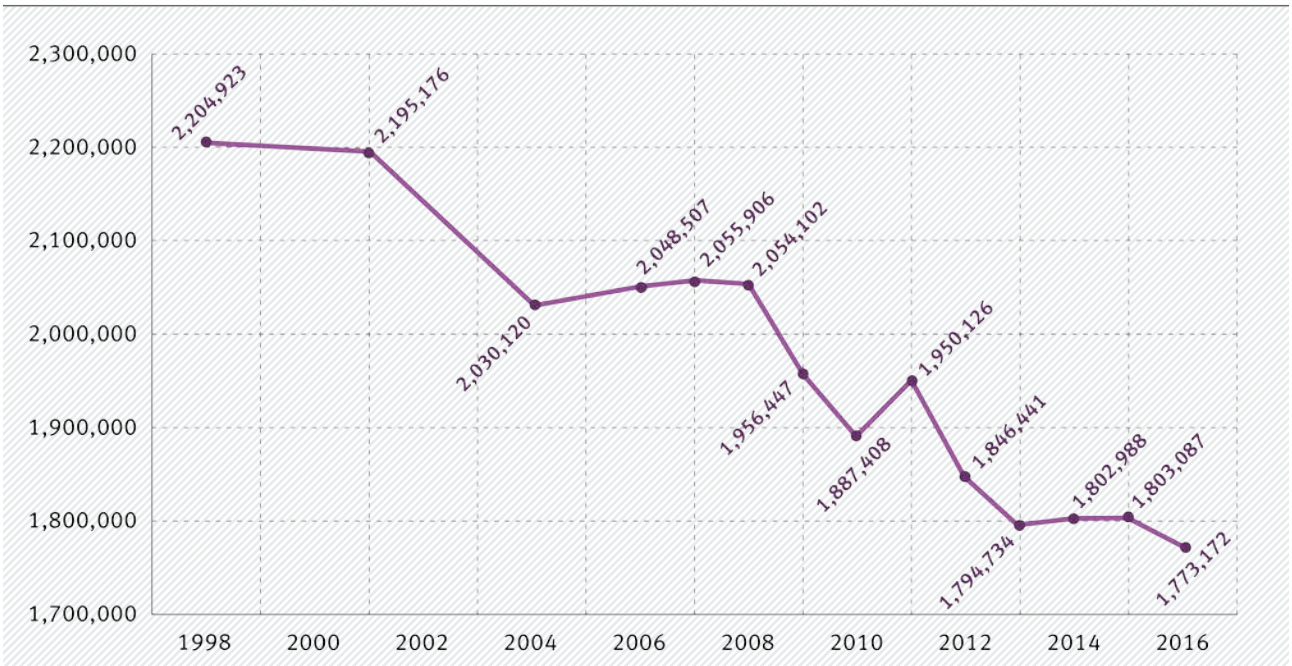
Percentage distribution of disposal pathways in the states (Länder) 2016



Source: [DESTATIS B]

Figure 11

Trend of sewage sludge volume



* Sewage sludge 1998, 2011 and 2004 calculated from the Federal Statistical Office total amount minus the indicated amount of sewage sludge for delivery to other wastewater treatment plants

Source: [DESTATIS B – L]

Trend of sewage sludge volume

In 1998, about 2.2 million t TS of sewage sludge was disposed of. Since then, the amount of sewage sludge to be disposed of annually has steadily decreased and in 2016 amounted to 1.77 million t TS. The causes of the considerable – almost 20 % – reduction in the amount to be disposed of can be found in the expansion and efficiency increase of anaerobic sludge stabilisation. Figure 11 illustrates this trend.

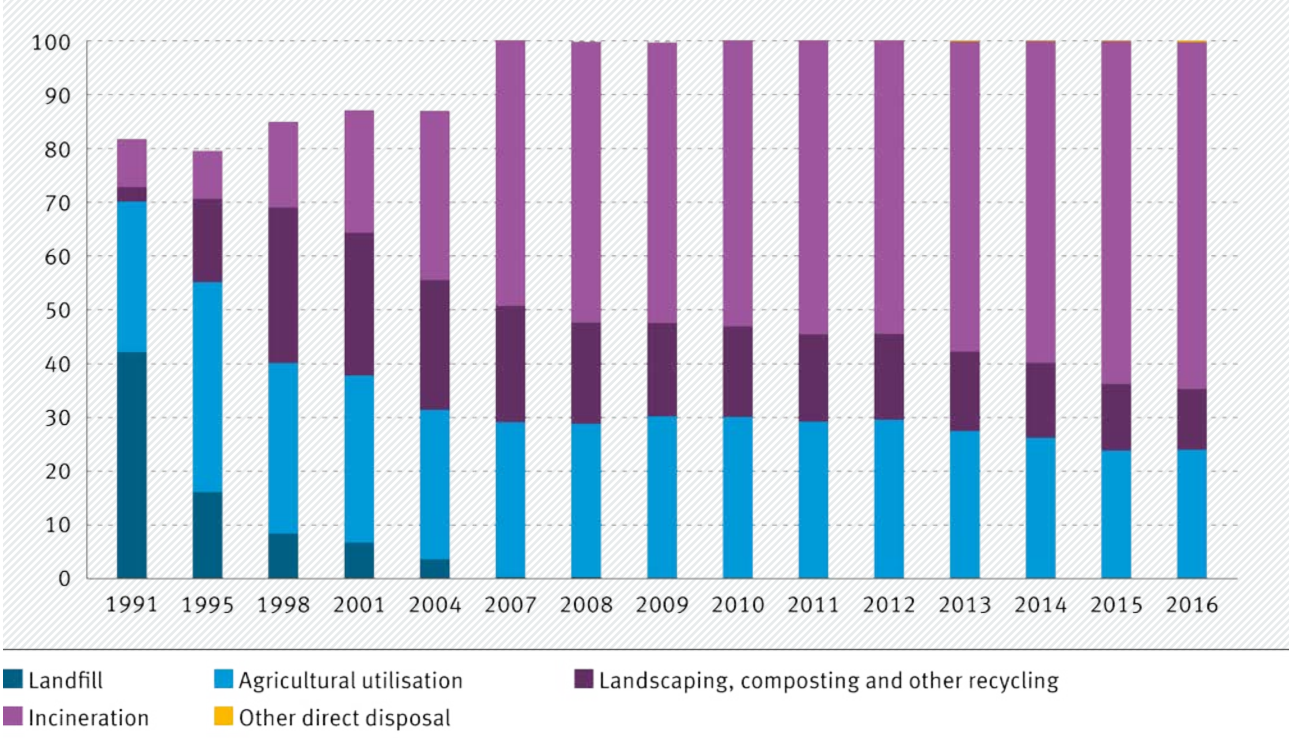
The amount of sewage sludge was taken from the data of the Federal Statistical Office for sewage sludge disposal from biological wastewater treatment [DESTATIS A, B, C, D, E]. The amount of sewage sludge transferred to other wastewater treatment plants has been subtracted from the total quantity for 1998, 2001 and 2004 to ensure comparability. This is because the following statistics do not show this amount in the statistics. Likewise, the column “Interim storage” no longer appears in the newer statistics.

Table 19 illustrates the quantities of sewage sludge disposed of over the years and methods of disposal. This clearly shows the shift in the amount of sewage sludge to be disposed of from landfilling and landscaping towards thermal treatment.

Figure 12 shows the various ways of disposal. Thermal treatment of sewage sludge increased from 9 to 64.4 % from 1991 to 2016. Landfilling of sewage sludge decreased from 42 to 0 %. This is due to the landfill ban on untreated waste being in force since 1 June 2005. Also, utilisation in landscaping declined. While 628,550 t TS was still used in this way in 1998, it was only 169,439 t in 2016. Agricultural utilisation, at around 30 %, provided a relatively constant contribution to sewage sludge disposal by 2012, but it fell to around 24 % by 2016. In 2012, 544,065 t TS of sewage sludge was still spread on agricultural land compared to only 423,483 t TS in 2016.

Figure 12

Sewage sludge disposal from 1991 to 2016



Source: [DESTATIS B – I.]

Table 19

Trend of sewage sludge volume and disposal pathways

Year	Sewage sludge (total)	Recycling						
		Total	In the agriculture		Landscaping measures		Other recycling	
	t TS	t TS	t TS	%	t TS	%	t TS	%
2016	1,773,172	623,986	423,483	23.9	169,439	9.6	31,064	1.8
2015	1,803,087	651,410	427,736	23.7	190,127	10.5	33,547	1.9
2014	1,802,988	722,416	470,882	26.1	216,148	12	35,386	2
2013	1,794,734	755,731	491,327	27.4	203,712	11.4	60,692	3.4
2012	1,846,441	837,611	544,065	29.5	235,439	12.8	58,107	3.2
2011	1,950,126[1)]	882,695	567,187	29.1	254,402	13	61,106	3.1
2010	1,887,408[1)]	883,659	566,295	30	259,312	13.7	58,052	3.1
2009	1,956,447[1)]	927,516	589,149	30.1	282,455	14.4	55,912	2.9
2008	2,054,102[2)]	973,997	587,832	29	331,556	16	54,609	3
2007	2,055,906[2)]	1,036,844	592,561	29	368,912	18	75,371	4
2006	2,048,507[2)]	1,078,264	611,598	30	399,712	20	66,954	3
2004	2,260,846	1,175,694	627,989	27.8	492,768[3)]	21.8	54,937	2.4
2001	2,429,403	1,399,456	754,837	31.1	583,269[3)]	–	61,350	2.5
1998	2,459,177	1,490,074	783,662	31.9	628,550[3)]	–	77,862	3.2

1) Darin enthalten ist auch die Entsorgung der von anderen Kläranlagen bezogenen Klärschlammmenge, nicht einbezogen ist jedoch die Abgabe an andere Kläranlagen.
2) Ohne Abgabe an andere Kläranlagen
3) Kompostierung und landwirtschaftliche Maßnahmen wurden zusammengefasst

Capacities for thermal treatment of sewage sludge

Currently, a total of about 1.15 million tonnes of sewage sludge TS per year are used in mono- and co-incineration plants in Germany [SIX; ITAD and VDZ]. In 2016, the utilised capacity of mono-incineration plants was around 460,500t TS; the capacity used in all co-incineration plants was around 568,500t TS (see Table 20). However, the existing capacities are higher (e. g. by increasing the volumes, use of new facilities).

Currently about 401,000t TS/a are co-incinerated in coal-fired power plants and the utilisation of the approved co-incineration capacities is about 48 % [SIX]. According to [BURGER et al.], lignite-fired power plants will reduce their energy provision from 160 TWh in 2015 to 38 TWh in 2035, and the acceptance capacity for sewage sludge will decrease accordingly in the future. Cement works have had more and more co-incineration capacity available for sewage sludge in recent years, which inceased more than ninefold in relation to 2004 [VDZ A; VDZ N]. Co-incineration of sewage sludge in waste incineration plants is currently at a low level (below 3 % of total amount of sewage sludge).

Sewage sludge utilisation in the EU Member States

In the European Union, about 9.2 million tonnes TS of sewage sludge are produced annually. Table 21 shows the quantities of sewage sludge to be disposed of in the Member States of the EU and Switzerland (absolute figures).

Other direct disposal		Thermal treatment		Deponie		Transfer to other wastewater treatment plants	Interim storage
t TS	%	t TS	%	t TS	%	t TS	t TS
6,293	0.4	1,142,893	64.5	0	0		
2,998	0.2	1,148,679	63.7	0	0		
2,642	0.1	1,077,930	59.8	0	0		
4,232	0.2	1,034,771	57.7	0	0		
–		1,008,830	54.6	0	0		
–		1,067,431	54.7	0	0		
–		1,003,749	53.2	0	0	–	–
–		1,028,034	52.5	897	0.05	–	–
–		1,077,624	53	2.481	0.12	–	–
–		1,015,014	49	4.048	0.2	–	–
–		965,115	47	5.128	0.25	–	–
–		711,170	31.5	79.052	3.5	230,726	64,204
–		554,924	22.8	159.673	6.57	234,227	81,123
–		395,859	16.1	205.140	8.34	254,254	113,850

Source: [DESTATIS B – L]

The percentage distribution of waste disposal practices in the Member States is shown in Figure 13.

The Federal Republic of Germany has the largest share of the total amount of sewage sludge in the EU-27 countries with 19.7 %, followed by Spain (13.2 %). The high population and the high degree of access to municipal wastewater treatment plants explain these sewage sludge proportions. The United Kingdom also disposes of a large amount of sewage sludge per year (11.8 % of the total). Based on the assumption that the part of the population with access to municipal wastewater treatment plants in the EU increases, the sewage sludge to be disposed of will also increase. This, in turn, poses new challenges to sewage sludge disposal in the EU.

