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Transformation of Biogenic Waste Materials through Anaerobic Digestion and Subsequent Composting of the Residues – A Case Study

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ABSTRACT

Anaerobic digestion of biogenic waste materials has become an important strategy for energy supply and organic matter stabilization. This study focuses on the characterization of input materials, digestates and composted digestates throughout the processes. Changes of the materials due to both anaerobic degradation/composting and annual variation under actual conditions were revealed using the example of the Viennese biogas plant. Besides the comprehensive characterization by infrared spectroscopic and thermo-analytical investigations, biological activity, nutrients and heavy metals were determined. Lab-scale composting experiments with digestates and different bulking agents were performed in order to assess the influence on humification that is considered a quality criterion.

Keywords: Composting of digestates, quality control, heavy metals, nutrients, humification

INTRODUCTION

The urgent demand for energy supply has promoted the production of biogas by anaerobic biological processes from renewable resources for the last decade. Moreover, mitigation of greenhouse gas emissions by anaerobic digestion of organic wastes is a matter of particular interest (Kaparaju and Rintala 2010). Besides energy crops that are intentionally cultivated for this purpose, harvest residues from agricultural activities (Chen *et al.* 2010), solid and liquid manure (Singh *et al.* 2010), biogenic urban waste (Kuo and Lai 2010), municipal solid waste (Kumar and Ting 2010), food waste (Izumi *et al.* 2010), slaughterhouse waste (Cuetos *et al.* 2010), leftovers and residues from the food industry (Gupta *et al.* 2011), pulp and paper sludge (Yunqin *et al.* 2010) are appropriate ingredients for anaerobic digestion. Sewage sludge from waste water treatment has been a source for anaerobic digestion for a long time. In terms of resource management and recycling economy, residues from anaerobic digestion (digestates) are directly used as fertilizer or subjected to an additional aerobic treatment (Spencer 2007; Abdullahi *et al.* 2008). For the booming anaerobic technology, emphasis has been placed on the optimization of process operation in the anaerobic digester, on improvement of gas yields (Cline *et al.* 2010; Godbout *et al.* 2010; Molinuevo-Salces *et al.* 2010; Sbarciog *et al.* 2010; Kreuger *et al.* 2011) and on the evaluation of energy efficiency (Morris *et al.* 2010; Pöschl *et al.* 2010). The corresponding legal frame and financial support have promoted the emergence of many plants with the focus on energy supply. This situation is reflected by the available literature that focuses primarily on optimization of methanogenesis (Kaparaju *et al.* 2010; Siles *et al.* 2010; Menardo *et al.* 2011), separation techniques and gas purification and on the technical aspects of energy transformation (Iakovou *et al.* 2010).

Currently the residues and the appropriate treatment come to the fore and attract increasing attention. Large amounts of digestates require adequate areas for application. The quantification of nitrogen losses and the total energy balance of the anaerobic process including the additional treatment of digestates are the main questions to be answered (Kupper *et al.* 2008). The development of marketable products that reflect the value in terms of nutrients and organic matter quality would be a crucial economic aspect. Digestates from processes operating with low dry matter contents are usually applied on soils by irrigation without any additional treatment. Combustion of digestates is sometimes a subject of discussion, but the high water content has a negative effect regarding the energy efficiency. Composting of digestates is a common strategy to obtain an additional product besides methane for energy recovery. Separation of water by centrifugation or filtration and addition of bulk materials is a prerequisite for a well running composting process. The City of Vienna operates a biogas plant where 17,000 tons a year of biogenic waste from households and markets and leftovers from public institutions are processed. Biogenic household waste originates from the separate collection. After a 21-day retention time in the reactor and waste water separation by centrifugation, digestates are mixed with bulk materials and subsequently subjected to aerobic treatment in the composting plant of Vienna. The standard quality of a defined compost class regarding heavy metal contents is guaranteed by the stipulated limit values of the Austrian Compost Ordinance (Bundesminister für Land- und Forstwirtschaft 2001).

