Chapter

Does Sustainable Management of Biodegradable Sludge Exist at All? A BACOM Project Case

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Abstract

Due to the modern lifestyle and the formation of large amounts of biodegradable sludge, its processing is becoming a demanding technological and logistical project. Stabilization with pozzolanic ash and its reuse in construction industry represents one of the possible sustainable solutions. Mixing biodegradable sludge with pozzolanic ash triggers a set of physiochemical reactions such as converting heavy metals into insoluble hydroxides, forming heat due to hydration of metal oxides, and forming of a set of pozzolanic structures due to high pH and heat. Studies showed that the produced material is biologically and chemically inert and safe for use under controlled conditions. Comparison of different most widely used technologies, using life cycle analysis, indicated advantages of using material conversion of biodegradable sludge into materials rather than using it for energetic purposes. Based on the calculation of their negative influence on the environment and human health, the analyzed technologies can be categorized from those with less impact to those with higher impact: stabilization with ash < pyrolysis < anaerobic digestion < composting < landfilling. The life cycle assessment (LCA) showed that the decentralized technologies enabling material use of biodegradable sludge are more sustainable than centralized installations for composting biodegradable sludge in large quantities.

Keywords: biodegradable sludge, sustainable, stabilization, pozzolanic ash, LCA

1. Introduction

The management of biodegradable sludge (BS) is becoming an important challenge for developers, investors, and managers of wastewater treatment plants (WWTPs) over the world. BS is an unavoidable by-product of advanced techniques of biological purification of wastewater. In general, global population generates between 70 and 90 g BS/person or 1 ton of dry substance/10,000 persons [1]. The management of BS is not only a trivial problem, and investors should be aware about it during the designing of the WWTPs, because studies made in Austria showed that the management of BS (stabilization, drying, pretreatment, and transport) can easily exceed 40 to 53% of all operational costs during the processing of waste waters [2]. Proper and sustainable management with biodegradable waste is the outmost important topic in developed countries, because more expert studies showed that inappropriate approach to management with those waste includes high risks for human health and environment. Legislators all over the world are promoting methods and techniques allowing decreasing amount of BS on sanitary landfills with the aim of decreasing the greenhouse emission as well as decreasing the quantity of landfill leachate [3–6]. In accordance with Council Directive on the landfill of waste (1999/31/EC), landfilling of BS on sanitary landfills is forbidden within the EU-28 countries from July 2009. The Directive on waste from 2008 (2008/98/EC) even more restrictively implements hierarchy with which the European Commission is trying to promote material and energetical use of waste.

Nevertheless, blindly following the Directives does not necessarily result in the implementation of optimal and sustainable solutions, and we need to think about new approaches. However, because of those new approaches, all decisions need to be supported by different scientific data, and after that all individual solutions need to be evaluated on the same basis.

In order to allow equal treatment and consistent evaluation of different approaches in the management of BS, the EU Joint Research Centre has developed the "life cycle thinking" (LCT) and "life cycle assessment" (LCA) methodologies and has given the interpretation/instructions on how to use these methods, which should facilitate the decision-making and help managers to establish the most effective and sustainable management system for BS treatment [7]. The guidelines were prepared in cooperation with the International Organization for Standardization (ISO) and are registered under the number SIST EN 14040 and 14,044 [standards for LCA and the International Reference Life Cycle Data System (ILCD) Handbook]. A similar approach in the assessment is used in most European countries and almost by all authors of professional publications.

Each year, EU-28 member states produce more than 10 Mt. of communal BS calculated on dry matter [8, 9]. According to the official data, more than 40% of BS is still being disposed on municipal waste landfills [10]; approximately 36% are reused in agriculture or incinerate [8]; however, Eurostat has no data on the remaining 24% BS [7]. Biodegradable sludge is generated during the operation of urban WWTP utility and contains heavy metals, poorly dissoluble organic compounds (residues of detergents, washing agents, personal hygiene preparations, medicines, etc.), and possibly pathogens microorganisms (**Tables 1–4**).

Both unprocessed and processed BS contains heavy metals, residues of phytopharmaceutical products, and surfactants. Their content depends on the origin of the municipal sludge (sludge from the municipal, industrial, or combined treatment plant). In addition to active microorganisms, pathogenic bacteria listed in **Table 3** are also present in unhygienic feces. Because of that, it is difficult to compost them, and the manufactured compost is prohibited for uses in agriculture as fertilizer.

The method for the management of BS is different and depends on their origin, composition, especially contents of hazardous and biodegradable substances, and on available infrastructure and local regulations. BS, which is disposed on landfills, is subject to uncontrolled aerobic and anaerobic processes that cause the release of a large amount of greenhouse and noxious gasses (CH_4, CO, CO_2, H_2S, etc.) and emissions of heavy metals. Currently, the EU and the USA are using incineration, composting, stabilization, and landfilling as recognized methods for bio sludge disposal. All mentioned methods have negative environmental impacts, especially landfilling and incineration. The special problem for the environment presents pathogenic microorganisms of different species that exist inside biodegradable sludge and which must be stabilized or neutralized before further application. One of the most economical and environmentally accepted methods for stabilization of BS is their mixing with wasted alkaline materials as ash, slag, foundry sand, and foundry dust.

According to the available data from the literature and the LCA analyses, the disposal of BS is the worst choice between the possible solutions, even if landfills are equipped with gas capturing systems and devices for its energetic use [12–14].

Constituent	Unit	Unprocessed BS		Processed BS		Active BS
		Range	Avg.	Range	Avg.	
Dry solid	% d.s.	2.0–8.0	5.0	6.0–12.0	10.0	0.83–1.16
Volatile sub.	% on d.s.	60–80	65	30–60	40	59–88
Fats and oils	% on d.s.	6–30	—	5–20	18	5–12
Proteins	% on d.s.	20–30	25	15–20	18	32–41
Nitrogen (tot)	% on d.s.	1.5–4.0	2.5	1.6–6.0	3.0	2.4–5.0
Phosphorous	% on d.s.	0.8–15.0	1.6	1.5–4.0	2.5	2.8–11.0
Ash (K_2O)	% on d.s.	0–1	0.4	0.0–3.0	1.0	0.5–0.7
Cellulose	% on d.s.	8.0–15.0	10.0	8.0–15.0	10	—
Iron	% on d.s.	2.0–4.0	2.5	3.0–8.0	2.5	—
Silicates (SiO_2)	% on d.s.	15.0–20.0	—	10.0–20.0	—	—
Alkalis ($CaCO_3$)	% on d.s.	500–1500	600	2500–3500	—	580–1100
Organic acids	% on d.s.	200–2000	500	100–600	3000	1100–1700
Energetic value	TJ/ton	10–12.5	11	4–6	0.2	8–10
pH value		5.0–8.0	6	6.5–7.5	7	6.5–8.0

Table 1.
Average composition of BS in Europe—combined WWTPs [1].