Table 20

Used incineration capacities in Germany in 2016

Installations	Used capacity [t TS]	Share of sewage sludge total volume [%]
Power plants, total	448,550	25
Sewage sludge mono-incineration plants	460,410	26
Cement works	125,250	7
Waste incineration plants	42,320	3
Sewage sludge incineration in Germany, total	1,143,000	64.5

114,020 unknown

Source: [DESTATIS A; SIX; VDZ A; ITAD]

Table 21

Sewage sludge volume in Europe and its utilisation pathways

Sorted by Member States according to [Eurostat], as of 2015

	Amount kt	Landfill %	Agriculture %	Compost-ing %	Thermal treatment %	Others %
Albania	92	0	77.32	0	0	22.68
Belgium [1]	107	0	17.24	0	82.76	0
Bosnia and Herzego-vina [3]	1	100	0	0	0	0
Bulgaria	47	18.05	64.54	7.22	0	10.19
Denmark [4]	115	1.22	64.46	0	29.44	4.88
Germany	1,803	0	23.72	12.41	63.71	0.17
Estonia [3]	19	9.78	1.63	88.59	0	0
Finland [1]	141	6.86	5.02	65.68	22.43	0
France [2]	937	3.32	44.96	32.56	18.21	0.95
Greece [2]	119	33.61	19.63	7.75	33.17	5.84
Ireland	58	0.17	79.97	18.66	0	1.2
Italy [4]	954	48.46	33.09	0	3.85	14.6
Croatia	17	94.35	5.65	0	0	0.01
Latvia [3]	21	0.97	36.23	11.11	0	51.69
Lithuania	37	0	30.11	41.78	0	28.11
Luxembourg	9	0	34.36	24.12	8.28	33.25
Malta	8	100	0	0	0	0
Netherlands [2]	320	0	0	0	100	0
Norway	142	15.15	61.73	16.07	0	7,05
Austria [2]	239	1.34	16.58	32.52	49.56	0
Poland	568	7.13	18.93	8.29	13.96	51.69
Portugal [1]	113	10.08	89.83	0	0.09	0
Romania	156	66.69	6.81	0	0.32	26.18
Sweden [2]	184	1.96	27.72	32.12	1.2	37.01
Switzerland [3]	195	0	0	0	96.81	3.19
Serbia	11	100	0	0	0	0
Slovakia	56	8.25	0	44.22	30.07	17.46
Slovenia	29	0.69	0	2.08	52.25	44.98
Spain [4]	1,205	14.9	74.56	0	3.9	6.64

	Amount kt	Landfill %	Agriculture %	Compost-ing %	Thermal treatment %	Others %
Czech Republic [3]	260	6.8	31.17	53.38	2.27	6.38
Hungary	111	4.6	8.47	75.45	11.48	0
United Kingdom [1]	1,078	0.44	78.3	0	21.23	0.04
Cyprus	7	0	13.98	0	0	86.02

1) 2012 Belgium, Finland, Portugal and United Kingdom
2) 2014 France, Greece, Netherlands and Sweden
3) 2013 Bosnia and Herzegovina, Estonia, Latvia, Switzerland und Czech Republic
4) 2010 Denmark, Spain and Italy

Figure 13

Practiced sewage sludge utilisation in Europe (by individual Member States) as of 2015

Source: [EUROSTAT]

08

Cost of sewage sludge disposal

A change in sewage sludge treatment and disposal will usually also affect the costs. However, the amount of wastewater treatment depends on many factors. According to [FELS et al.] these are mainly:

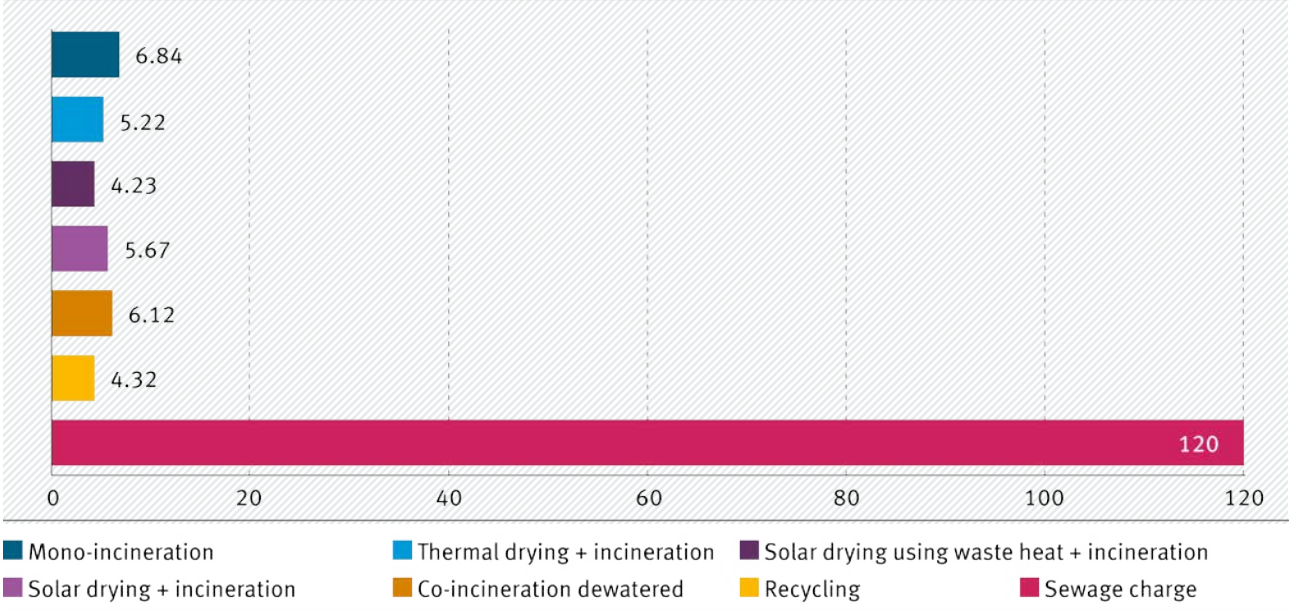
- size and state of the wastewater treatment plant,
- seasonal influences (e. g. due to tourism),
- type of sewage sludge disposal,
- structural properties (e. g. through landscape elevations)
- population density per channel meter
- subsidy

The investment costs of wastewater treatment plants and sewer systems in particular have a very long-term impact on the costs of wastewater treatment according to FELS et al. About 75–85 % of the costs are fixed costs and do not depend on the amount of the wastewater. The second largest item included in the wastewater costs is depreciation and interest. Personnel costs are about 14 %. An additional 10 % is spent on operating material and energy. Thus, the treatment and disposal of sewage sludge accounts for only 4 %, which means that the downstream disposal pathway has so far made little difference compared to the other costs. A change in disposal method therefore usually has only a small impact on the overall costs and thus only makes a small contribution to increasing the sewage charges [FELS et al; JACOBS].

Figure 14 shows the disposal costs depending on the specific treatment methods based on assumed comparative values. An average transport distance of 150 km, an acceptance price of 40 €/t of sewage sludge original substance (OS) and a mean sewage charge of 120 € or an average specific sewage sludge amount of 18 kg DR per inhabitant per year were assumed.

Figure 14

Cost of sewage sludge disposal including dewatering and transport cost
in Euro per tonne TS in relation to average sewage charge



Base = Averages:
Waste water amount = 55 m³/EW a
Sewage charge = 2,20 €/m³
Sewage sludge amount = 18 kg DR/PE a

Source: [JACOBS]

For the determination of costs in co-incineration, those costs incurred by the drying of 20 to 25 €/t DR were also considered.

The resulting cost structure is influenced significantly dependent on achievable throughputs and the degree of utilisation of existing waste heat achieved in (co)incineration of the sewage sludge content. The detailed cost comparison shown in Figure 15 clearly shows that, in particular, drying systems that use waste heat from nearby biogas plants or power plants have a cost advantage. Furthermore, the drying costs can be additionally reduced by scaling the throughputs.

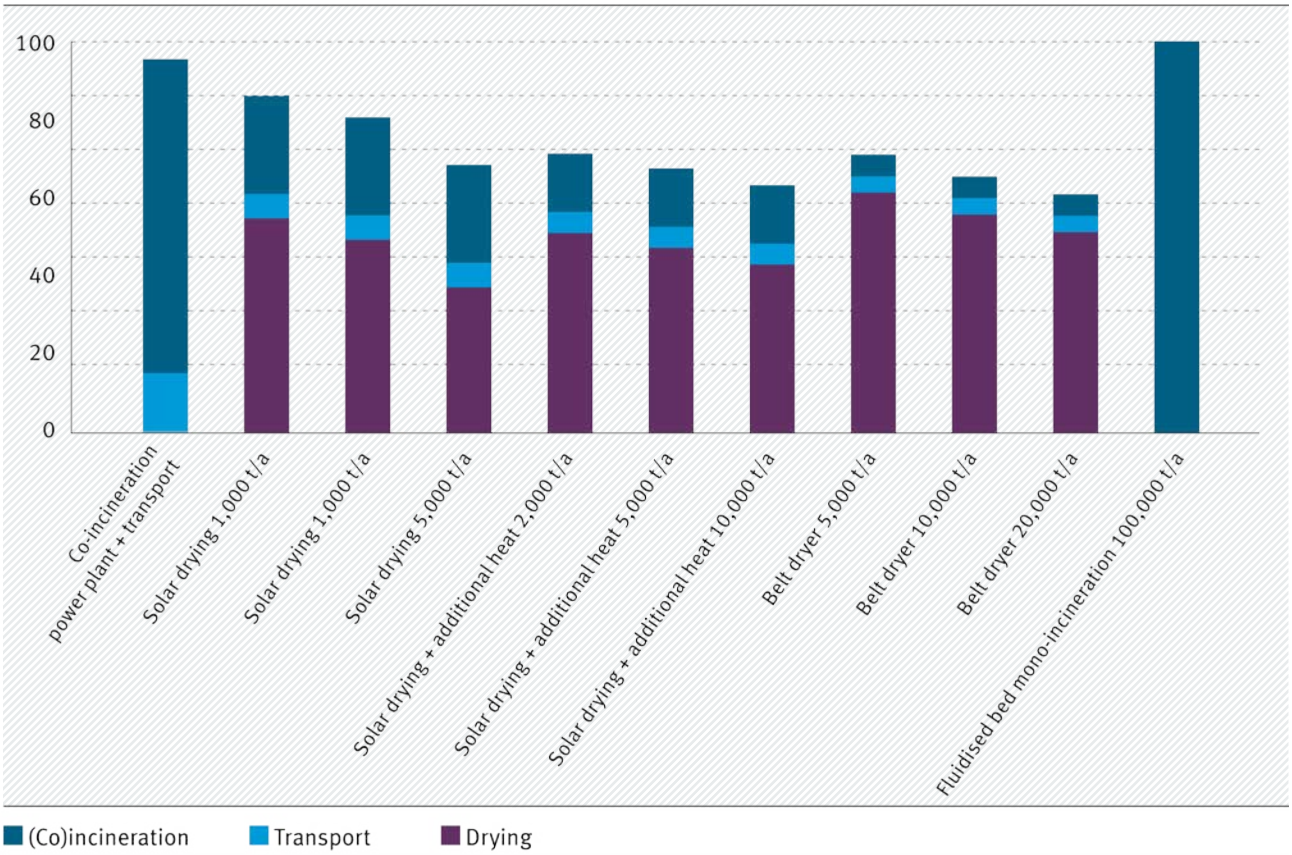
Figure 16 shows that recycling has been the most cost-effective option of sewage sludge disposal to date. The cost of agricultural sewage sludge application is between 160 and 320 €/t DR. Regionally, however, sewage sludge utilisation on soil can compete with the use of manure, which may lead to an increase in sewage sludge disposal costs if the utilisation capacity is limited (see Chapter 5). Co-incineration in power plants is estimated at around 280 to 400 €/t. By contrast, mono-incineration costs between € 280 and € 480/t DR. Regional or local conditions (transport distances, sewage sludge amount, existing treatment capacities) can sometimes cause considerable price differences within a disposal pathway. In the vicinity of metropolitan areas in particular, there are often co-incineration capacities. However, such disposal facilities are not available to the same extent in rural areas, which ultimately increases the necessary logistic effort and thus the transport costs.

The impact of abandoning sewage sludge application on soil is as follows: According to the [FELS et al.] study, only 4 % of the total cost of wastewater management is spent on sewage sludge disposal. The rest is caused by wastewater technology, interest and depreciation. On average, the wastewater costs are around € 2.2 per cubic metre. The study calculated an increase of three cents per cubic metre. For a four-person household this would mean an increase from 484 to 491 € per year (around 7 € per year).