Digestates differ greatly depending on input materials, process operation and retention time in the reactor. Previous experiments have shown that the residual microbial activity can improve humification in a co-composting process with biogenic waste (Meissl and Smidt 2007). The presented study focuses on the characterization of digestates and the resulting composts using FTIR spectroscopy, thermal analysis and biological tests. Lab-scale experiments with different mixtures of digestates and bulk materials were performed in order to find out the influence on humification. The assessment of composted digestates regarding their value as soil amendment is based on the synopsis of conventional data, contents of humic substances and infrared spectroscopic and thermal characteristics. Data evaluation is supported by statistical methods.

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Original Research Paper

Table 1 Materials used in this study and their origin.

Materials	Sample ID	Origin
Digestates		Different Austrian and foreign plants
Stages of the anaerobic process (sampling two monthly)		
Input materials (waste delivery)	A1 – A5	Biogas plant of Vienna
Feeding mixture (reactor input)	FMix	Biogas plant of Vienna
Digestate	D	Biogas plant of Vienna
Separated waste water	WW	Biogas plant of Vienna
Digestate compost	DC	Composting plant of Vienna
Biowaste compost	BC	Composting plant of Vienna
Lab-scale experiments		
Digestate		Biogas plant of Vienna
Bulk material		
Wood		Composting plant of Vienna
Fresh biogenic material		Composting plant of Vienna
Composted biogenic material (14 days)		Composting plant of Vienna
Composted biogenic material (28 days)		Composting plant of Vienna
Samples from other plants (Austrian and foreign)		
Manure		17 samples from Switzerland
Food waste		2 samples from Lower Austria
Straw		9 samples from Upper Austria
Residues from juice production		4 samples from Upper Austria
Leftovers with glycerol		9 samples from Upper Austria
Biowaste and leftovers		5 samples from Vienna

MATERIALS AND METHODS

Sample sets, sampling procedure and sample preparation

One sample set of digestates originated from different Austrian and foreign biogas plants. Different stages of the anaerobic process were investigated using samples from the Viennese biogas plant and the composting plant, where sampling took place every second month during a period of one year (input materials, mixture for feeding the reactor, digestate after waste water separation, separated waste water, composted digestate, composted biogenic waste for comparison reasons). The series of waste deliveries (A) comprises biogenic waste from the separate collection (A1 and A2), market waste (A3), leftovers (A4) and material from the grease separator (A5). Sampling of the composts was carried out according to the Austrian Standards (ON S 2123-1, 2003). Liquid samples were taken as a composite sample of at least five single samples collected over a day. It should be emphasized that all samples, representing different stages of degradation, were collected at the same time and therefore do not represent a single continuous process.

Biological tests, ammonium nitrogen and nitrate nitrogen were determined using the fresh sample. Apart from input materials A1 to A4 (where these parameters were not determined) the particle size < 20 mm was guaranteed by process operation. For the other analyses the materials were air dried, ground by an agate mill and sieved < 0.5 mm. Waste water from anaerobic digestion and the feeding mixture were freeze-dried for infrared spectral investigations.

Lab-scale experiments

Lab-scale composting experiments were performed with mixtures of digestates from the Viennese plant and different materials serving as bulking agent and part of the input (**Table 1**). Composting took place on a small scale system as described by Smidt *et al.* (2008a). Due to the small scale the material was sieved through 10 mm The vessels (diameter: 110 mm, height: 60 mm) were located in a climate chamber. The material was rotated by hand daily during the first week, then twice a week. The small scale system was operated during 42 days, each variant in duplicate.

Table 1 compiles the sample sets investigated in this study.