Constituent	Range	Average	Unit
Cr	20–60	35	mg/kg of dry solid
Cu	200–600	375	mg/kg of dry solid
Pb	100–400	175	mg/kg of dry solid
Ni	15–50	30	mg/kg of dry solid
Sb	1–5	3	mg/kg of dry solid
Zn	500–1500	900	mg/kg of dry solid
As	5–20	12	mg/kg of dry solid
Hg	0.5–3	1.4	mg/kg of dry solid
Cd	1–5	2	mg/kg of dry solid
Mo	4–20	8	mg/kg of dry solid

Table 2.
Average composition of heavy metals in sewage sludge in Europe—combined WWTPs [11].

Disposal of 1 ton of BS with 20% dry substance emits up to 296.9 kg of $CO_{2(eq)}$ into the atmosphere.

The incineration of BS which is generated by the operation of WWTPs is therefore becoming a common practice of management with BS. The incineration is primarily used for the reduction of the volume and not for energy production, because ash represents only about 30% of the dry matter volume in BS [15]. However, ash disposal remains a serious problem as it still contains heavy metals. LCA analyses showed that the incineration of BS is meaningful only in cases where the systems of the so-called industrial symbiosis exist, such as the co-incineration of BS [15] with coal [16] but with a presumption that the BS is sufficiently dry and the incineration chamber is specially designed (FBR). The incineration of 1 ton of

Pathogen	Disease(s) and/or symptoms
Salmonella spp.	Salmonellosis, typhoid
Shigella spp.	Bacillary dysentery
Escherichia coli (enteropathogenic strains)	Gastroenteritis
Pseudomonas aeruginosa	Otitis externa, skin infections (opportunistic pathogen)
Yersinia enterocolitica	Acute gastroenteritis
Clostridium perfringens	Gastroenteritis (food poisoning)
Clostridium botulinum	Botulism
Bacillus anthracis	Anthrax
Listeria monocytogenes	Listeriosis
Vibrio cholera	Cholera
Mycobacterium spp.	Leprosy, tuberculosis
Leptospira spp.	Leptospirosis
Campylobacter spp.	Gastroenteritis
Staphylococcus	Impetigo, wound infections, food poisoning
Streptococcus	Sore throat, necrotizing, fasciitis, scarlet fever

Table 3.
List of pathogens found in BS originated from combined WWTPs.

Pollutant in sewage sludge	Domestic use	Combined sewage system	Industrial discharges
Pathogens	Human metabolism	Animal faces	Meat industry
Heavy metals	Paints (Pb), amalgam filling (Hg), thermometers (Hg), pipe corrosion (PB, Cu), batteries (Ni, Cd, Pb)	Rain (Pb, Cd, Zn), tires (Cu, Cd), roof corrosion (Zn, Cu), oil (Pb)	Various
Persistent organic pollutants	Paints, solvents, medicines, wood, treatment, cosmetics, detergents, etc.	Oil, pesticides, tar, road deicing, rain, combustion	Various

Table 4.
List of origin of different pollutants and pathogens in BS.

BS contributes 232.2 kg of $CO_{2(eq)}$ on climate change, pyrolysis up to 146.1 kg of $CO_{2(eq)}$, while burning of equal quantities of BS and energy-rich RDF can reduce pressure on climate change for 15.4 kg $CO_{2(eq)}$ [17].

The LCA itself is dependent on the environment as well on economic, social, and political conditions where the studied example is positioned. Hospido et al. [18] had studied and conducted a comparative study of agricultural use, incineration, and pyrolysis of BS and came to the conclusion that the ecologically acceptable solution is the co-incineration of BS with a coal, but at the same time, this option is least economically acceptable. It has been established that maximum efficiency and minimal environmental impact is achieved when 10–40% of dry BS are added to coal [15]. Different authors have shown practical examples where environmental impacts are mostly reduced when BS are used as fuel and produced ash used as a binder in cement production [19] and as a binder for roofing production [20].

Notwithstanding, at the EU level, composting is the most common way of managing with BS, although in the last few years, there has been made a big step towards the implementation of anaerobic degradation and energetic use of produced biogas [21, 22].

The material use of BS, composting, and anaerobic digestion with energetic use and disposal of compost on sanitary landfills seems to be the most acceptable solution [14], because large plants can be subject of discontent on heavily populated areas due to the emission of stench, bioaerosols, and heavy cargo traffic and the associated negative impacts on the environment.

These problems can be partially resolved with decentralization, namely the construction of smaller local but still economically acceptable systems with production capacity of less than 3000 tons per year [14, 23].

The advantages of the decentralized system are (1) shorter transport routes, which mean reduction of the transport costs, reducing emissions into the atmosphere and reducing noise and freight transport; (2) reducing the amount of storage of BS and consequently the reduction of stench emissions; (3) acquisitions for the local community (e.g., the exploitation of the heat produced in biogas incineration processes, which is impossible to transport on greater distances); and (4) use of smaller plants, which are attached to the environment and are less likely to be noticed. The usability of a decentralized approach by different authors has been confirmed with the introduction of the project named ForBiogas in Bologna [14].

The implementation of technologies for the material processing of BS into value-added products, which are also economically acceptable, is totally complied with the abovementioned guidelines.

This is an example of Eco-Bis technology, developed by a company GreenLife GmbH from Austria and which enables the production of bio-charcoal from BS. Particularly, this is the process of efficient drying of biodegradable sludge using vacuum filtration and subsequently pyrolysis of BS into bio-charcoal which is further used as a supplement to improve the quality of the soil. Bio-charcoal acts as a retainer for fertilizers, pesticides, and water and, at the same time, acts as fertilizer [24]. This standard is also close to BACOM technology (Biosludge Alkaline Composite Material), developed by the Slovenian company Insol d.o.o. [25].