In the case of wastewater treatment plants where sewage sludge is not dewatered, an increase of four cents per cubic metre (more than € 8 per year) could be expected. The results are model calculations and their outcome depends on the figures used (specific water consumption or sewage charge) [FELS et al.].

Figure 15

Comparison of cost structures of thermal sewage sludge treatment

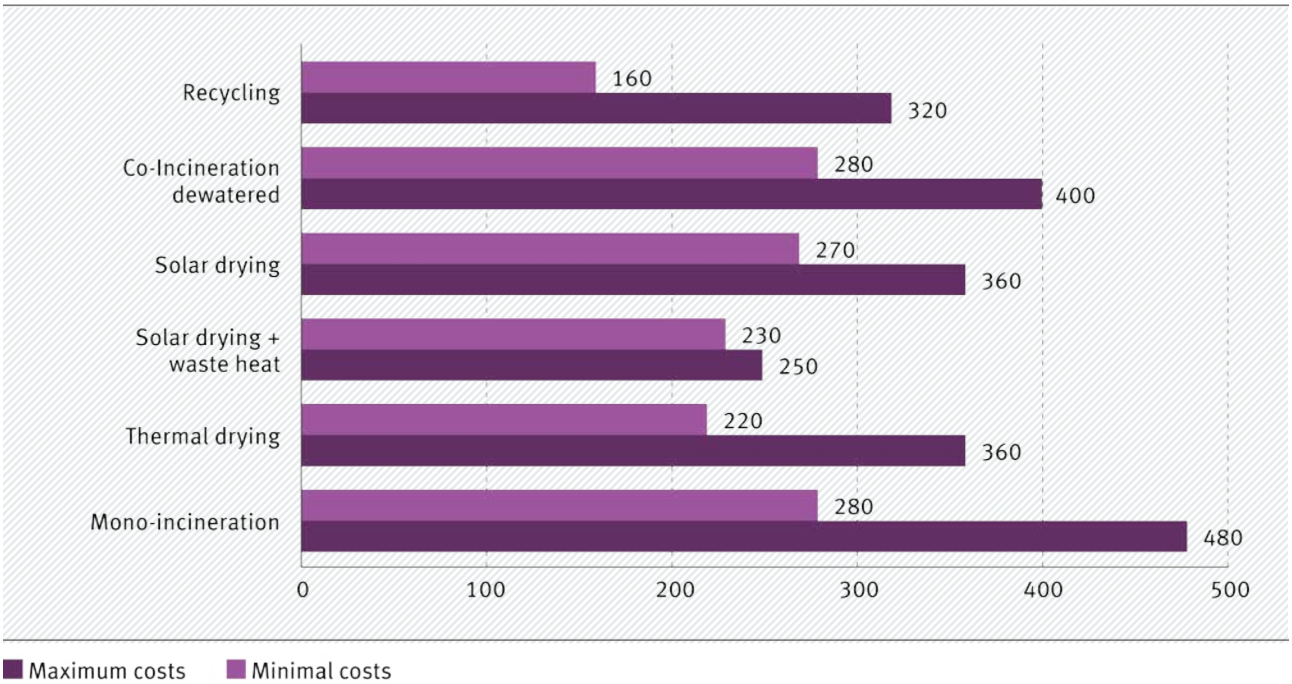


Source: [JACOBS]

Figure 16

Resulting costs of sewage sludge utilisation

resulting minimum and maximum utilisation sosts (€/t DR)



Source: [JACOBS]

The amended Sewage Sludge Ordinance will add phosphorus recovery as a further factor to the costs of sewage sludge disposal. First of all, the question arises whether phosphorus recovery can be allocated to wastewater charges. According to current knowledge, it is possible to re-allocate the costs additionally incurred for the methods of recovery. Thus funding would be secured at the local level [DPP]. Estimates show that, depending on regional conditions, wastewater charges may increase by around € 3 to € 11 per person per year. The methods used to recover phosphorus at a wastewater treatment plant will play a major role in how the various processes will be established on the market in the long term.

For example, if only the treatment of sewage sludge is needed, using a precipitation method such as Airprex could possibly even reduce costs.

These processes provide benefits (such as the prevention of incrustation and thus damage due to struvite creation, improving sludge dewatering) which reduce the cost of wastewater treatment. Methods that require a mono-incineration with subsequent phosphorus recovery from the ash, for example, usually mean high investment costs. If sewage sludge incineration ash or carbonaceous residues were introduced directly into the process, of mineral fertiliser production after thermal treatment, only the costs of transporting the ashes would be incurred.

Abandoning utilisation on soil would also have other advantages and disadvantages for the various stakeholders. In some cases, increased transport costs will be incurred for sewage sludge as it will need to be thermally treated elsewhere. The farmers will have to replace the sewage sludge previously used as fertiliser and take measures to maintain the humus. If it is replaced by industrial fertilisers or recyclates from phosphorus recovery, it will incur higher costs. This cost disadvantage is positively offset by a reduced pollutant input into the soil. In addition, the cost of soil-related utilisation for the sewage sludge producer will also be higher because the sewage sludge is increasingly in competition with farm manures such as liquid manure. Application restrictions and tightening of limits (see DüV, DüMV and AbfKlärV, Chapters 1 and 5) make it increasingly difficult to find customers for sewage sludge. A big advantage of phosphorus recovery is that both mineral fertilisers and recycled fertilisers, in contrast to sewage sludge, have a defined composition and plant availability of nutrients. This makes a good need-based fertilisation practice possible, which in turn saves costs.

09

Summary and recommendations

Sewage sludge is a multi-substance mixture and, in addition to nutrients such as phosphorus, nitrogen and potassium as well as humus-forming organics, it can also contain a number of ingredients of concern such as heavy metals, organic residues (e. g. pharmaceutical residues, hormonally active substances), nanoscale substances, microplastics and various pathogens. These wastewater constituents pass from households, businesses and diffuse sources (e. g. via polluted rainwater) into the sewage system and finally into the sewage sludge. In most cases, little is known about their environmental relevance and impact. If the sewage sludge is treated thermally, i.e. incinerated, many of these substances, in particular the organics, are destroyed. However, by applying sewage sludge in or on soils, as a (cheap) fertiliser in agriculture, sewage sludge ingredients of concern can reach the soil and thus the environment. Despite the legal regulations in the Sewage Sludge Ordinance and the fertiliser legislation a transfer of individual substances into the food cycle cannot always be completely ruled out.

The use of sewage sludge in agriculture always involves a possible risk of proliferation of pathogens and antibiotic-resistant bacteria for humans, animals and plants. A specific hygiene guideline is currently available only for salmonellae. Therefore, the Sewage Sludge Ordinance sets stringent restrictions for the application of sewage sludge. For example, the application of sewage sludge to vegetable and fruit growing areas, on grassland as well as in water and nature reserves, is generally not permitted. On arable land, which is used for the cultivation of field vegetables, waiting periods must be observed. In addition, demand-based application regulations for phosphorus and nitrogen limit the amount of permissible sewage sludge fertilisation.

With the amended Sewage Sludge Ordinance, which came into force on 03/10/2017, a transitional period to 01/01/2029 and 01/01/2032 was set for direct sewage sludge utilisation on soil from sewage treatment plants >100,000 or >50,000 PE. For smaller installations sewage sludge can still be used in agriculture or landscaping.

Due to the occurrence of substances of concern and pathogens, the German Environment Agency (UBA) critically assesses the direct use of sewage sludge on soil under preventive measures and advocates as far as possible the abandonment of this type of use. First steps have been taken in this direction by the requirements of the new Sewage Sludge Ordinance.

By refraining from using sewage sludge fertilisation, the organic substance within the sewage sludge is no longer able to act as a humus-former in the soil. To compensate for the missing quantity of humus or a possible negative humus balance in the soil, replacement measures must be taken that correspond to good professional practice in agriculture according to the Federal Soil Protection Act (BBodSchG). UBA assumes that intelligent humus management (e.g. via crop rotation methods) and the ongoing expansion of bio-waste collection and recycling can help bridge this gap. Manure fertilisers (such as manure, fermentation residues) can also be used if they meet the legal requirements. Many places have already switched to alternative measures, due to the decline in agricultural sewage sludge application.

The sewage sludge produced in Germany offers a recovery potential of about 50,000 tonnes of phosphorus per year. With the amendment to the Sewage Sludge Ordinance and the compulsory recovery of phosphorus, a legal basis was created for technically exploiting a considerable part of the recoverable potential in the future.

The amended Sewage Sludge Ordinance stipulates that at a level of ≥ 20g phosphorus in sewage sludge (TS) at least 50 % of this phosphorus must be recovered at the sewage treatment plant or the phosphorus content should be reduced to below 20 g/kg.

If the sewage sludge is treated thermally, at least 80 % of the phosphorus contained in the incineration residue must be recovered. Alternatively, the long-term storage of incineration ash or carbonaceous residues is possible if mixing and loss of the phosphorus are excluded and the subsequent recovery or use of phosphorus is ensured.

For the recovery of phosphorus, the sewage treatment processes (for example precipitation) come into question – either that which re-dissolves and/or precipitates a sufficient amount of phosphorus from the sewage sludge or sludge water, or thermal or downstream thermal treatment processes, in which the material recovery of incineration ashes or carbonaceous residues for fertiliser or other material uses is possible. Since many of the developed processes either achieve too low a recovery rate or are rarely tested on an industrial scale, it is still currently necessary to further develop and promote appropriate technologies. Statements about which phosphorus recovery processes will prevail in the future cannot so far be made since the selection of the appropriate process depends on many factors (e.g. size and mode of operation of the wastewater treatment plant and/or incineration plant, heavy metal content of the sewage sludge ash, regional connection of the wastewater treatment plant to incineration plants, transport costs, price development of phosphorus on the world market, etc.).

For the thermal treatment of sewage sludge, which due to new legislation can no longer be used on soil in the future, further capacities are required, i.e. additional incinerators. The expansion of these capacities is already taking place. In co-incineration of sewage sludge, for example, in cement plants, coal-fired power plants or waste incineration plants, although fossil fuels can be saved, valuable phosphorus is still currently being withdrawn from the cycle. This is because, as a rule, no previous phosphorus recovery from the sewage sludge takes place. Either the phosphorus is solidly embedded in the product or so heavily diluted in slag and other combustion residues that recovery is not economically viable.

Therefore, co-incineration of sewage sludge in accordance with the Sewage Sludge Ordinance will only be permitted in future if the phosphorus in the sewage sludge has a content of less than 20 g/kg TS, or it was previously removed from the sewage sludge using a suitable technique, or no dilution effect of the phosphorus has taken place in the incineration residues. The latter is possible, for example, in the thermal treatment of sewage sludge with low-ash coals. If the sewage sludge remains undiluted or separated, i.e. it is treated in mono-incineration plants, then the recovery or the recycling of the ashes must be guaranteed.

According to current understanding, the financing of phosphorus recovery at wastewater treatment plants can be allocated to the sewage charge [DPP]. This ensures financing at a municipal level. It is estimated that the expected additional costs for consumers switching from agricultural use to thermal treatment, combined with phosphorus recovery, will increase wastewater charges only marginally (around € 3-11 per inhabitant per year).

The changeover from direct use on soil to thermal sewage sludge treatment with upstream or downstream phosphorus recovery brings with it other benefits in addition to the avoidance of possible hygiene and material risks to soil and the environment, as well as the possibility of nutrient recycling.

As the properties of raw phosphates may continue to deteriorate in quality in the future, and the price may increase due to higher global demand, the implementation of phosphorus recovery offers the advantage of Germany becoming somewhat less dependent on imports of mineral phosphates. In addition, the changeover will open up new markets while a positive impact on technology transfer can be expected. In addition, recovery installations and incineration capacities would create jobs.

In UBA's opinion, the following measures are necessary for the successful implementation of the requirements of the amended Sewage Sludge Ordinance and for consideration of future developments beyond this:

- The pollutant limit values in Sewage Sludge Ordinance (AbfKlärV) and Fertiliser Ordinance (DüMV) should continue to be updated until there is a complete withdrawal from sewage sludge utilisation on soil. In addition, from the point of view of precautionary soil and health protection, consideration must be given to previously unrecognised pollutants (e. g. residues of medicines) as to whether they should be regulated in the medium term by means of limit values.

- Implementation of an effective separation of pollutants from sewage sludge, for example, the separation from the municipal sewage system of those discharges with high health risks, such as hospitals.

- The hygiene requirements for sewage sludge which can still be used on agricultural land or in landscaping measures, should continue to be reviewed and, if necessary, adjusted. In doing so, it would be possible to minimise the risk of a spread of pathogens and antibiotic resistance that cannot be excluded through further treatment of sewage sludge (sanitation measures).