Analytical methods and data evaluation

The loss of ignition (LOI), the total organic (TOC) and inorganic (TIC) carbon, total nitrogen (TN) contents, NH_4-N, NO_3-N, pH, plant available phosphorus and potassium (Calcium-Acetate-Lactate = CAL and water extraction method) were determined according to ÖNORM S 2023 (Austrian Standards Institute 1986). Humic acid (HA) analysis was based on alkaline extraction and precipitation according to Gerzabek *et al.* (1993). The operation procedure was slightly modified, in that gray humic substances were not separately determined. Phosphorus, potassium and heavy metals were determined by means of an ICP AES spectrometer (Thermo Iris Intrepid II, Thermo Scientific) after disintegration of the dried sample with *aqua regia*.

Respiration activity was measured during a 4-day incubation period (RA_4) in a Sapromat (Voith Sulzer®) according to ÖNORM S 2027-1 (Austrian Standards Institute 2004a) by recording the oxygen uptake in milligram and referring it to one gram of dry matter (mg O_2 g^{-1} DM). The Sapromat method is based on the absorption of CO_2 released by metabolic activities of the microorganism, using NaOH pellets. The measured underpressure is equalized by a chemical oxygen production. The gas generation sum (GS_{21}) was determined according to ÖNORM S 2027-2 (Austrian Standards Institute 2004b), by recording the gas generation during a 21-day incubation period (NL kg^{-1} DM). For the GS_{21} the sample with a water content of the water holding capacity is incubated under anaerobic conditions at 20°C.

FT-IR absorbance spectra were recorded using a Bruker® EQUINOX 55 FT-IR spectrometer equipped with a DTGS detector as described by Smidt *et al.* (2008b). Spectra were vector normalized for principal component analysis.

Thermal analyses were performed by means of an instrument for simultaneous thermal analysis STA 409 CD Skimmer (Netzsch GmbH®). Combustion was carried out according to Smidt *et al.* (2008b).

For data evaluation the Unscrambler 9.2 (© CAMO) and SPSS 15.0 (© IBM) were used.

RESULTS AND DISCUSSION

Input materials

Fig. 1 displays the portion of different input materials for anaerobic digestion in 135 Austrian plants (Amlinger 2010). Most input materials are wastes or residues from agriculture, industry and the urban collection systems for biogenic waste. Only a small amount (8%) is provided by cultivation of energy crops. Therefore anaerobic digestion has become an important strategy in waste management for the stabilization of organic matter and load removal of municipal solid waste with the benefit of energy supply and soil conditioner production.

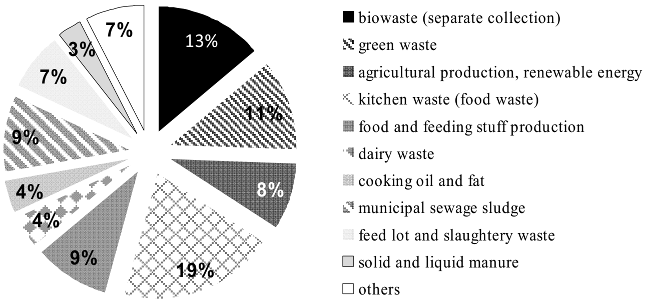

Fig. 1 Portion of different input materials used for anaerobic digestion in Austria.

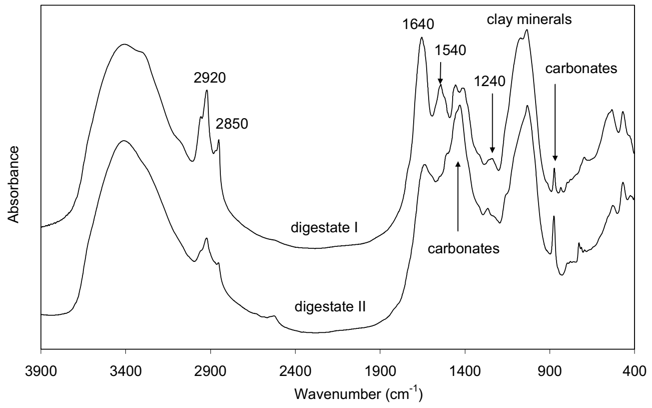

Fig. 2 Infrared spectra of digestates from wet (I) and dry (II) anaerobic processes.