The technology is based on the stabilization of BS, trough mixing pozzolanic ash, or other waste with alkaline properties. The final product of BACOM technology is a water-impermeable material, which can be used for as a substitute for clay in the construction and closure of different types of landfills, the construction of the beds for sewage systems and roads, the construction of inner filler of anti-flooding barriers and restoring of degraded landscapes, and the closure of degraded areas [25]. This technology is also suitable for natural storage of phosphorous. Additional drying is not necessary because ash reacts with moisture present in BS. Hydration of active metal oxides present in ash enables their conversion into alkalis. Due to the high pH and rising temperature, the heavy metals convert into water-insoluble hydroxides and chelate what prevent their further extraction. Released heat and high pH destroy pathogenic and other microorganisms which make the mixture biologically stable.

As we can see, there are different approaches and ideas about managing BS. As part of our study, we chose the typical technologies that are currently being operated and compared them with decentralized technologies that enable the material use of BS.

1.1 BACOM technology: mechanism

The BACOM technology base on the stabilization of BS, where the BS is mixed with ash and converted into prepared mixture useful for the construction of the composite material.

Parameter	Unit	KP/PPLP	EP/PLS	EP/PPLP
SiO_2	% wt.	32.92	43.70	19.90
CaO	% wt.	49.03	12.14	35.70
MgO	% wt.	3.50	1.91	1.64
Al_2O_3	% wt.	14.13	20.45	10.56
Fe_2O_3	% wt.	0.82	5.23	2.20
MnO	% wt.	0.05	0.10	0.03
K_2O	% wt.	0.55	2.95	0.40
P_2O_5	% wt.	0.31	0.46	0.14

Table 5.
Average composition of ash [26].

The process is based on mixing wet biodegradable sludge with ash where the ash is a wasted by-product of energy generation. In general, the rule is that the ash produced from paper, paper sludge, wood chips, and wood biomass (PPLP) contains more live lime (CaO) than ash resulting from the incineration of coal, lignite, and peat (PLS). The boiler dust (KP) and the electric filter ash (EP) are suitable for the hygiene and stabilization of the BS at the CEN-EN 12832, where KP/PPLP is more effective than the EP due to a higher content of free CaO (**Table 5**).

After mixing, chemical hydrolyzation and hydration of active earth metal and metal oxides (CaO, MgO, Fe_2O_3) present in ash occurs:

$$Me\,(H_2O)_n{}^{m+} + H_2O \rightleftarrows Me\,(H_2O)^{(m-1)+}\,(OH)^{(m-1)+} + H_3O^+ \qquad (1)$$

$$n\,Me^{m+} + m\,OH^- \rightarrow Me_n\,(OH)_m + \Delta H_h \qquad (2)$$

This reaction releases heat, which increases mixture temperature up to 65°C and pH value above 12. Under that conditions heavy metals convert into heavy soluble metal hydroxides $Me_m(OH)_n$. However, different heavy metal hydroxides have different solubility depending on pH (see **Figure 1**), and adjustment of pH of the mixture is necessary to get chemically inert product. Due to high pH value of the mixture that can increase up to 12.4, the salts of heavy metals are converted into water-insoluble form which prevents further extraction.

Because of alkaline conditions, proteins in the presence of water undergo hydrolytic decomposition and ammonia is formed. In such conditions all pathogenic microorganisms and their spores are destroyed which ensures biological and biochemical stability of the product. A few minutes after stabilization, no *Salmonella* was detected, and the number of *Escherichia coli* was below legal limits [27].

After that the mixture passes into the phase of solidification. Because of a specific mixture of oxides and the CaO content, ash has a high pozzolanic power comparable to Portland cement. Pozzolans are a mixture of silicate and aluminum oxides which itself do not possess the cement values but, in dusty form and in the presence of water, react with CaO already at room temperature and form cement-like materials. The alkali conditions trigger a set of pozzolanic reactions similar as in crystallization of the cement.

Using X-ray diffraction spectrometry lime, portlandite, calcite, quartz, alumina, muscovite, cellulose, and other different C-H-S structures were detected (see **Figure 2**) [29]:

$$CaO + H_2O \rightarrow Ca(OH)_2 + \Delta H_h \quad (3)$$

$$3Ca(OH)_2 + 2SiO_2 \rightarrow 3(CaO)_2(SiO)_2{*}3(H_2O) + \text{C-S-H structures} \quad (4)$$

$$3Ca(OH)_2 + Al_2O_3 + 3H_2O \rightarrow 3(CaO)Al_2O_3{*}6(H_2O) \quad (5)$$

After 28 days, ettringite structures $Ca_6Al_2(SO_4)_3(OH)_{12} \times 26H_2O$ may be developed in the presence of sulfates.

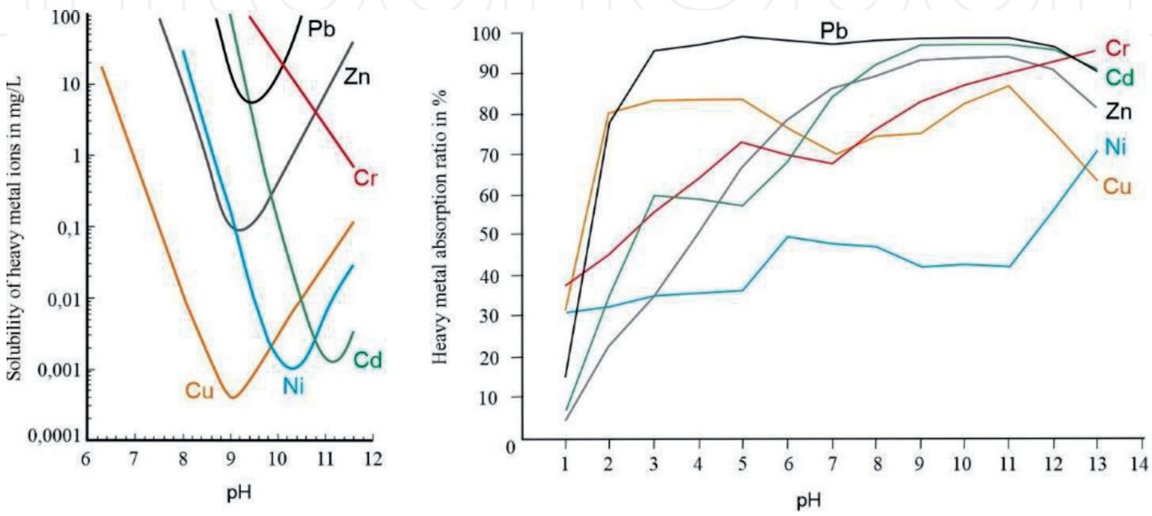

Figure 1.
Solubility of heavy metal in independence of pH (left) and adsorption of heavy metal ions in dependence of pH (right).