- As far as possible, wastewater treatment should be converted to processes that support phosphorus recovery (e. g. conversion to biological phosphorus elimination and reduction of iron precipitation, as poor nutrient availability of recyclates).

- The (mono) incineration capacities should continue to be thoughtfully expanded. Concepts should be developed that take into account both the phosphorus recovery and energy efficiency aspects (infrastructure, transport routes, waste heat recovery, etc.).

- Co-incineration of sewage sludge in coal-fired power plants and cement works, as well as in waste incinerators, should continue to be used if the phosphorus content can be sufficiently depleted or for low-phosphorus sewage sludge – and adapted to the development of future capacities.

- The new requirements largely cause increased costs for dewatering, drying and transport of sewage sludge. Therefore, energy- and cost-effective ideas for sewage sludge drying (e. g. drying at the site of the incineration plant, for example by means of waste heat recovery) should preferably be implemented.

- The (further) development, and in particular the large-scale implementation of promising phosphorus recovery processes, should continue to obtain, e. g. financial assistance from support programmes.

- In the development of phosphorus recovery processes with the aim of directly using the recyclate as a fertiliser, sufficient nutrient availability (plant availability of the phosphorus) and reduction of pollutants should be promoted.

- For good quality, the newly developed fertilisers from or with recovered phosphorus must facilitate access to the market (e. g. end of waste properties).

- Legal requirements should be successively updated in order to ensure a high proportion of recovered phosphorus from relevant material flows and to enable a long-term complete withdrawal from soil-related use.

Only through the combination of these measures can the goal of environmentally sound disposal of sewage sludge be guaranteed and independent and resource-saving phosphorus recovery and utilisation realised.

Directories and annexes

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Laws/Regulations

AbfKlärV	Sewage Sludge Ordinance
BBodSchV	Fed. Soil Protect. and Contam. Sites Ordinance
BImSchG	Federal Immission Control Act
KrWG	Circular Economy Act
DepV	Landfill Ordinance
DüMV	Fertiliser Ordinance
DüngG	Fertiliser Act
DüV	Fertiliser Application Ordinance
17. BImSchV	17th Ordinance for the Implementation of the Federal Immission Control Act
TA-Luft	Technical Instructions on Air Quality Control
TA-Si	Technical Instructions on Municipal Waste

Authorities/Institutes

BMBF	Federal Ministry of Education and Research
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
DWA	German Association for Water, Wastewater and Waste
EFSA	European Food Safety Authority
DPP	German Phosphorus Platform
EC	European Commission
EG	European Community
EU	European Union
EU-27	27 Member States of the European Union
EPA	United States Environmental Protection Agency
FAO	Food and Agriculture Organization
HELCOM	Baltic Marine Environment Protection Commission – Helsinki Commission
GTK	Geological Survey of Finland
ITAD	Public Interest Group of Thermal Waste Treatment Plants in Germany
IWA	Institute for Water Quality
IWW	Rhineland-Westphalian Institute for Water Research
LAGA	Government/States Waste Working Group
LfL	Bavarian State Office for Agriculture
OECD	Organisation for Economic Co-operation and Development
SRU	German Advisory Council on the Environment
UBA	German Environment Agency
USGS	United States Geological Survey
VDZ	German Cement Works Association

Chemical compounds/elements

As	Arsenic
AOX	Adsorbable organic halogen compounds
B(a)P	Benzo(a)pyrene
C	Carbon
Ca	Calcium
$Ca(OH)_2$	Calcium hydroxide
Cd	Cadmium
Cl	Chlorine
Co	Cobalt
CO_2	Carbon dioxide
Cr	Chromium
Cr(VI)	Chromium (VI)
Cu	Copper
DEHP	Di(2-ethyl-hexyl)phthalate
Fe	Iron
F	Fluorine
H	Hydrogen
Hg	Mercury
H_2O	Water
K	Potassium
K_2O	Potassium oxide
LAS	Linear alkyl sulfonate
MAP	Magnesium ammonium phosphate
Mg	Magnesium
$MgNH_4PO_4$	Magnesium ammonium phosphate
MKW	Petroleum hydrocarbon
Mn	Manganese
N	Nitrogen
Na	Sodium
Ni	Nickel
O	Oxygen
P	Phosphorous
PAH	Polycyclic aromatic hydrocarbons
Pb	Lead
PFT	Perfluorinated tensides
PCB	Polychlorinated biphenyls
PCDD/PCDF	Polychlorinated dibenzodioxins/furans
P_2O_5	Phosphorus pentoxide
S	Sulphur
Sb	Antimony
Se	Selenium

Sn	Tin
Th	Thallium
TBT	Tributyltin
Zn	Zinc
V	Vanadium

Parameters

IR	Ignition residue [%]
IL	Ignition loss [%]
LCV	Lower calorific value [kJ/kg, MJ/kg]
pH	pH value [-]
TEQ/TE	Toxic equivalents [-]
TS	Total solids [mg, g, kg]
TOC	Total organic carbon [%; mg/l; mg/m³]
DR	Dry residue [%]
DS	Dry substance [mg, g, kg]
TS_R	Total solids content [kg/m³, g/L]
WC	Water content [%]
WM	Wet mass

Units

a	Year
d	Day
€	Euro
ha	Hectare (10,000 m^2)
kg	Kilogram (10^3 g)
kJ	Kilojoule (10^3 Joule)
kt	Kilotonne (10^9 g)
l	Litre
m^3	Cubic metre
MJ	Megajoule (10^6 Joule)
µg	Microgram (10^{-6} g)
mg	Milligram (10^{-3} g)
nm	Nanometer (10^{-9} m)
t	Tonne (10^6 g)
%	Percent

Further abbreviations

ATS	Aerobic thermophilic sludge stabilisation
CHP	Block heating power plant
EAggEC	Enteroaggregative Escherichia coli
EHEC	Enterohemorrhagic Escherichia coli
PE	Population equivalent
HTC	Hydrothermal carbonisation

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Annex I

Table 22

Technical data for mono-incinerators of municipal sewage sludge (as of 2012)

Location	State (Land)	Operator	Capacity [t/a]	DR [%]	Capacity [t DS/a]
Altenstadt	BV	Emter GmbH	160,000	25–30	55,000
Balingen	BW	Joint Administration Wastewater Treatment Balingen	1,500	75–80	1,200 (Expanded to 2,400)
Berlin-Ruhleben	BE	Berlin Water Works	325,000	26	84,100
Bitterfeld-Wolfen*	SA	Community Wastewater Company mbH & Co. KG Greppin	50,700	25–90	15,200
Bonn	NW	Civil Engineering Office Bonn	29,100	23,5	8,000
Bottrop	NW	Emscher cooperative	110,000	40	44,000
Dinkelsbühl	BV	KSV GmbH	21,425	25–30	5,326
Düren	NW	Water Board Eifel-Rur	35,000	40	14,000
Elverlingsen-Werdohl	NW	WFA E Elverlingsen GmbH	200,000	28–32	61,320
Frankfurt am Main	HE	City Drainage Frankfurt am Main	188,000	28	52,560
Gendorf*	BV	Infraserv	40,000	20–35	10,000
Hamburg	HH	VERA Sewage Sludge Incineration GmbH	197,100	40	78,840
Herne	NW	BAV Processing Herne GmbH	50,000	25–90	22,200
Karlsruhe	BW	City of Karlsruhe	80,000	25	20,000
Lünen	NW	Innovatherm GmbH	235,000	25–95	95,000
München	BV	Munich City Drainage	88,000	25	22,000
Stuttgart	BW	Civil Engineering Office Stuttgart	130,000	25	32,000
Neu-Ulm	BV	Joint Administration Wastewater Treatment Steinhäule	64,000	25	16,000
Wuppertal	NW	Wupperverband	128,000	25	32,000
Sande/Wilhelmshaven	LS	Spitz GmbH	N/A	N/A	2,250
Straubing	BV	Huber SE	9,000 t/a dewatered SS	28	2,500
Mannheim	BW	Kopf	10,800	N/A	N/A

* Verbrennen kommunalen und industriellen Klärschlamm. Deshalb auch Nennung in Tabelle 23.

			Input		Drainage	
	Commissioning [-]	Operating hours in 2009 [h/a]	Sludge condition (Raw/digested sludge) [-]	Sludge type [-]	Aggregate for dewatering [-]	Residual water content (average) [%]
	2008	7,000	N/A	Municipal sewage sludge	Decanter	N/A
	2002	N/A	Digested sludge	Sewage sludge	Chamber filterpress	69
	1985	8,760	Raw sludge 3,5 % DS	Sewage sludge	Centrifuge	74
	1997	7,738	Raw sludge	Industrial and municipal sewage sludge	Centrifuge	74
	1981	6,854	Digested sludge	Sewage sludge, scum	Centrifuge	76,5
	1.991	7,800	Digested sludge	Sewage sludge	Membrane-filterpress	60
	2008	4,309 (out of service since 2010)	Digested sludge	Municipal SS	N/A	72
	1975	8,400	2009 Raw sewage; (from 2010 also digested sludge)	Sewage sludge	Centrifuge	74
	2002	7,.313	Digested sludge	Sewage sludge	KFP ZF	68–72
	1981	6,851 per line on average; 20,552.5 total of 3 lines in parallel operation	Raw sludge	Sewage sludge	Centrifuge	71
	2006	N/A	Raw sludge	Industrial and municipal sewage sludge	Decanter	26
	1997	23,463 h = 3 lines = 7,821 per line	Digested sludge	Sewage sludge	Centrifuge	78
	1990	N/A	Digested sludge	Sewage sludge	N/A	10–75
	1982	6,500	Raw sludge	Sewage sludge, screenings, fatballs	Centrifuge	75
	1997	7,850	Digested sludge	Sewage sludge, Filter cake	Centrifuges, Membrane-filterpress	60
	1997	8,430	Digested sludge	Sewage sludge	Centrifuge	72
	2007	Line 3: 4,809	Raw-, digested-, excess-sludge	Sewage sludge, screenings, fatballs	Centrifuge	75
	1979	N/A	Raw sewage/ digested sludge	Sewage sludge, screenings, sand- and fatballs	Centrifuge	75
	1977	8,586	Digested sludge	Sewage sludge	Centrifuge, Chamber filterpress	75
		Out of service	Digested sludge	Sewage sludge	external	N/A
	2012	Designed for 7,500 h/a	Digested sludge	Sewage sludge, screenings	Centrifuge	72
	2010	7,000 h/a planned	Digested sludge	Sewage sludge, screenings	N/A	N/A

Source: [UBA's OWN SURVEY]

General	DRYING			
Location	Aggregate [-]	Residual water content after drying [%]	Incineration technology [-]	Incineration units [-]
Altenstadt	Thermal oil cycle	25–30	Grate firing	2 furnaces
Balingen	Solar drying	20–25	Fluidised bed gasifier	Gasification line
Berlin-Ruhleben	N/A	N/A	Static fluidised bed	3
Bitterfeld-Wolfen*	Disk dryer	55	Static fluidised bed	1
Bonn	N/A	N/A	Static fluidised bed	2
Bottrop	N/A	N/A	Static fluidised bed	2
Dinkelsbühl	Belt dryer	‹ 10	Pyrobuster	1
Düren	Disk dryer	60	Static fluidised bed	1
Elverlingsen-Werdohl	N/A	N/A	Static fluidised bed	1
Frankfurt am Main	Floor fluidised bed	ca. 30 (entry into fluidised bed)	Floor fluidised bed	4
Gendorf*	Disk dryer	50	Fluidised bed	1
Hamburg	Disk dryer	58	Static fluidised bed	3
Herne	N/A	N/A	Static fluidised bed	1
Karlsruhe	Disk dryer	55	Static fluidised bed	2 (1+1)
Lünen	N/A	N/A	Fluidised bed	1
München	Contact disk dryer	55	Static fluidised bed	2
Stuttgart	Diskdryer	55	Static fluidised bed	2
Neu-Ulm	Thin-layer dryer	60	Static fluidised bed	2
Wuppertal	Thin-layer dryer	55	Static fluidised bed	2
Sande/Wilhelmshaven	Fluid bed dryer	15	Cycloid combustion chamber	1
Straubing	Belt dryer	35	Grate (entrained inciner-ation)	1
Mannheim	Drum dryer	N/A	Fluidised bed gasifica-tion	1

* Incinerated municipal and industrial sewage sludge. Hence mentioned in Table 23