Digestates – variation revealed by infrared spectroscopic characteristics

The degree of organic matter transformation during anaerobic digestion is revealed by infrared spectroscopic characteristics, the remaining respiration activity and the gas forming potential. **Fig. 2** shows spectra of digestates from different plants. In plant I (digestate I) food waste is digested with a retention time of 2 weeks ("wet", mesophylic process). In plant II (digestate II) biogenic waste (kitchen and yard waste) is processed with a retention time of 2 weeks ("dry", mesophylic process). "Wet" in this context means a water content of 97 %, "dry" a water content of about 65%. Output materials from "dry" digestion differ considerably from "wet" digestion as they contain a high portion of bulking agents which allows the composting process to continue immediately after the anaerobic treatment. Spectral characteristics of digestate II are similar to the composted material. The strong absorption bands in the spectrum of digestate I that can be assigned to organic functional groups (e.g. aliphatic methylene at 2920 and 2850 cm^{-1}, the amide bands at 1640, 1540 and 1240 cm^{-1}, carboxylates and alkenes at 1640 cm^{-1}) indicate the additional degradation potential. According to previous investigations (Böhm *et al.* 2010) the development of prediction models for the gas forming potential by means of infrared spectral characteristics and partial least squares regression might be an interesting task to estimate the available biogas yield under specific process conditions very fast.

Depending on the input material digestates differ considerably. A principal component analysis based on spectral characteristics of digestates originating from different wet digestion processes of biogenic materials visualizes the position of samples in the scores plot (**Fig. 3**). Food waste comprises industrial frozen and tinned food that exceeded the sell-by date. Manure mixed with straw and leftovers with glycerol addition show a distinct grouping.

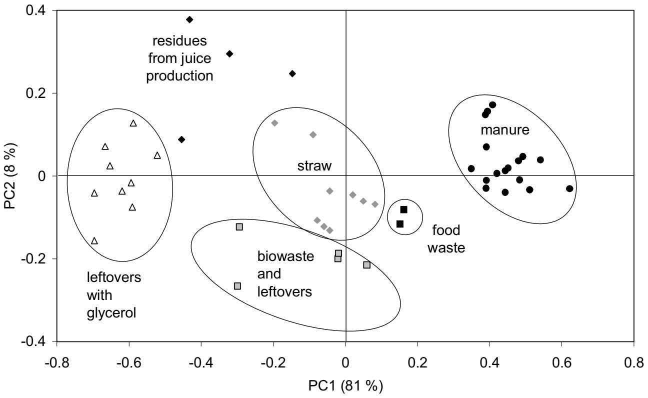

Fig. 3 Principal component analysis of digestates from different input materials and similar wet digestion processes, based on infrared spectra (wavenumber range from 4000-400 cm^{-1}).

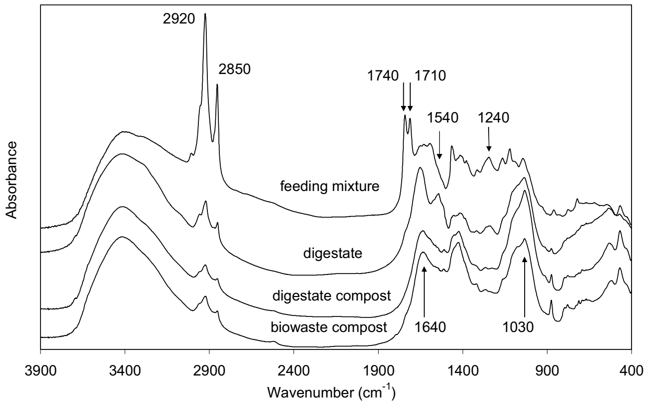

Fig. 4 Changing spectral characteristics during anaerobic (wet process) and aerobic degradation.