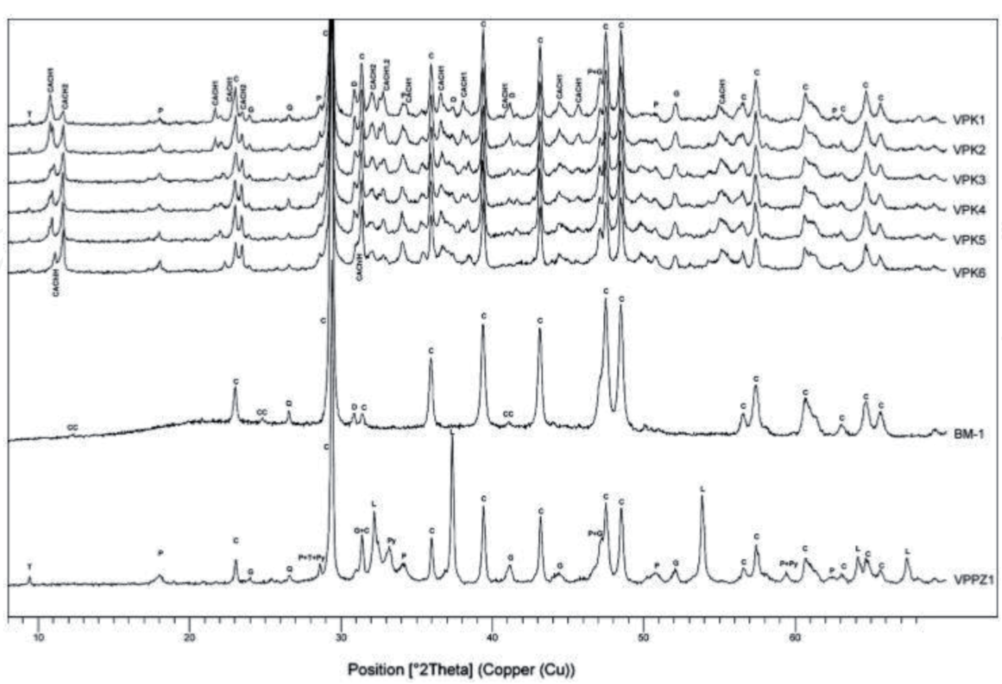

Figure 2.
X-ray diffraction pattern of biodegradable sludge (BM), biomass ash (VPPZ1), and the composites after 3, 7, 14, 28, 56, and 90 days (VPK-1 to VPK-6, respectively). Legend: C, calcite; T, talc; P, portlandite; Q, quartz; L, lime; G, gehlenite; CC, clinochlor; D, dolomite; Py, pyrite; CACH1, $Ca_8Al_4O_{14}CO_2{*}24H_2O$; CACH2, $Ca_4Al_2O_{14}CO_9{*}11H_2O$; CaCh1H, $Ca_4Al_2O_6Cl_2{*}10H_2O$ [28].

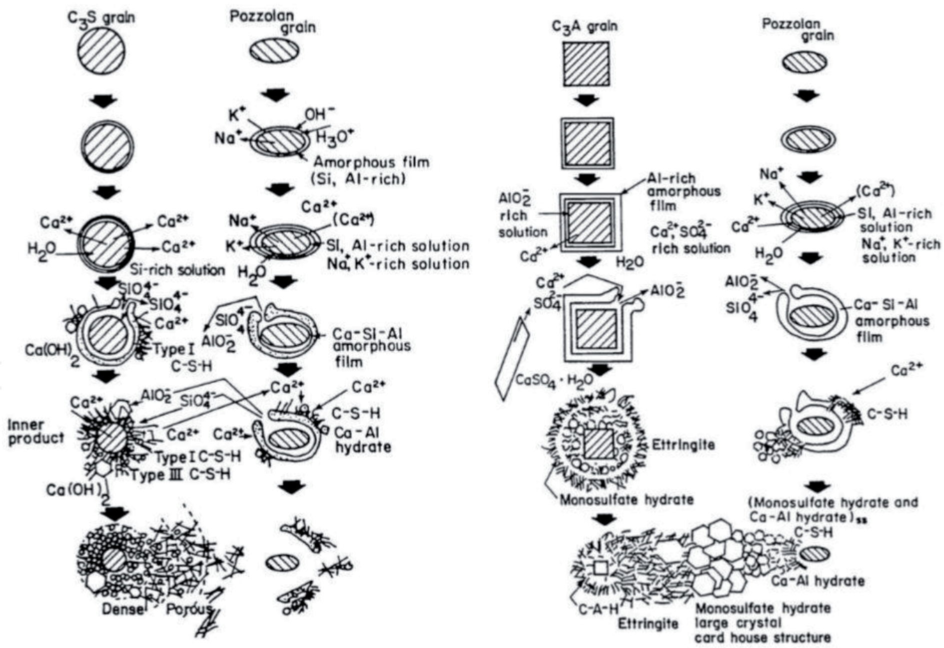

Figure 3.
Schematic explanation of the mechanism of hydration in hydration in the C3S-pozzolan system and the C3A-pozzolan system in the presence of $Ca(OH)_2$ and $CaSO_4$ $2H_2O$ [30].

Component	Detection method	Legal limit in leachate in mg/kg s.s.	Result in mg/kg s.s.
As	SIST EN ISO 17294-2:2005	0.5	<0.02
Ba	SIST EN ISO 17294-2:2005	20	0.94
Cd	SIST EN ISO 17294-2:2005	0.04	<0.005
Cr (total)	SIST EN ISO 17294-2:2005	0.5	<0.01
Cu	SIST EN ISO 17294-2:2005	2	0.94
Hg	SIST EN ISO 17294-2:2005	0.01	<0.001
Mo	SIST EN ISO 17294-2:2005	0.5	<0.05
Ni	SIST EN ISO 17294-2:2005	0.4	0.18
Pb	SIST EN ISO 17294-2:2005	0.5	0.15
Sb	SIST EN ISO 17294-2:2005	0.06	0.013
Se	SIST EN ISO 17294-2:2005	0.1	<0.01
Zn	SIST EN ISO 17294-2:2005	4	0.21
Chloride	SIST EN ISO 10304-1:2009	800	57.3
Fluoride	SIST EN ISO 10304-1:2009	10	1.2
Sulfate	SIST EN ISO 10304-1:2009	6000	25.7

Table 6.
Main characteristics of leachate of final product produced by mixing BS and pozzolanic ash in ration 70/30 [29].