INCINERATION					
	Calorific value of sewage sludge as annual average [kJ/kg]	Theor. capacity per unit (average) [t DS/h]	Actual amount incinerated 2009 [t DS/a]	Manufacturer Incineration unit [-]	Additional fuel [-]
	8,000	each 2.5 t TS/h	23.000	N/A	N/A
	N/A	0.18	N/A	Kopf	Biogas
	ca. 17 MJ/kg DR	3.20	41,128	Uhde	Heating oil
	5,950 oder 10,200 kj/kg DS	2	10,262	Uhde	Natural gas
	N/A	1.42	6,600	Raschka	Biogas, heating oil
	4,500	3.00	46,000	Raschka	Heating oil
	10.9 / 11.8	0.6	1,290	Eisenmann AG	Heating oil/propane
	2009: 14,604 kJ/kg DS only raw sludge incinerated (2010: raw sludge: 12,820 kJ/kg DS, digested sludge: 3,700 kJ/kg DS)	1.75	10,924	Lurgi	Natural gas
	1,000 in OS or between 10,000 and 13,000 kJ/kg DS	7.00	185,421	TKEC	Coal/ natural gas/heating oil/ surrogate fuel
	17,000 kJ/kg DS; 3,100 kJ/kg damp	2.00	33,946	Lurgi	Heating oil (light oil)
	N/A	1.25	N/A	N/A	Natural gas
	3,650; (or 13 MJ/kg DR in 2009). 2010: 13.6 MJ/kg DR	3.4	60,256	AE & E	Heating oil, biogas
	N/A	8	N/A	Raschka	Heating oil
	14,000–15,000	1.90 2.70	13,000	Raschka	Heating oil
	4,000	13	12	Raschka	Heating oil
	4,500 /10,000	3	21,421	Raschka	Sewer gas
	13.8 MJ/kg DS	4.00	22,700	Bamag	Sewer gas, heating oil
	N/A	2.00	16,389	Thyssen	Heating oil
	Annual calorific value (weighted): 12,100 kJ/kg DS; Range: 9,300 to 14,370 kJ/kg DS	4.60	29,557	Thyssen	Heating oil
	N/A	0.30	0	Steinmüller	Natural gas
	7,000 kJ/kg	530 kg/h	3,500	Fa. Zauner	N/A
	N/A	N/A	N/A	Kopf	N/A

Source: [UBA's OWN SURVEY]

GENERAL	HEAT USE					
Location	Aggregate [-]	Manufacturer [-]	Steam parameters (average) [bar/°C]	Gross electrical power [MW]	Energy use [-]	Emission control lines [-]
Altenstadt	Thermal oil boiler	N/A	N/A	N/A	Heat for drying	1
Balingen	CHP	Kopf / EAG	N/A	N/A	Electricity, heat	1
Berlin-Ruhleben	Water pipe boiler (natural circulation)	L. & C. Steinmüller	46/460	1 x 2.8 2 x 2.0	Electricity, heat	3
Bitterfeld-Wolfen*	Natural circulaton	Bertsch	10/180	N/A	Heat	1
Bonn	Waste heat forced-flow boiler	Stahl	10/180	N/A	Electricity, heat	2
Bottrop	Forced-flow boiler	Raschka	35/400	3.5	Electricity, heat	2
Dinkelsbühl	Waste heat boiler	HTA GmbH	10/184	N/A	Drying	1
Düren	Waste heat boiler, heat transfer oil	Ohl	N/A	N/A	Heat	1
Elverlingsen-Werdohl	Steam boiler	Bertsch	17 / 320	N/A	Auxiliary steam for power plant demand	1
Frankfurt am Main	Steam boiler	Lentjes	38/380	3	Electricity, heat	4
Gendorf*	N/A	N/A	20/215	N/A	N/A	N/A
Hamburg	Natural circulation boiler	AE & E	40/400	32 DT and steam AHK	Electricity, heat	3
Herne	Rotary dryer for sludge	Hoffmeyer	N/A	N/A	Heat	2
Karlsruhe	Natural circulation boiler	Raschka, Oschatz	25/300 25/300	N/A	Electricity, heat	2
Lünen	Natural circulation boiler	Noell-KRC	40/400	8.5	Electicity	1
München	Waste heat boiler	Wamser	40/400	0.27	Heat for own use, electricity	4
Stuttgart	Waste heat boiler	Bertsch	63/410	1.2 MW	Electricity, heat	2
Neu-Ulm	Water pipe boiler	UMAG, Baumgarte	24/250 40/400	N/A	Electricity, heat	4
Wuppertal	Waste heat boiler with natural circulation	Blohm + Voss	31/355	N/A	Electricity, heat	2
Sande/Wilhelmshaven	Waste heat boiler with natural circulation	Wulff	19/210	N/A	Heat	4
Straubing	Heat exchanger/micro gas turbine	Turbine: Turbec	N/A	80 kW el.	800 kW therm.	1
Mannheim	CHP	N/A	N/A	3.6 MW	Heat	1

* Incinerated municipal and industrial sewage sludge. Hence mentioned in Table 23

EMISSION CONTROL				SLAG OR ASH RECOVERY/DISPOSAL	
Dust separator [-]	Further emission control [-]	Further emission control [-]	Further emission control [-]	Recovery/ elimination in [-]	Amount t/a
Cyclone + fabric filters after air stream adsorber	Denitrification (SNCR)	Entrained flow absorbent	2-stage washer	Mainly agricultural use otherwise asphalt mixing plant	8,500
Cyclone + ceramic filter	Wet washer	Tar condensation	N/A	Asphalt mixing plant	500
Electrostatic filter	Wet/absorber	N/A	N/A	Mine stowage	14,400
Electrostatic filter, fabric filter	Wet/2-stage washer	Entrained flow absorbent	N/A	Mine stowage	5,233
Electrostatic filter	Semi-dry/absorber	Entrained flow absorbent	N/A	Landfill capping	3,200
Electrostatic filter	Wet/2-stage NaOH-washer	N/A	N/A	Asphalt mixing plant	18,000
Cyclone	Sorbents	Dust filter	N/A	Tested as construction aggregates on landfills	to 1,700 (442 in 2009)
Wet washer	SO_2 washer	Fixed bed filter for mercury separation	SNCR-plant	Landfill/landfill construction	3,467
Electrostatic filter	Spray dryer, acid washer, SO_2 washer	Activated carbon + fabric filter	N/A	Landfill/landfill construction	35,000
Electrostatic filter	Wet/4-stage washer	Fixed bed adsorber (Activated carbon)	N/A	Mine stowage	6,803
N/A	N/A	N/A	N/A	N/A	N/A
Electrostatic filter	Wet/quencher, counter-current scrubber	Entrained flow absorbent	N/A	Copper smelter, fly ash	21,834
Fabric filter	Dry sorption	Primary additive	N/A	Asphalt mixing plant	8,900
Electrostatic filter	Wet/oxidation Venturi scrubber, 3-stage	N/A	N/A	Mine stowage	4,000
Electrostatic filter, fabric filter	Semi-dry 2-stage washer	Entrained flow absorbent	N/A	Landfill/landfill construction	40,000
Electrostatic filter	Fabric filter	2-stage washer	Wet electrostatic filter	Landfill/landfill construction	8,500
Electrostatic filter	Semi-dry/jet wash, filler scrubber	Entrained flow absorbent + activated carbon	Electrostatic filter 2	Mine stowage	8,220 (2009)
Electrostatic filter, fabric filter	Semi-dry/jet ash, filler scrubber	Dry additive, fabric filter, entrained flow absorbent	N/A	Mine stowage	7,400
Electrostatic filter	Wet/2-stage washer; acidic without installations, basic with filler	Active coke adsorber and fabric filter	N/A	Mine stowage	12,412
Fabric filter, Hot gas-cyclone	Dry/evaporation cooler	Stove coke filter	N/A	N/A	N/A
Hydrocyclone	Fabric filter	SNCR	Lime injection	P recycling planned	1,400 t/a
Ceramic filter	Dryer	2-stage gas washer	N/A	N/A	N/A

Source: [UBA's OWN SURVEY]

Table 23

Technical data of operators' own sewage sludge incineration plants (as of 2012)

	GENERAL					
Location	State (Land) [-]	Operator [-]	Technology [-]	Continuous operation from [-]	Operating hours [h/a]	Capacity [t/a]
Burghausen	BV	Wacker Chemie	1 fluidised bed	1976	N/A	20,000
Frankenthal-Mörsch	RP	BASF AG	2 fluidised beds	1992	Oven1: 7,158 Oven2: 6,445	420,000
Frankfurt Hoechst	HE	Infraserv GmbH	2 fluidised beds	1994	Str I: 8,164h; Str II: 8,055h	205,000
Leverkusen	NW	Currenta GmbH	1 multiple-hearth furnace	1988	8,000	120,000
Marl	NW	Infracor GmbH	1 fluidised bed	1980	N/A	40,000
Bitterfeld-Wolfen	SH	GKW	Technical data in Table 22			
Gendorf/Burgkirchen	BV	Infraserv GmbH	Technical data in Table 22			

GENERAL	INCINERATION					
Location	Residual water content after drying [%]	Incineration technology [-]	Incinerator units [-]	Calorific value of sewage sludge, annual average [kJ/kg]	Theor. capacity per unit (average) [t DS/h]	Amount actually incinerated in 2009 [t DS/a]
Burghausen	60	Stat. fluid. bed	1	N/A	0.6	N/A
Frankenthal-Mörsch	N/A	Stat. fluid. bed	2	2,000	7 t TR	110,000
Frankfurt Hoechst	N/A	Stat. fluid. bed	2	3,500	4.2	70,000
Leverkusen	N/A	Multiple-hearth furnace	1	4,200	4.5	23,387
Marl	N/A	Stat. fluid. bed	1	N/A	3	N/A
Bitterfeld-Wolfen	Technical data in Table 22					
Gendorf/Burgkirchen	Technical data in Table 22					

GENERAL	EMISSION CONTROL			
Location	Energy use [-]	Emission control line [-]	Dust collector [-]	Further emission control [-]
Burghausen	Steam for drying	1	Cyclone	Pre-saturator and Venturi scrubber
Frankenthal-Mörsch	Heat, electricity	2	Electrostatic filter	Wet/filler column
Frankfurt Hoechst	Heat, steam	2	Electrostatic filter	Wet/2-stage wet washer
Leverkusen	Heat, steam	1	Wet/injection cooler, 2-stage rotary scrubber, jet scrubber	Entrained flow reactor
Marl	Steam	4	Fabric filter	Dry and wet
Bitterfeld-Wolfen	Technical data in Table 22			
Gendorf/Burgkirchen	Technical data in Table 22			

		INPUT		DEWATERING		DRYING	
	DR [%]	Capacity [t TS/a]	Sludge condition (raw/digested sludge) [-]	Sludge types [-]	Aggregate for dewatering [-]	Total residual water content (average) [%]	Aggregate [-]
	21	4,125	Raw sludge	(Com. +) industrial sewage sludge	Belt filter press	80	Thin-layer dryer
	40	110,000	Raw sludge	Industrial sewage sludge	Chamber-/membrane filterpress	57	N/A
	35	80,000	Raw sludge	Com. + industrial sewage sludge	Membrane filterpress	65–70	N/A
	27–40	36,000	Raw sludge	Industrial sewage sludge	Membrane filterpress	60	N/A
	25	10,000	Raw sludge	Com. + industrial sewage sludge	Clarifier, sieve belt press	75	N/A

		HEAT USE				
	Incinerator units [-]	Additional fuel [-]	Aggregate [-]	Manufacturer [-]	Steam parameters (average) [bar/°C]	Electric gross power [MW]
	Lurgi	Natural gas	Waste heat boiler	Wehrle	16.5/200	N/A
	Rheinstahl/ MAB-Lentjes	Hard coal, surrogate fuel, heating oil EL	Natural circulation	Lentjes	63/420	max. 13 MW (2009: 60,190 MWh (gross)
	Uhde	Coal, heating oil, natural gas	Waste heat boiler, natural circulation	MAN/GHH	16/280	N/A
	Lurgi	Natural gas, heating oil substitute in after- burner	Radiation channel, superheater, economiser	Lentjes	41/360	N/A
	Raschka	Natural gas, in-house fuel gases	Waste heat boiler	Wehrle	25/220	N/A

		SLAG UTILISATION/DISPOSAL		
	Further emission control [-]	Further emission control [-]	Recovery/disposal [-]	Amount t/a
	Aerosol separator	Absorption washer	N/A	N/A
			Avoidance, mine stowage in salt domes	42,736 (SS+coal+surrogate fuel)
	None	None	Landfill, mine stowage	33,000
	N/A	Disposal, Leverkusen hazardous waste landfill	16,992	N/A
	SCR, fixed bed adsorber		N/A	N/A

Source: [UBA's OWN SURVEY]