Development from biogenic materials to composts via anaerobic digestion, revealed by spectral and thermal characteristics

Chemical changes of biogenic materials due to degradation under anaerobic and aerobic conditions are visualized by spectral and thermal characteristics. Samples originated from the Viennese biogas plant and the Viennese composting plant, where sampling took place every two months for a period of one year.

Fig. 4 shows the changing characteristics of the feeding mixture due to anaerobic digestion, the resulting digestate and the composted digestate. Additionally the spectrum of composted biowaste (yard and kitchen waste) that only underwent an aerobic process is demonstrated. Changes of the spectral pattern are clearly indicated by the aliphatic methylene bands (2920 and 2850 cm^{-1}) and by the fingerprint region (1800-1000 cm^{-1}). The feeding mixture features prominent methylene bands and distinct bands in the fingerprint region, indicating marginal degradation. Several indicator bands are labeled: C=O vibrations (1740 and 1710 cm^{-1}) that can be assigned to aldehydes, carboxylic acids and ketones, C=O and C=C vibrations at 1640 cm^{-1} (carboxylates, amide I, alkenes), N-H vibration at 1540 cm^{-1} (amide II), C-O and C-N vibrations at 1240 cm^{-1} (carboxylic acid, amide III) and clay minerals at 1030 cm^{-1}. More details on band assignment in waste materials were reported by Smidt and Schwanninger (2005) and Smidt and Meissl (2007).

Changes in the spectral pattern correspond to changes of the thermal behavior that is illustrated in **Fig. 5** by thermograms and heat flow curves (Smidt and Lechner 2005). The heat flow profiles indicate exothermic (arrow) and endothermic reactions. Incineration of organic matter under oxidative conditions leads to exothermic reactions. The decreasing organic matter content is reflected by decreasing

Table 2 Material characteristics revealed by conventional parameters (pH, electrical conductivity, loss of ignition and total organic carbon), biological reactivity (respiration activity and gas sum potential), and the ratio of enthalpies referring to dry and organic dry matter.

Material	**pH**	**el. cond.**	**LOI**	**TOC**	**RA_4**	**GS_{21}**	**$E_{DM}*E_{oDM}^{-1}$**
		$mS*cm^{-1}$	**% DM**	**% DM**	**$mg\ O_2*g\ DM^{-1}$**	**$NL*g\ TM^{-1}$**	
A1	6.1/ 7.6^{c}	3.51/ 6.14^{b,c,d}	59.8/ 82.0^{d}	25.9/ 46.9^{c}			
A2	4.5/ 5.2^{a,b}	5.77/ 8.26^{d}	84.7/ 94.7^{e}	46.7/ 54.0^{d}			
A3	6.9/ 8.6^{c,d}	3.83/ 7.95^{c,d}	54.4/ 79.0^{c,d}	26.8/ 43.1^{b,c}			
A4	3.6/ 6.1^{a,b}	5.06/ 9.12^{d}	72.2/ 100.0^{e}	37.5/ 57.3^{d}			
A5	4.9/ 6.1^{d}	0.47/ 2.95^{a}	95.3/ 99.2^{e}	65.7/ 75.6^{e}			
FMix	3.5/ 4.9^{a}	8.15/ 12.88^{e}	84.6/ 87.9^{e}	44.0/ 53.8^{d}		64.7/ 432.5^{a}	0.69/ 0.75^{c}
D	7.2/ 8.7^{c,d}	2.94/ 3.68^{a,b,c}	70.7/ 74.9^{d}	33.9/ 37.5^{b,c}	82.7/ 105.1^{b}	71.6/ 120.0^{b}	0.85/ 0.90^{d}
WW	7.9/ 8.0^{c,d}	12.98/ 16.70^{f}	18.6/ 35.2^{a}				
DC	7.8/ 8.8^{d}	2.73/ 3.08^{a,b}	55.0/ 58.7^{b,c}	21.8/ 29.3^{a,b}	4.9/ 16.4^{a}		0.53/ 0.59^{b}
BC	7.6/ 8.3^{c,d}	0.96/ 1.74^{a}	41.1/ 53.9^{b}	17.5/ 25.1^{a}	0.6/ 15.2^{a}		0.40/ 0.54^{a}