Crystal structures (see **Figure 3**) capture heavy metal hydroxides, other pollutants, and stabilized organics inside the net and prevent further extraction of pollutants. At the same time, crystal structures give the final material geomechanical characteristics (**Tables 6** and 7).

1.2 BACOM technology

BACOM technology is an approved technology for the processing of BS in construction composites. It is based on the idea of the alkalization of biological sludge by mixing with the ash, which expresses pozzolanic activity. The BACOM technology operates in

Property	Measuring method	Result
Humidity	ISO/TS 17892-1:2001/AC:2010	23% wt.
Max. dry density	SIST EN 13286-2:2010/AC:2013	1.2 Mg/m^3
Optimal humidity on standard Proctor test	SIST EN 13286-2:2010/AC:2013	29.1% wt.
Uniaxial compressive strength	SIST EN 13286-41:2004	96 kPa
Shear strength	SIST TS ISO/TS 17892-10:2004/AC:2010	φ = 38.47 c = 42.6 kPa
Compressibility module at load rate: • 50 kPa • 100 kPa • 200 kPa • 400 kPa • 800 kPa	SIST TS ISO/TS 17892-5:2004/AC:2010	8213 kPa 8213 kPa 10,704 kPa 15,850 kPa 19,390 kPa 23,693 kPa
Water impermeability at load rate 200 cm/s	SIST TS ISO/TS 17892-11:2004/AC:2010	2.35×10^{-7}

Table 7.
The main geomechanical characteristics of final product produced by mixing BS and pozzolanic ash in ration 70/30 [29].

accordance with the European CEN-EN 12832 and complies to the conditions for the processing and use of biodegradable, municipal, and similar sludge, including chemical hygienization and inertization of BS and by mixing with live lime and/or ash.

It enables to mix biodegradable sludge, which contains from 2 to 30% of dry matter with ash (or other alkaline materials) which usually contains up to 80% of earth alkali and/or metal oxides. When the content of dry matter increases up to 60%, the mixture passes to semisolid state and solidify after a short time (in average after 72 hours). The construction and mechanical characteristics can be improved by further admixing different materials such as ash, cement, lime, micro silica, porcelain, slag, foundry sand, natural and artificial fibers, and different kinds of vermiculites. With careful choice of additives, the chemical, mechanical, geotechnical, and hydromechanical characteristics of produced materials can be adjusted and improved before further application.

The technological process of BACOM includes three main process operations that are shown in **Figure 4**:

- In the first stage, raw biodegradable sludge (1) is mixed with ash (2).
- Inside mixing device (3), semisolid mixture (4) is formed.
- Thickened material (4) is additionally admixed with composite material (5) and the final product (6) is formed.

Applying the BACOM technology in the processes of disposal of the biodegradable sludge enables reduction of investment costs in the beginning due to the smaller storage capacities needed for storage biodegradable sludge and alkaline materials. Due to the fast exploitation of the biodegradable sludge, the biological decomposition of the organic components is reduced on the lowest possible level, and because of that, additional reduction of negative impacts on the environment is achieved. The technology can be built as independent facility for the processing of the biodegradable sludge or as technological part of the existing biological wastewater treatment plant.

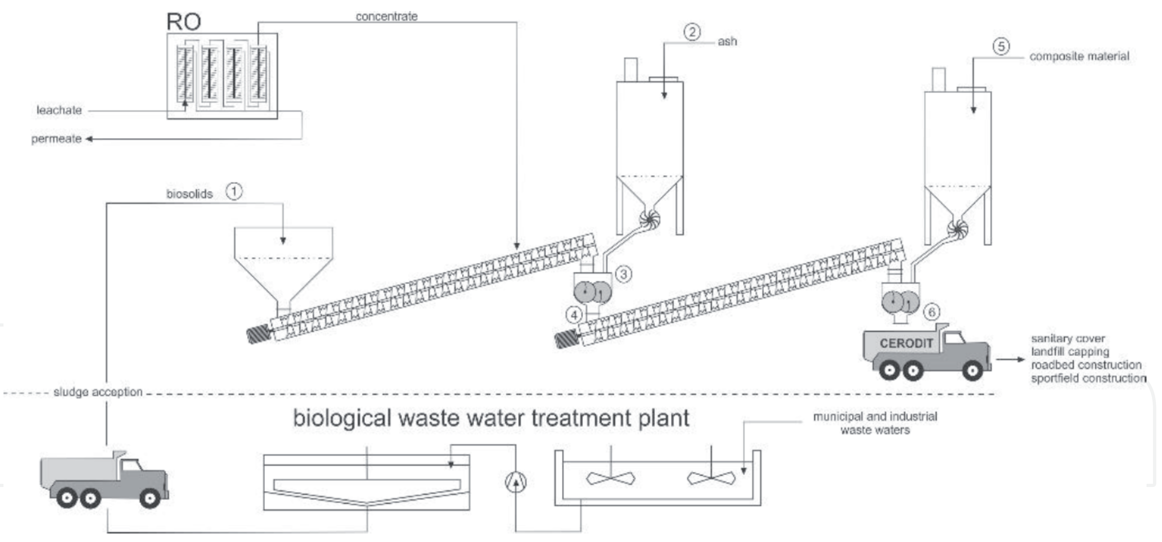

Figure 4.
Schematic explanation of BACOM process.

Overall, the implementation of BACOM technology into processes of recycling and disposal of BS can decrease investment costs for about 90% comparing to the other mentioned technologies, and overall costs of disposal calculated on dry matter can decrease by 88%. At the same time, the greenhouse effect decreases by 95% compared to incineration. The produced composite can be of further use for cheap replacement for geo-composite material or clay which additionally contributes to decreasing of the greenhouse effect due to reduction of land degradation which is a consequence of the opening of a new mining site.

Up to today the usage of alkaline waste for the stabilization of biodegradable sludge did not get application in big extent due to batch processes of stabilization which demands organization of relatively large storage capacity for biodegradable sludge and large storage capacities for final product. During the uncontrolled storage of the sludge, aerobic and anaerobic degradation processes occur inside the sludge that cause organic decay of organic part and consequently releasing of greenhouse gasses and unpleasant smell into environment. The BACOM technology solved those issues with enabling continuous stabilization of biodegradable sludge with online mixing of the alkaline materials and composite materials into the sludge, and the production of construction composite materials and long storage is not needed. The solution is based on innovative connection of two batch processes inside one efficient continued process, which at the end leads to sustainable production of replacements of geo-composites and clay.