Table 24

Plant data from waste incineration installations that co-incinerate sewage sludge (as of 2016)

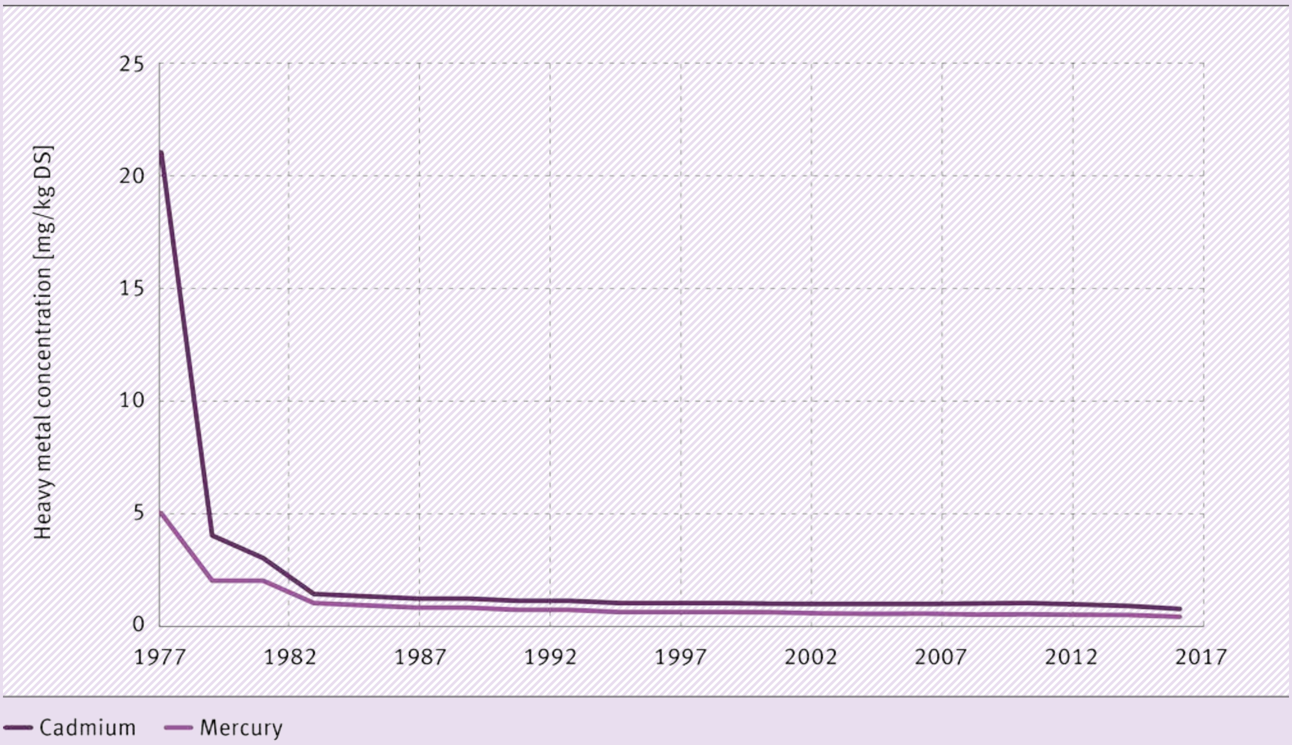
Location	State (Land)	Operator	Quantity of incinerated sludge from municipal wastewater treatment (AVV 190805 only) in Mg DR/a in 2016
Asdonkshof	NW	Waste Disposal Centre Asdonkshof	7,993
Bamberg	BV	Joint Administration for Waste-to-energy Plant Bamberg	3,773
Bremen	HB	Waste-to-energy Bremen	3,723
Coburg	BV	Joint Administration for Waste Management in North West Upper Franconia	1,407
Großräschen	BB	EEW Energy from Waste Großräschen GmbH	2,185
Helmstedt	LS	EEW Energy from Waste Helmstedt GmbH	2,118
Herten	NW	AGR Operation Management GmbH	873
Ingolstadt	BV	Joint Administration for Waste Recovery Plant Ingolstadt	2,064
Krefeld	NW	EGK Disposal Company Krefeld GmbH & Co. KG	7,795
München	BV	Waste-to-energy Plant München North	291
Neunkirchen	SL	Waste Heat Power Plant Neunkirchen	186
Olching	BV	AHKW Geiselbullach	414
Salzbergen	LS	Thermal Waste Treatment Plant Salzbergen (TAS)	3,962
Schweinfurt	BV	GKS-Community Power Plant Schweinfurt GmbH	315
Würzburg	BW	Joint Administration Waste Management Würzburg	1,596
Zella-Mehlis	TH	Joint Administration for Waste Management South-west Thuringia (ZASt)	385
9 other unnamed installations			3,242
Average			*2,489*
Total			**42,320**

Quelle: [ITAD]

Annex II

Figure 17

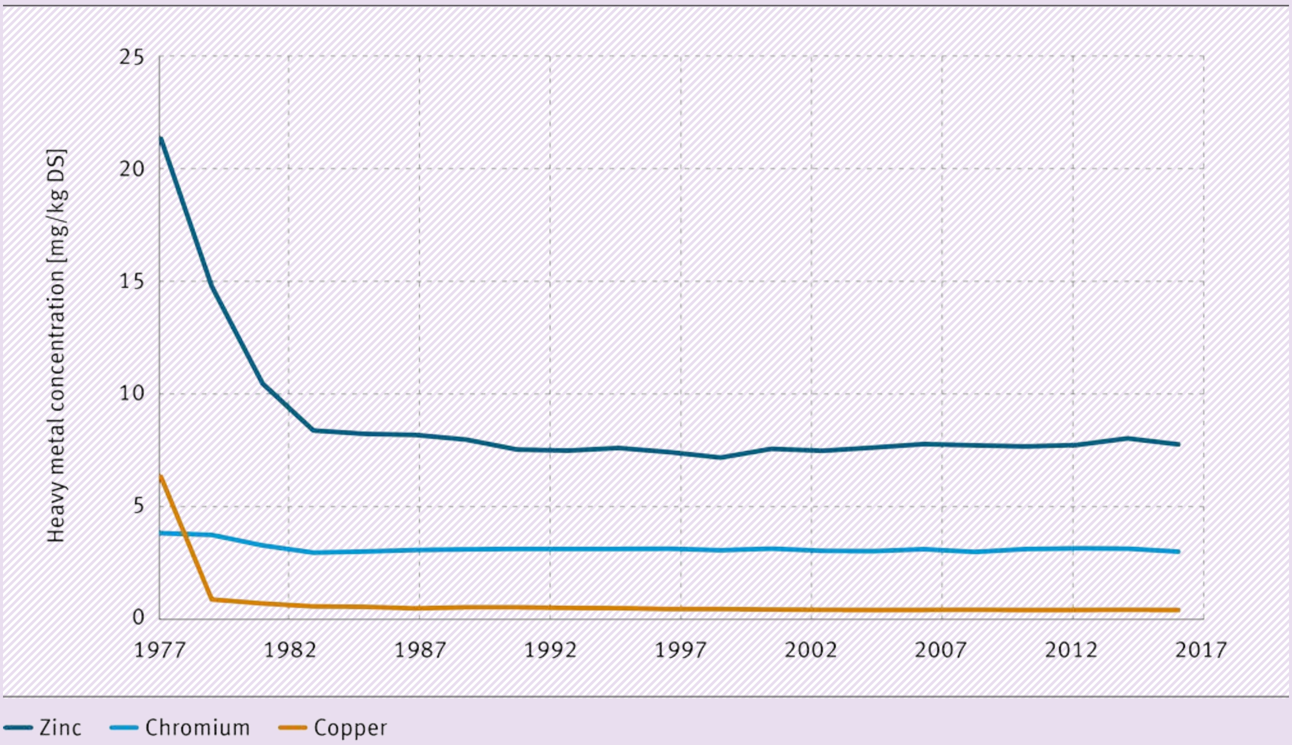
Heavy metal concentrations of cadmium and mercury from 1977 to 2015



Source: [UBA's illustration based on the states' sewage sludge reporting pursuant to Commission Decision 94/741/EC]

Figure 18

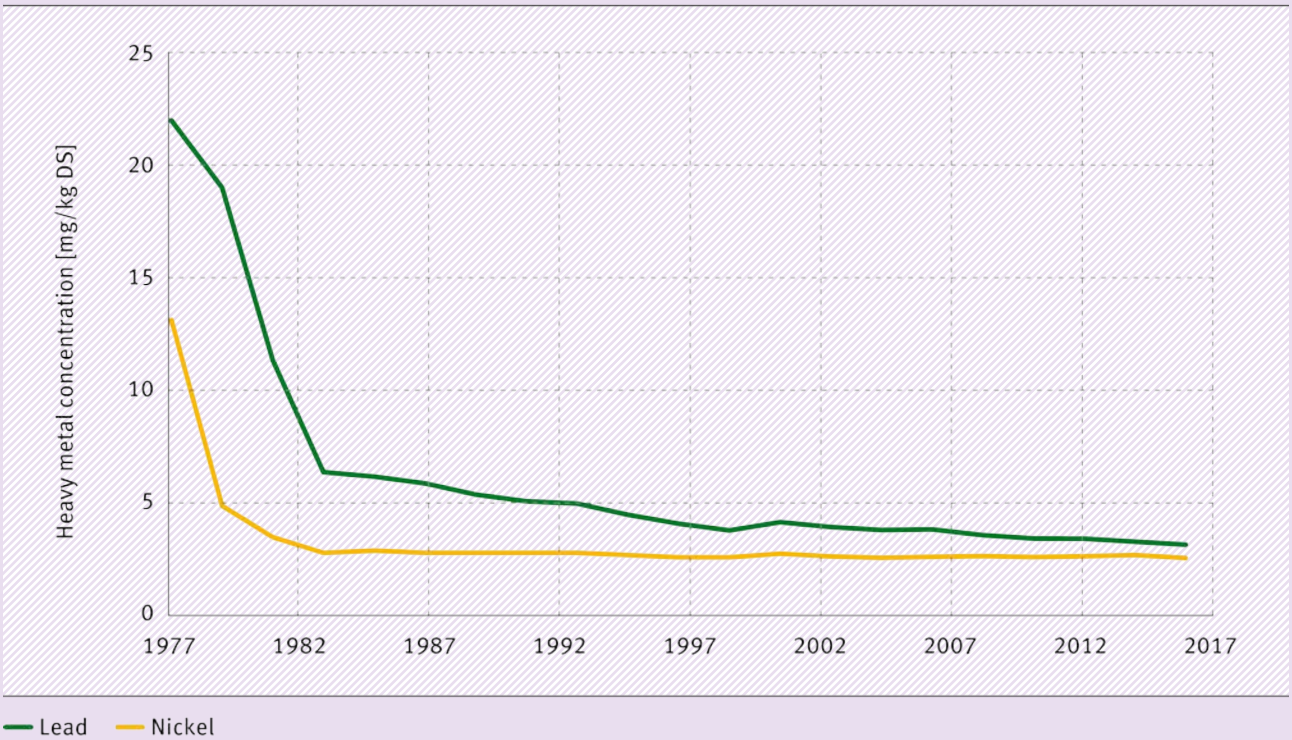
Heavy metal concentrations of chromium, copper and zinc from 1977 to 2015



Source: [UBA's illustration based on the states' sewage sludge reporting pursuant to Commission Decision 94/741/EC]