* confidence levels (lower level/upper level) with significant differences indicated by superscript letters (similar letters indicate the same groups; Tukey HSD test); type 1 error probability = 0.05

mass losses. The mass loss > 700°C of the biowaste compost sample (**Fig. 5A**) is due to the carbonate decay that corresponds to the endothermic reaction in the heat flow profile (**Fig. 5B**). The second exothermic peak of the digestate is stronger and found at a higher temperature compared to the feeding mixture. This shift to a higher temperature indicates increasing stabilization. The exothermic peak of the composts moves to a lower temperature. This behavior is characteristic of anaerobically stabilized biogenic materials that are subjected to further aerobic treatment which leads to additional degradation. Increasing stabilization of the compost, e.g. by humification, shifts the curve again to a higher temperature. The enthalpy of the material is calculated by integration of the area below the heat flow profile and the baseline. The enthalpy (E) of the whole sample (E referring to dry matter, E_{DM}) decreases with organic matter degradation compared to the enthalpy of the remaining organic matter (E referring to organic dry matter, E_{oDM}) that increases. The ratio of E_{DM}/ E_{ODM} therefore decreases and indicates proceeding stabilization (**Table 2**).

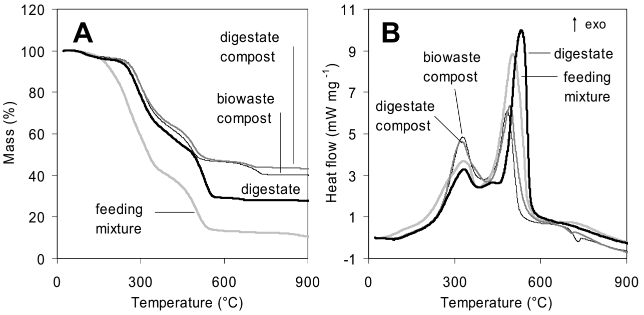

Fig. 5 Changing thermal characteristics during anaerobic and aerobic degradation. (**A**) Mass losses (thermogravimetry), (**B**) heat flow profiles (differential scanning calorimetry).

Development from biogenic materials to composts via anaerobic digestion, revealed by pH, electrical conductivity, loss of ignition and TOC – annual variation

Table 2 presents several parameters usually applied for these materials. The pH values of the input materials (A1 – A5) vary widely depending on their composition (kitchen and market waste, material from the grease separator, leftovers) and the stage of degradation. Variation is also high within each of these groups. The feeding mixture features the lowest pH value. Progressing degradation is paralleled by its increase. Compared to biowaste composts (BC) the pH of composted digestates (DC) is in general higher. The electrical conductivity is the highest in the waste water (WW) fraction by which salts are separated to a large degree. Hence plant compatible salt concentrations are obtained in the compost. The organic matter content (LOI) and the TOC of the solid material are highest in the fraction of the grease separator. The other input materials (A1 – A4) feature organic matter contents > 60% and TOC contents > 30%. The continuous decrease of organic matter during the anaerobic and aerobic processes is revealed by the LOI and the TOC values.