2. Case study

The example for the determination of sustainability of BACOM technology compared to other available technologies has been placed in Slovenia, which represents a small, closed, and relatively densely populated area. Slovenia has a smaller incinerator in Celje, so the incineration of BS was not taken into account in the performance of the study, but we have therefore studied possible involvement of Eco-Bis technology. The study model is appropriate for smaller, more populated areas with less developed systems for BS management. According to the ARSO (Slovenian Environment Agency) data, in Slovenia 203,059 tons of BS or approximately 100,000 tons of dry matter was produced in 2017. About 70,000 tons of these were exported to Hungary for the preparation of artificial soil; 34,000 tons were driven to incineration; 12,000 tons in landings; 20,000 tons on composting; and the rest wastes were exported to other processing operations. The use in agriculture has been exceptionally small already from 2006. The main transport distance for the transport of BS to processing/landings was less than 250 km.

3. Methodology

Environmental profiles and comparative studies were made by the LCA methodology standardized according to ISO 14040 and 14,044, which is suitable for comparison and evaluation of different technologies within the prescribed boundaries. Using the SimaPro 7.1 software package and its database, the comparison was made by the IMPACT 2002 + method [31]. The methodology included (1) purpose and definitions, (2) inventory list, (3) determination of effects, and (4) interpretation. The specifics of the methodology, the main hypothesis, the key assumptions, and conclusions will be described through the accompanying text.

3.1 Purpose and definition

The aim of the study was to evaluate and compare the different management systems with BS in closed densely populated areas, as well as defining environmental impacts and energy balances. Although in most cases the transport of BS represented a large proportion of emissions, transport was neglected with the reason that the boundaries were determined at the entrance to the processing. The independent evaluation of individual technologies was enabled. In the analysis, due to the continuation of the calculation, the drying process of BS from 2 to 20% of the dry matter is excluded. All calculations were based on the presumption that biodegradable sludge with 20% of dry matter is being processed. The LCA also ignored the construction and dissembling of individual technologies because in this analysis, only the influence of the working activities of individual technologies is of interest.

Scenario 1 (landfilling) represents the disposal of BS on sanitary landfills which have arranged system for capturing biogas and burning of biogas on torches. According to the predictions, about 45% of the generating biogas is captured, and 55% of the generated biogas is emitted into the atmosphere through the different part of the landfill as, for example, drainage system and the boundary slopes. Although such a scenario is undesirable and banned in the EU, it should be considered due to undeveloped and inefficient management systems and because it is used in more than 50% of examples.

Scenario 2 (composting) represents composting of BS with 20% of dry substance, with a technique of aerobic digestion in open digs equipped with active aerating systems. According to the experience and literary data, it was presumed that active composting lasts 24 days and further ripening of the compost for another 60 days. The compost with approximately 40% of dry substance is landfilled on sanitary depot. Power consumption for processing 1 ton of BS in compost is 90 kWh; embedding of the compost in the body of the landfill requires additional use of 0.6 kg of diesel fuel for 1 ton of BS.

Scenario 3 (AD&L) represents anaerobic digestion of BS and use of a manufactured biogas for electricity production. The heat is not used, and the compost is embedded in the sanitary landfill. For anaerobic processing 1 ton of BS with 20% of dry substance in average 34 kWh of electric power and 20 liters of water is used. Processing of BS with 20% of dry matter in biogas and its active use ensures production of about 175 kWh surplus of electricity.

Scenario 4 (BACOM) represents the solidification/stabilization of the BS with pozzolanic ash in proportions from 30/70 to 70/30 which depends on the final use of the product. The product can be used for replacing clay or bentonite. For the processing of 1 ton of BS with 20% of dry matter, 0.3 kWh of electric power and additional 0.6 kg of diesel fuel for its embedding are used. The emissions into the environment are reduced to 1% compared to uncontrollable landfilling of BS. From 1 ton of BS with 20% dry matter, up to 1.3 tons of clay replacement can be produced.

Scenario 5 (Greenlife Eco-Bis) represents a technology for controlled pyrolyzing of BS into biochar. BS is dried from 20 to 75% dryness with the use of the heat produced with pyrolytic processes. The average use of energy for drying is 192.73 MJ/kg of BS. After that, the dry sludge is pyrolyzed into bio-coal under controlled conditions. The gain of heat using pyrolytic processes is around 243.10 MJ/kg of dry BS, taken into account that the electricity consumption for processes itself is 40 kWh. From 1 ton of BS with 20% of dry substance, the 300 kg of coal can be produced. Produced biochar can efficiently replace artificial and growing fertilizers in agriculture.

3.2 System boundaries

System boundaries are defined with the input of BS at the entrance into the processing. Due to the equalized assessment, transport and system of drying of the BS are neglected. It is necessary to note that the technology of the BACOM drying the sludge is not necessary because it also works with the sludge where the content of the dry substance is lower than 10%. Greenlife Eco-Bis technology has a built-in effective drying system with the system of vacuum filtration which is exploit surplus heat which is generated within pyrolytic processes. System boundaries are graphically displayed in **Figure 5**.

3.3 Functional unit

The functional unit is used for the definition of input or output from the system. The purpose of introducing a functional unit is equalizing evaluation of different scenarios. In our case, the functional unit used for evaluation is 1 ton of BS containing 20% of dry substance.