Figure 19

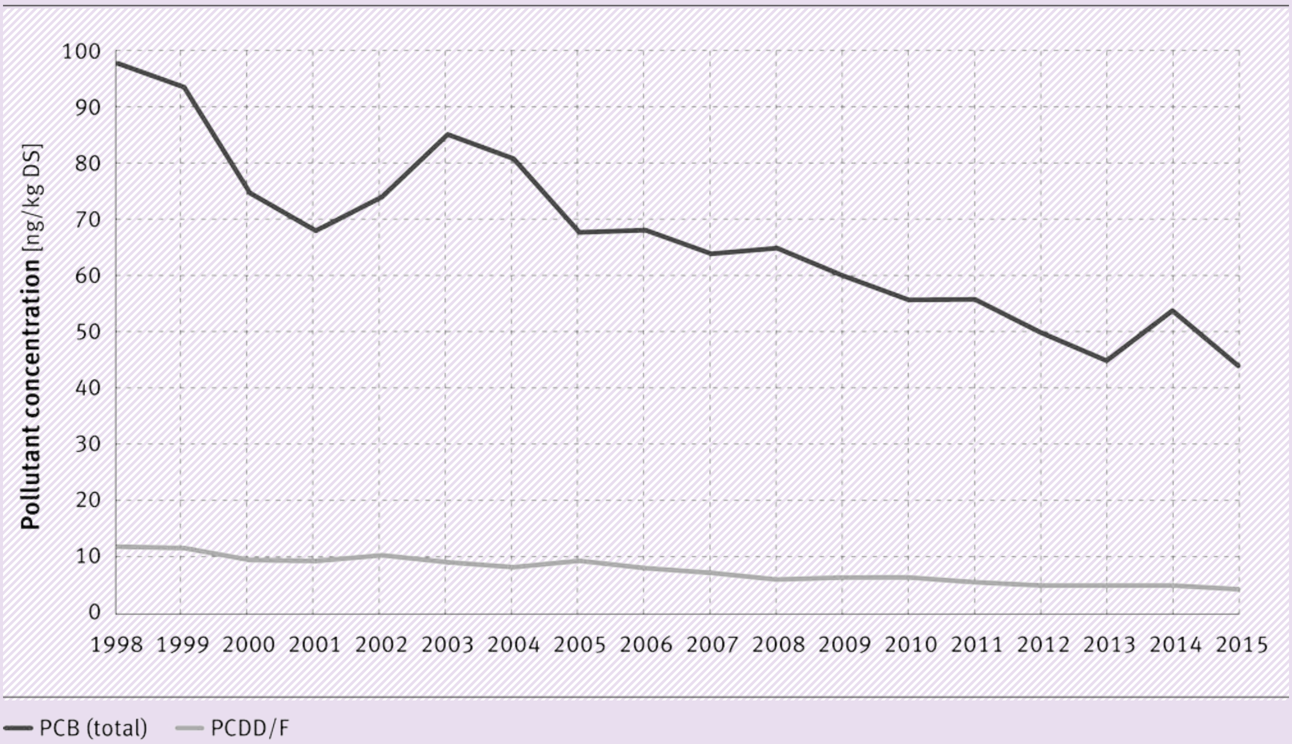
Heavy metal concentrations of nickel and lead from 1977 to 2016



Source: [UBA's illustration based on the states' sewage sludge reporting pursuant to Commission Decision 94/741/EC]

Figure 20

Pollutant concentrations of PCB (total) and PCDD/F from 1998 to 2015



Source: [UBA's illustration based on the states' sewage sludge reporting pursuant to Commission Decision 94/741/EC]

Figure 21

Pollutant concentrations of AOX from 1977 to 2015

Source: [UBA's illustration based on the states' sewage sludge reporting pursuant to Commission Decision 94/741/EC]

Annex III

Table 25

Technical parameters of sewage sludge drying plants in Germany (as of 2018)

No	Location/Operator	State (Land)	Method	Manufacturer	
1	**Albstadt**	BW	Belt dryer	Haarslev/Sevar	
2	**Allershausen**	BV	Solar dryer	IST Energietechnik	
3	**Allmendingen**	BW	Drum dryer	Andritz	
4	**Altenstadt – EMTER**	BV	Screw conveyor dryer	KonTroTec	
5	**Anhausen**	RP	Hall drying using waste heat	Kraus Umwelttechnik	
6	**Anhausen**	RP	Hall drying using waste heat	Seiler Biogasanlagen GmbH	
7	**Aschaffenburg**	BV	Hall drying using waste heat	Thermo System	
8	**Asdonkshof – Kamp-Lintford**	NW	Fluidised-bed dryer	Kraftanlagen Heidelberg	
9	**Asse**	LS	Solar dryer using waste heat	Thermo System	
10	**Augustdorf**	NW	Solar dryer using waste heat	Thermo System	
11	**Backnang**	BW	Belt dryer using waste heat	HUBER	
12	**Bad Tölz**	BV	Solar dryer	Solartiger	
13	**Balingen**	BW	Belt dryer using waste heat	HUBER	
14	**Bayreuth**	BV	Solar dryer using waste heat	HUBER	
15	**Bergen**	MV	Screw conveyor dryer	KonTroTec	
16	**Bernburg**	SA	Paddle dryer	Andritz	
17	**Bernstadt**	BW	Solar dryer	Thermo System	
18	**Bitterfeld-Wolfen**	SA	Disk dryer	Wulff / Haarslev	
19	**Blaufelden**	BW	Solar dryer	RATUS	
20	**Blindham**	BV	Solar dryer	Solartiger	
21	**Bodnegg**	BW	Solar dryer	Thermo System	
22	**Bonndorf**	BW	Hall drying using waste heat	Seiler Biogasanlagen GmbH	
23	**Bonndorf im Schwarz-wald**	BW	Hall drying using waste heat	Kraus Umwelttechnik	
24	**Bredstedt**	SH	Solar dryer	Thermo System	
25	**Bruchmühlbau-Miesau**	RP	Belt dryer	Sülzle Klein	
26	**Bruckmühl**	BV	Belt dryer	Sülzle Klein	
27	**Buch a. Erlbach**	BV	Solar dryer	Solartiger	
28	**Burgebrach**	BV	Solar dryer	Thermo System	
29	**Burgrieden**	BW	Solar dryer	IST Energietechnik	
30	**Crailshaim-Dinkelsbühl**	BV	Belt dryer	Andritz	
31	**Darmstadt**	HE	Thin-layer/disk dryer	BUSS-SMS-Canzler/Pondus	

Throughput t DS/a	Drying rate	Performance kg H_20/h	Note
5,000	90 %	1,000	Cement industry
150	60–70 %	N/A	N/A
N/A	90 %	14,300	Cement industry
30,000	90 %	2x5,600	Incineration in-house roasting furnace
3,200	90 %	N/A	Cement industry
900	› 90 %	290	Cement industry
2,700	75 %	N/A	Thermal utilisation
16,000	95 %	6,000	Co-incineration in in-house waste incinerator
88	70 %	N/A	N/A
190	75 %	N/A	N/A
3,680	90 %	1,400	Co-incineration in Heilbronn power plant
650	› 75 %	N/A	Thermal
1,876	85 %	600	Thermal utilisation (in house)
2,700	5– › 90 %	7,000	According to TR achieved, at › 90 % cement industry
N/A	N/A	550	In-house incineration
35,000	90 %	2x5,000	Cement industry
220	70–90 %	N/A	N/A
15,170	45–50 %	N/A	N/A
100	85 %	N/A	Incineration
200	80 %	N/A	N/A
90	90 %	N/A	N/A
500	› 90 %	161	Cement industry
2,000	90 %	N/A	Cement industry
108	70 %	N/A	N/A
600	88 %	240	Landscaping
266	90 %	190	Recultivation
90	› 90 %	N/A	N/A
190	70 %	N/A	N/A
300	50–90 %	N/A	Composting / recultivation
5,200	90 %	2,000	N/A
13,500	90 %	2x2,630	N/A

No	Location/Operator	State (Land)	Method	Manufacturer	
32	**Deißlingen**	BW	Belt dryer	Sevar	
33	**Düren, AV Rur**	NW	Disk dryer	Haarslev	
34	**Düsseldorf-Nord**	NW	Drum dryer	Andritz	
35	**Düsseldorf-Süd**	NW	Disk dryer	Wehrle	
36	**Edemissen**	LS	Solar dryer	Thermo System	
37	**Eißel**	LS	Solar dryer using waste heat	Thermo System	
38	**Ellwangen**	BW	Solar dryer	Thermo System	
39	**Elsenfeld**	BV	Belt dryer	Sülzle Klein	
40	**Engen**	BW	Hall drying using waste heat	Kraus Umwelttechnik	
41	**Engen**	BW	Hall drying using waste heat	Seiler Biogasanlagen GmbH	
42	**Enkenbach-Alsenborn**	RP	Belt dryer	Sülzle Klein	
43	**Erfurt**	TH	Disk dryer	Suelzle Klein (GU), Haarslev-Modul	
44	**Erfurt**	TH	Disk dryer	Sülzle Klein	
45	**Ertingen-Binzwangen**	BW	Hall drying using waste heat	Seiler Biogasanlagen GmbH	
46	**Frankenhardt**	BW	Solar dryer	Thermo System	
47	**Freiburg-Forchheim**	BW	Disk dryer	Haarslev	
48	**Freystadt**	BV	Solar dryer	HUBER	
49	**Füssen**	BV	Solar dryer	Thermo System	
50	**Gärtringen**	BW	Solar dryer using waste heat	I+M	
51	**Georgsmarienenhütte**	NW	Belt dryer	Klein	
52	**Gera**	TH	Thin-layer/disk dryer	BUSS-SMS-Canzler	
53	**Gifhorn**	LS	Thin-layer/disk dryer	BUSS-SMS-Canzler/Pondus	
54	**Großbottwar**	BW	Hall drying using waste heat	Kraus Umwelttechnik	
55	**Großbottwar**	BW	Hall drying using waste heat	Seiler Biogasanlagen GmbH	
56	**Grünstadt**	RP	Solar dryer using waste heat	Thermo System	
57	**Hagen**	LS	Solar dryer	IST Energietechnik	
58	**Hamburg/Köhlbrandhöft**	HH	Disk dryer	Haarslev	
59	**Handewitt**	SH	Solar dryer	Thermo System	
60	**Hayingen**	BW	Solar dryer using waste heat	HUBER	
61	**Heilbronn**	BW	Belt dryer	Sülzle Klein	
62	**Heilbronn EnbW**	BW	Belt dryer	Andritz	
63	**Herdwangen**	BW	Solar dryer	Thermo System	
64	**Hochdorf Assenheim**	RP	Solar dryer using waste heat	Roediger	
65	**Hohentengen am Hochrhein**	BW	Hall drying using waste heat	Kraus Umwelttechnik	
66	**Horgau-Bieselbach**	BV	Solar dryer using waste heat	Roediger	

	Throughput t DS/a	Drying rate	Performance kg H_2O/h	Note
	N/A	90 %	1,750	N/A
	11,000	40 %	2,600	Fluidised-bed incineration
	5,000	92 %	2,660	N/A
	6,300	N/A	2x3,600	Thermal utilisation
	288	75 %	N/A	N/A
	219	50 %	N/A	Agriculture
	700	70 %	N/A	N/A
	4,000	90 %	1,800	Incineration
	3,300	90 %	N/A	Cement industry
	900	› 90 %	290	Cement industry
	600	85 %	240	Landscaping
	6,250	90 %	2,431	Incineration
	5,600	90 %	2,500	Incineration
	900	› 90 %	290	Cement industry
	143	75 %	N/A	N/A
	8,000	90 %	2x1,500	N/A
	100	75 %	332	N/A
	625	70 %	N/A	2.000 m^2
	N/A	N/A	N/A	N/A
	1,800	90 %	800	Cement industry
	700	N/A	700	N/A
	1,200	90 %	264	Mono-incineration
	3,300	90 %	N/A	Cement industry
	900	› 90 %	290	Cement industry
	500	50–70 %	N/A	N/A
	180	70–80 %	N/A	Agricultural utilisation/incineration
	45,000	42 %	6x3.750	Fluidised-bed incineration
	220	75 %	N/A	N/A
	101	75 %	325	Agriculture
	5,600	90 %	2.500	Currrently decommissioned
	6,500	90 %	2.500	Co-incineration in coal-fired power plants, depending on boiler operation
	69	90 %	N/A	N/A
	1,250	90 %	N/A	Cement industry
	2,900	90 %	N/A	Cement industry
	N/A	N/A	N/A	N/A