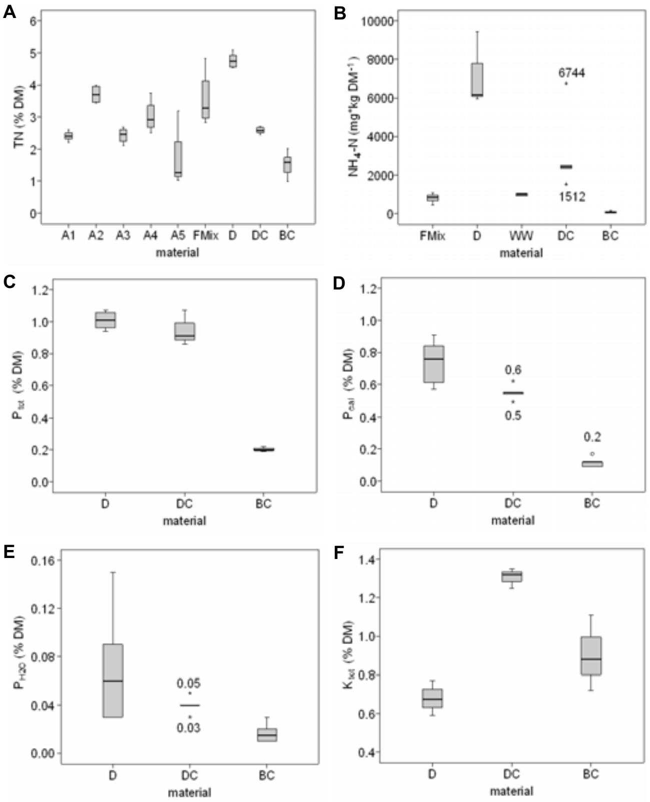

Fig. 6 Minima, maxima, median, 25% and 75% quantile of total (**A**) nitrogen (TN), (**B**) NH_4-N, (**C**) total phosphorus (P_{tot}), (**D, E**) extractable phosphorus (CAL and H_2O) and (**F**) total potassium in input materials (A1 – A5), feeding mixtures (FMix), digestates (D), waste water (WW), composted digestates (DC) and biowaste compost (BC).

Nutrients

Nutrients are an important quality criterion for composts. Their fate during the anaerobic and the subsequent aerobic process is of high interest. The range of total nitrogen (TN), ammonium nitrogen (NH_4-N), phosphorus and potassium is demonstrated in **Fig. 6**. Digestates feature the highest contents of TN and ammonium nitrogen (NH_4-N) which indicates enrichment and transformation compared to the feeding mixture. Some NH_4-N is lost by the waste water fraction. The high ammonium content of the composted digestate indicates missing stabilization of the final product.

During composting a considerable amount of nitrogen disappears by NH_3 losses due to increasing pH values (Whelan *et al.* 2010). These losses are a critical issue that requires additional research on how to immobilize nitrogen in the compost by process operation. Ammonia stripping is one of the suggested technologies of nitrogen recovery (de la Rubia *et al.* 2010; Park *et al.* 2010; Zhang and Jahng 2010). The relatively high ammonium concentrations indicate an incomplete composting process. Therefore, nitrate did not play a role in digestate compost up to the sampling date. Contrary to laboratory experiments in a small scale the air supply is not continuously ensured in a full scale plant, especially when centrifuged digestates that tend to lump formation are processed. In biowaste compost nitrate contents between 25 and 1500 mg kg^{-1} DM were determined, in digestate compost between 0 and 65 mg kg^{-1} DM. Phosphorus contents were determined in digestates, composted digestates and biowaste compost. Biowaste composts contain much less phosphorus than digestate composts. Plant available phosphorus (P_{cal}) is lower in digestates and much lower in the composted digestate which indicates the immobilization of this element. Regarding the plant available phosphorus biowaste features similar values despite lower total contents. Water soluble phosphorus is very low compared to the total content. By contrast, CAL and water extractable potassium contents (not shown) are nearly as high as total potassium contents, indicating that the availability of this element does not pose a problem in digestates, composted digestates and biowaste compost.