3.4 Inventory analysis

At this stage, the input materials, energy used, as well as emissions into the atmosphere, water, and soil were evaluated. Data about the BS which is processed by the

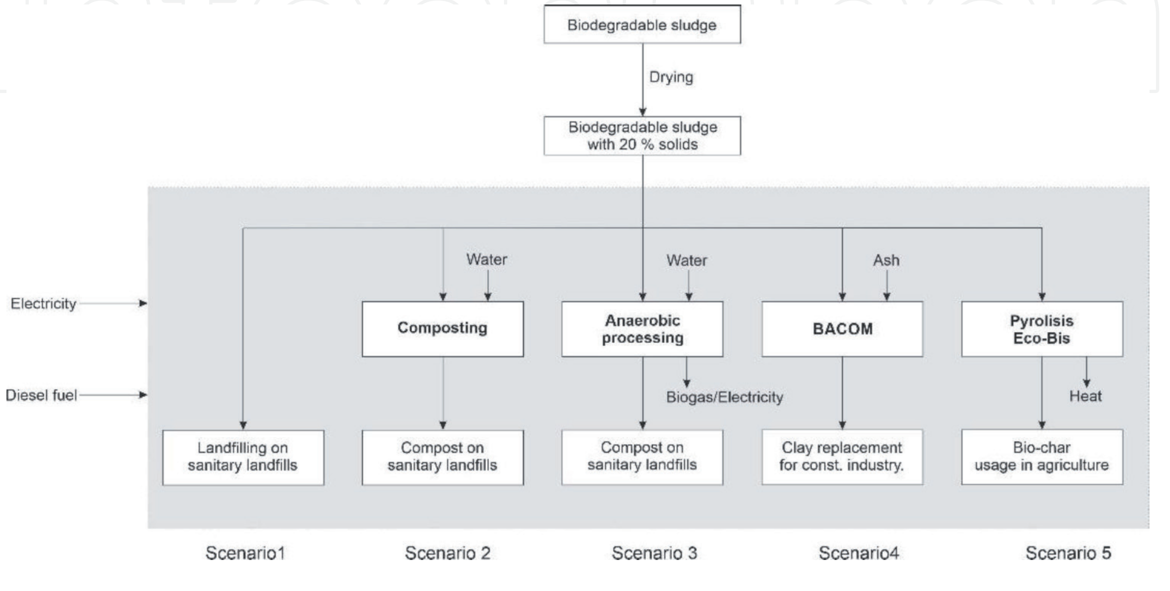

Figure 5.
System boundaries for LCA.

	Landfilling	Composting	Anaerobic	BACOM	Pyrolysis
Scenario	**1**	**2**	**3**	**4**	**5**
Emissions into air					
CO_2	14.23	61.81	61.81	0.1423	0.1020
CO	0.02	0.10	0.10	0.0020	0.0128
CH_4	15.14	0.05	—	0.1514	0.0002
VOC	0.02	0.01	0.30	0.0002	—
NO_X	0.04	—	0.30	0.0004	—
Nitrogen	4.63	—	—	0.0463	—
Oxygen	0.02	—	—	0.0002	—
H_2S	0.02	0.02	—	0.0020	—
PM_{10}	—	0.11	—	—	—
NH_3	—	0.04	—	—	—
SO_2	—	0.01	0.01	—	—
HCl	—	0.01	0.01	—	—
Emissions into water					
Chlorides	0.028	0.028	0.028	0.00028	0.1020
KPK_5	0.011	0.011	0.011	0.00011	0.0128
BPK_5	0.056	0.056	0.056	0.00056	0.0002
Nitrogen	0.003	0.003	0.003	0.00003	0.0062
Suspended part.	0.002	0.002	0.002	0.00002	0.0146
NH_4OH	0.001	0.001	0.001	0.00001	0.0005
P (total)	0.001	0.001	0.001	0.00001	0.0000

Table 8.
Partial list of emissions into the atmosphere and water for particular scenarios in kg per ton BS with 20% dry solids.

company CeROD d.o.o. and CeROP (for year 2013 and 2015) were obtained from the BS analysis; data on emissions of gasses in the process of degradation of BS were measured and equalized with data obtained from the peer reviewed literature [14, 15, 32] and are shown in **Table 8**. Data about electricity production for Slovenia were obtained from the database BUWAL 250 and data about clay from the ETH-ESU database.

4. Discussion

Potential effects of five different scenarios (technologies) are listed in **Tables 9** and **10**.

4.1 Impacts on human health

From **Table 10** and **Figure 6**, it is evident that the total impact on human health in the case of landfilling of BS, which is equipped with the system for the active capture and incineration of biogas, is by 16.55 units lesser than the impact on human health caused by composting. Such conclusions come from the fact that the effects in the case of landfilling are limited to fenced and guarded spaces and that there are no emissions of dust, as well as from the fact that the disposal of BS does not require additional

Subgroup	Unit	Landfill	Compost	AD&L	BACOM	Eco-Bis
Emissions of carcinogenic substances	DALY	3.03E-05	0.000613	0.000231	−5.08814	1.75173
Emissions of non-carcinogenic substances	DALY	0.024072	0.032287	0.032183	−4.2439	−11.8864
Emissions of substances harmful for respiratory system	DALY	5.046047	21.85825	21.85621	−291.066	−162.069
Ionization	DALY	1.66E-07	1.66E-07	0	−0.38479	−0.00135
Emission of substances which destroying ozone layer	DALY	4.73E-07	8.39E-07	1.45E-07	−0.35543	−0.0001
Emission of organic pollutants harmful for respiratory path	DALY	0.291465	0.018953	0.018951	−0.72645	0.007838
Aquatic toxicity	PDF*m2*l	2.68E-05	0.000227	9.92E-05	−0.92158	−1.75714
Soil toxicity	PDF*m2*l	2.1E-05	0.002301	0.002271	−21.251	−0.24776
Soil acidification	PDF*m2*l	0.166662	0.454253	0.454224	−3.56515	−3.98712
Land use	PDF*m2*l	5.86E-07	5.86E-07	0.00	−5.03381	−0.33184
Acidification of water environ.		—	—	—	—	—
Water eutrophic.		—	—	—	—	—
Climate change	kg CO2(eq)	121.444	0.357449	0.35498	−176.323	−203.961
Non-renewable energy sources	MJ prim.	0.000434	0.005132	0.001863	−162.77	−212.651
Extraction of minerals	MJ prim.	1.52E-08	1.52E-08	0.00	−1.3E-05	−0.0015

Table 9.
List of effects on subgroups IMPACT 2002+.

Effect on:	Unit	Landfill	Compost	AD&L	BACOM	Eco-Bis
Human health	DALY	5.361614	21.91011	21.90758	−301.864	−172.197
Ecosystem	PDF*m^2*l	0.166711	0.456783	0.456594	−30.7715	−6.32386
Climate changes	kg $CO_{2(eq)}$	121.444	0.357449	0.35498	−176.323	−203.961
Natural resources	MJ prim.	0.000434	0.005132	0.001863	−162.77	−212.652

Table 10.
List of effects on groups IMPACT 2002+.