No	Location/Operator	State (Land)	Method	Manufacturer	
67	**Huglfing**	BV	Solar dryer	IST Energietechnik	
68	**Ingolstadt**	BV	Belt dryer using waste heat	HUBER	
69	**Innerstetal**	LS	Thin-layer/screw conveyor dryer	BUSS-SMS-Canzler/Pondus	
70	**Itzehoe**	SH	Solar dryer using waste heat	Thermo System	
71	**Jerxheim**	LS	Solar dryer using waste heat	Thermo System	
72	**Juist**	LS	Solar dryer using waste heat	Thermo System	
73	**Karlsfeld**	BV	Solar dryer	IST Energietechnik	
74	**Karlsruhe**	BW	Disk dryer	Haarslev	
75	**Karlstadt**	BV	Belt dryer	Andritz	
76	**Kempten**	BW	Belt dryer	Sülzle Klein	
77	**Kirchheim am Neckar**	BW	Solar dryer	Thermo System	
78	**Kisslegg**	BW	Solar dryer	I+M	
79	**Koblenz**	RP	Belt dryer	Sülzle Klein	
80	**Krefeld**	NW	Disk dryer	Wehrle	
81	**Kreßberg**	BW	Solar dryer using waste heat	Thermo System	
82	**Kusterdingen**	BW	Hall drying using waste heat	Kraus Umwelttechnik	
83	**Ladbergen**	NW	Belt dryer	Sülzle Klein	
84	**Lambsheim**	RP	Solar dryer	Thermo System	
85	**Langenau**	BW	Solar dryer using waste heat	Roediger	
86	**Langeoog**	LS	Solar dryer	Thermo System	
87	**Lauterstein-Albdorf**	BW	Solar dryer using waste heat	Roediger	
88	**Leintal-Göggingen**	BW	Solar dryer	Thermo System	
89	**Leutershausen-Sachsen**	BV	Solar dryer using waste heat	Roediger	
90	**Main-Mud-Miltenberg**	BV	Solar dryer using waste heat (temporarily)	IST Energietechnik	
91	**Mainz Mombach**	BW	Belt dryer	Haarslev/Sevar	
92	**Mallersdorf**	BV	Belt dryer	Sülzle Klein	
93	**Mannheim**	BW	Belt dryer using waste heat	HUBER	
94	**Mannheim**	BW	Drum dryer	KHD	
95	**Markt Au**	BV	Solar dryer using waste heat	Thermo System	
96	**Markt Essenbach**	BV	Solar dryer using waste heat	Thermo System	
97	**Marktbergel**	BV	Solar dryer using waste heat	HUBER	
98	**Mengen**	BW	Belt dryer	Haarslev	
99	**Mintaching / Pfattertal**	BV	Belt dryer using waste heat	HUBER	
100	**München-Nord**	BV	Disk dryer	Wulff & Umag	
101	**Murnau**	BV	Solar dryer using waste heat	IST Energietechnik	
102	**Neckarsulm**	BW	Solar dryer using waste heat	Roediger	
103	**Neuburg (a.d.Donau)**	BV	Thin-layer/disk dryer	BUSS-SMS-Canzler	

	Throughput t DS/a	Drying rate	Performance kg H_20/h	Note
	120	70 %	N/A	N/A
	3,864	90 %	2x575	Waste incineration
	780	90 %	620	N/A
	517	75 %	N/A	Thermal utilisation
	200	80 %	N/A	N/A
	120	55 %	N/A	N/A
	400	70 %	N/A	N/A
	10,000	40 %	2,900	In-house incineration
	25,000	90 %	7,800	Cement industry
	2,700	90 %	1,200	Cement industry
	100	90 %	N/A	Thermal utilisation
	N/A	N/A	N/A	N/A
	3,200	90 %	1,400	Cement industry
	10,000	92 %	2x4,000	Co-incineration in waste incinerator
	90	75 %	N/A	N/A
	3,200	90 %	N/A	Cement industry
	5,300	90 %	2,300	Incineration
	230	70 %	N/A	Agricultural utilisation
	N/A	N/A	N/A	N/A
	120	90 %	N/A	Thermal utilisation
	2,000	90 %	N/A	Cement industry
	182	75 %	N/A	N/A
	2,000	90 %	N/A	Cement industry
	1,000	50–70 %	N/A	MVA
	5,200	77 %	2,000	N/A
	1,120	90 %	600	Cement industry
	9,620	90 %	3x1,500	Sewage sludge gasification/cement industry
	10,000	95 %	2x2,700	Cement industry
	130	75 %	N/A	N/A
	216	70 %	N/A	N/A
	264	70 %	723	N/A
	1,500	90 %	585	N/A
	1,600	90 %	600	N/A
	21,500	40 %	3x7,000	Mono-incineration
	476	70 %	N/A	Thermal
	2,000	90 %	N/A	Cement industry
	600	90 %	875	Cement industry

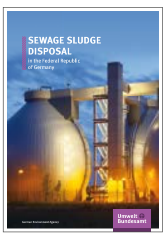
No	Location/Operator	State (Land)	Method	Manufacturer	
104	**Neufahrn (bei Freising)**	BV	Solar dryer	Thermo System	
105	**Neufahrn (bei Landshut)**	BV	Solar dryer	IST Energietechnik	
106	**Neu-Ulm "Steinhäule"**	BV	Thin-layer dryer	BUSS-SMS-Canzler	
107	**Niederkrüchten**	NW	Thin-layer dryer	BUSS-SMS-Canzler	
108	**Noell, Freiberg**	SA	Disk dryer	Haarslev	
109	**Nordstemmen**	LS	Solar dryer using waste heat	Thermo System	
110	**Oberndorf am Neckar**	BW	Hall drying using waste heat	Kraus Umwelttechnik	
111	**Oberndorf am Neckar**	BW	Hall drying using waste heat	Seiler Biogasanlagen GmbH	
112	**Obersontheim**	BW	Solar dryer	Thermo System	
113	**Oldenburg**	LS	Solar dryer using waste heat	Thermo System	
114	**Oyten/Ottersberg**	LS	Drum dryer	Andritz	
115	**Passau**	BV	Solar dryer using waste heat	Thermo System	
116	**Penzing**	BV	Solar dryer	HUBER	
117	**Pfullendorf**	BW	Hall drying using waste heat	Kraus Umwelttechnik	
118	**Pfullendorf**	BW	Hall drying using waste heat	Seiler Biogasanlagen GmbH	
119	**Pocking**	BV	Solar dryer	Thermo System	
120	**Radegast**	MV	Solar dryer using waste heat	Thermo System	
121	**Raubling**	BV	Solar dryer	Thermo System	
122	**Renningen**	BW	Solar dryer	Thermo System	
123	**Renquishausen**	BW	Solar dryer	Thermo System	
124	**Riedlingen**	BW	Solar dryer	IST Energietechnik	
125	**Riepe**	LS	Solar dryer	Thermo System	
126	**Rödental**	BV	Solar dryer	Thermo System	
127	**Röthenbach**	BV	Solar dryer	IST Energietechnik	
128	**Rudersberg**	BW	Solar dryer using waste heat	HUBER	
129	**Salzkotten**	NW	Belt dryer	Stela-Laxhuber	
130	**Scheßlitz**	BV	Solar dryer	Thermo System	
131	**Schlitz Hutzdorf**	HE	Solar dryer	Thermo System	
132	**Schlüsselfeld**	BV	Solar dryer	Thermo System	
133	**Schönaich**	BW	Solar dryer	Thermo System	
134	**Schönberg**	BV	Solar dryer	Solartiger /Rothmaier	
135	**Schönerlinde**	BE	Drum dryer	Bird Humboldt	
136	**Schongau**	BV	Solar dryer	Thermo System	
137	**Schwandorf**	BV	Belt dryer	Sülzle Klein	
138	**Siegen**	NW	Belt dryer	Sülzle Klein	
139	**Sigmaringen**	BW	Solar dryer	IST Energietechnik	
140	**Sinzig, Untere Ahr Sinzig,**	RP	Disk dryer	Bird Humboldt	

	Throughput t DS/a	Drying rate	Performance kg H_2O/h	Note
	500	70 %	N/A	N/A
	280	70 %	N/A	Recultivation
	10,000	40 %	2 x 2,200 + 1 x 3,900	In-house fluidised-bed combustion
	382	68 %	330	N/A
	400	› 95 %	400	N/A
	376	70 %	N/A	N/A
	3,200	90 %	N/A	Cement industry
	900	› 90 %	290	Cement industry
	200	80 %	N/A	Thermal utilisation
	10,000	70 %	N/A	6000 m^2
	750	92 %	1,300	Co-incineration
	2,400	50–75 %	N/A	N/A
	250	70–90 %	666	Incineration
	9,000	90 %	N/A	Cement industry
	1,800	› 90 %	2x290	Cement industry
	360	70 %	N/A	N/A
	334	80 %	N/A	Thermal utilisation
	250	60 %	N/A	N/A
	288	70 %	N/A	N/A
	21	90 %	N/A	N/A
	1,050	70 %	N/A	Co-incineration
	600	80 %	N/A	Agricultural utilisation
	400	75 %	N/A	N/A
	400	40–70 %	N/A	N/A
	220	90 %	756	N/A
	500	80 %	N/A	N/A
	110	75 %	N/A	N/A
	380	70 %	N/A	N/A
	300	75 %	N/A	N/A
	1,000	70 %	N/A	N/A
	150	› 85 %	N/A	Thermal
	7,500	95 %	3x2,500	Ruhleben mono-incineration
	496	40 %	N/A	N/A
	10,500	90 %	4,600	Incineration
	3,000	90 %	1260	Incineration
	450	40–70 %	N/A	Co-incineration
	350	95 %	1,000	N/A

No	Location/Operator	State (Land)	Method	Manufacturer	
141	St. Peter-Ording	SH	Solar dryer	Thermo System	
142	Steinbrück	LS	Solar dryer	Thermo System	
143	Steinen	BW	Disk dryer	Haarslev	
144	Stockach	BW	Solar dryer	Thermo System	
145	Stockstadt	BV	Disk dryer	Kraftanlagen Heidelberg	
146	Straubing	BV	Belt dryer using waste heat	HUBER	
147	Straubing	BV	Belt dryer using waste heat	HUBER	
148	Stuttgart-Mühlhausen	BW	Disk dryer	Haarslev/Atlas Stord	
149	Sulz/Vöringen	BW	Solar dryer using waste heat	Roediger	
150	Ühlingen-Birkendorf	BW	Solar dryer using waste heat	Kraus Umwelttechnik	
151	Unterpleichfeld	BV	Solar dryer using waste heat	Roediger	
152	Unterschneidheim	BW	Solar dryer using waste heat	Thermo System	
153	Villingen-Schwenningen	BW	Belt dryer	Haarslev/Sevar	
154	Waibstadt	BW	Solar dryer	Thermo System	
155	Waldenburg	BW	Solar dryer	Thermo System	
156	Waldshut-Tiengen	BW	Hall drying using waste heat	Kraus Umwelttechnik	
157	Wallmerod	RP	Belt dryer	Sülzle Klein	
158	Wangen	BW	Belt dryer	Sülzle Klein	
159	Wankheim	BW	Hall drying using waste heat	Seiler Biogasanlagen GmbH	
160	Warburg	NW	Solar dryer using waste heat	Thermo System	
161	Weddel-Lehre	LS	Solar dryer using waste heat	Thermo System	
162	Wegscheid	BV	Solar dryer	Thermo System	
163	Weil am Rhein	BW	Solar dryer using waste heat	IST Energietechnik	
164	Weinheim	BW	Belt dryer	Sevar	
165	Weißenhorn	BV	Belt dryer	Sülzle Klein	
166	Westerburg	RP	Solar dryer using waste heat	Thermo System	
167	Wilhelmsdorf	BW	Solar dryer	Thermo System	
168	Winterhausen	BW	Solar dryer	Thermo System	
169	Wolfratshausen	BV	Disk dryer	Haarslev	
170	Wolfsburg	LS	Belt dryer	Sülzle Klein	
171	Wuppertal	NW	Thin-layer dryer	BUSS-SMS-Canzler	
172	Wyk au Föhr	SH	Solar dryer	Thermo System	
173	Zeckern / Gemeinde Hemhofen	BV	Solar dryer	Rothmaier	
174	Zorbau bei Weißenfels	SN	Belt dryer	Sevar	
175	Zwiefalten	BW	Solar dryer	I+M	

	Throughput t DS/a	Drying rate	Performance kg H_2O/h	Note
	160	75 %	N/A	Agricult. utilisation
	240	75 %	N/A	N/A
	800	90 %	500	Co-incineration, coal-fired power plant
	750	70 %	N/A	N/A
	N/A	› 95 %	N/A	N/A
	2,800	90 %	900	Cement industry
	1,740	90 %	560	Cement industry
	25,000	45 %	2x4,770	In-house fluidised-bed combustion
	470	90 %	N/A	Cement industry
	2,000	90 %	N/A	N/A
	700	90 %	N/A	Cement industry
	250	80 %	N/A	N/A
	N/A	85–90 %	650	N/A
	275	70 %	N/A	N/A
	150	75 %	N/A	Co-incineration, coal-fired power plant
	3,000	90 %	N/A	Cement industry
	140	85 %	100	Currently decommissioned
	1,800	90 %	800	Cement industry
	900	› 90 %	290	Cement industry
	1,140	65–70 %	N/A	N/A
	350	55 %	N/A	N/A
	50	75 %	N/A	N/A
	1,440	70 %	N/A	Co-incineration
	1,800	85 %	1,600	N/A
	200	90 %	220	Currently decommissioned
	813	60 %	N/A	N/A
	264	75 %	N/A	N/A
	1,100	60 %	N/A	N/A
	1,050	90 %	1,500	N/A
	4,000	90 %	1,800	Cement industry
	15,000	45 %	4x2,540	N/A
	230	75 %	N/A	N/A
	54	75 %	N/A	N/A
	12,500	90 %	4,650	Waste incineration
	N/A	N/A	N/A	N/A

Source: UBA's compilation



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