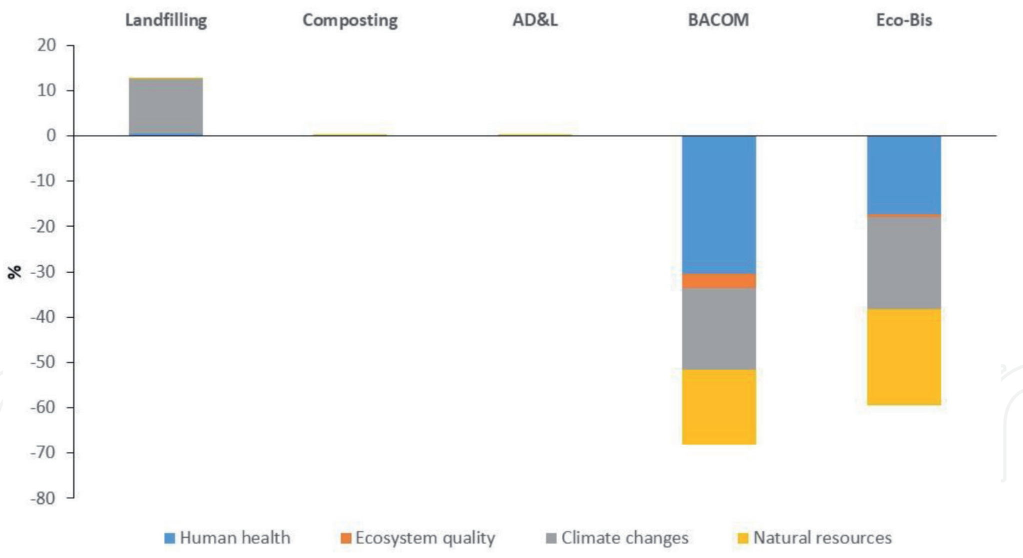

Figure 6.
Overall LCA result.

energy consumption for processing. The reduction of the impact on human health by additional 166.84 units is reflected in the use of Eco-Bis technology instead of landfilling of BS primarily due to the energy utilization and consequentially direct emission reductions as well as additional emissions reductions because of the replacement of artificial fertilizers with environmental friendly bio-coal. The additional reduction in impacts by the 135 units was calculated in case of using the technology of converting BS into replacements for clay and bentonite geo-composites (BACOM). Opening of new clay mines, where energy demanding processes are applied for clay production are not needed anymore in the case of implementation of BACOM technology.

4.2 Impacts on ecosystems

From **Table 10** and **Figure 6**, it is evident that direct landfilling of BS on the waste disposal site has approximately 2.5 times higher negative impact on the ecosystem as a controlled aerobic or anaerobic digestion of BS which also includes disposal of the produced compost on sanitary landfill. This is the result of the reduction of uncontrolled emission of biogas and toxic substances into the environment. A decrease of additional 6.16 units was calculated in the case of the use of Eco-Bis instead of landfilling of BS due to the prevention of its biological decomposing where decreasing impacts on the environment are based primarily on the replacement of the artificial fertilizer with biochar. Further reduction of negative impacts on the ecosystem for 24.45 units can be achieved by using BACOM technology and is the result of prevention of biologic breakdown of BS and of the fact that the manufactured material can be used as a substitute for clay, bentonite, and plastic materials.

4.3 Impacts on climate change

From **Table 10** and **Figure 6**, it is evident that landfilling of BS on the waste disposal site has 344 times more negative impact on climate change than composting and anaerobic processing and the subsequent disposal of compost to the waste disposal site. This is the result of the reduction of uncontrolled emission of greenhouse gasses into the environment. However, additional reduction of 297.76 units was noted when using BACOM technology which is the result of prevention of biologic breakdown of BS and the fact that the manufactured material can be used as a substitute for clay, bentonite, and plastic materials. An additional reduction of 27.6 units was calculated in the use of Eco-Bis technology, and it is the result of a completely prevented biological degradation of BS and of the replacement of the artificial fertilizers with biochar.

4.4 Impacts on the use of natural resources

From **Table 10** and **Figure 6**, it is evident that a landfilling of BS on sanitary landfill, composting, and anaerobic digestion and the subsequent disposal of the compost onto the landfill have no impact on the use of natural resources. Additional reduction of 162 units is enabled with the implementation of the BACOM technology because the manufactured material can be used as a substitute for clay, bentonite, and in some cases as plastic. The additional reduction of 66.9 units is enabled by the usage of Eco-Bis charcoal as the replacement of artificial fertilizers (**Table 9** and **Figure 6**).

The overall sustainability of using different technologies from the highest to the least efficient is as follows: BACOM > Eco-Bis > AD&L > composting > disposal.

5. Conclusions

According to expectations, landfilling of BS in sanitary landfills is the least acceptable option, even though modern landfills are equipped with modern biogas capture systems. Composting is an acceptable and widely accepted option because it is cheap and has rather neutral effect on the sustainability of the management of BS. However, considering the investment and operational costs which have no economic effect, it is less desirable option than anaerobic digesting, where the produced biogas can be exploited for energy production.

All abovementioned solutions need centralized organization. Successful operation requires large surfaces, and due to that, the local community must agree with the implementation of such a plant inside local areas. In addition, risk management in centrally organized technologies requires extensive and complex logistic operation and relatively large operating costs to achieve a small economic gain.

Material processing and material use of BS seems to be a much more acceptable and sustainable option than landfilling or incineration, because cheap replacements for materials produced from nonrenewable sources (e.g., artificial fertilizers, clays, bentonite, or even plastics in some cases) can be produced. In many cases these processes reduce negative pressures on the environment and improve life in the local communities.

These installations are usually small and mobile and can be placed directly in the vicinity of the WWTPs. The problems with burdening of the environment and rising costs because of extended logistics are solved or at least minimized in such a case. In addition, material processing and use of manufactured material mean the production of products with an added value, which can be used as raw materials or semifinished products in other industrial sectors, what is in accordance with the principles of industrial eco symbiosis and circular economy. The aforementioned technologies enable the creation of new jobs and the reduction of wastewater treatment costs.

The involvement of material processing technologies is in a consensus with the European Directive on waste (2008/98/EC) as shown in **Figure 2**.

Each technology has its own benefits or deficiencies, but in general the central organizing technologies as, for example, incineration, anaerobic digestion, composting, and landfilling, are more appropriate for processing of BS in a bigger scale (e.g., quantities above 30.000 tons of biosolids per year); meanwhile, smaller and more flexible technologies for material processing are more suitable for processing of BS in quantities below 30,000 tons per year.

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