Biological activity

The aim of the anaerobic and aerobic treatment of biogenic waste is the stabilization of organic matter which is an environmental request and a question of plant availability. The reduction of reactivity is confirmed by biological aerobic and anaerobic tests. The decrease of the gas generation sum from the feeding mixture to the digestate corresponds to the amount of biogas that can be yielded during anaerobic digestion (**Table 2**). However, digestates still have a considerable gas forming potential. The consideration of ecological and economic aspects should lead to process optimization regarding its worthwhile use. The decreasing oxygen uptake (RA_4) by microorganisms in composted digestates and biowaste compared to digestates is also demonstrated in **Table 2**. As reported above the remaining reactivity can also promote the synthesis of humic substances in the subsequent composting process (Meissl and Smidt 2007). In mature composts the respiration activity is low. Higher values (e.g. DC and BC) indicate an insufficient stabilization.

Due to the residual gas forming potential relevant greenhouse gas emissions can be expected. There are some environmental aspects that have to be considered regarding the storage of digestates. The temporary storage of digestates in lagoons is a widely held practice. In order to quantify the carbon losses and nitrogen mineralization, digestate was kept in 1 L bottles under anaerobic conditions at room temperature. After 10 months the TOC had diminished by 18% from 36.7 to 30.2% DM. Ammonium/ ammonia nitrogen increased from 9426 mg*kg^{-1} DM to 32,500 mg*kg^{-1} DM. It can be assumed that progressing degradation of nitrogen containing compounds leads to the formation of ammonium and depending on the increasing pH to ammonia. The fate of nitrogen in lagoons and during the aerobic treatment needs further investigations.

Heavy metal contents

Compost quality according to the Austrian Compost Ordinance is mainly defined by very low contents of pollutants. Limit values for heavy metals specify the compost quality class. The Austrian Compost Ordinance fixes three levels of compost quality "A+", "A" and "B". **Fig. 7** presents several heavy metal contents in the digestate (D), in composted digestate (DC) and in biowaste compost (BC). The black line indicates the limit value for "A+" compost quality according to the Austrian Compost Ordinance. "A+" labels the highest quality applicable in horticulture. The limit value of 70 ppm for Cr was not exceeded by any sample. Mercury was not detectable. **Table 3** compiles the results obtained by the Tukey HSD test (ANOVA).

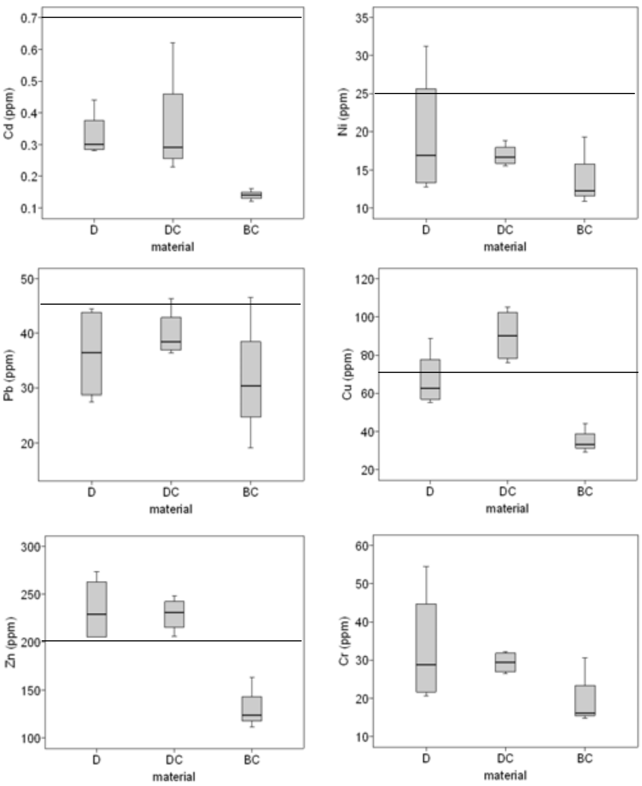

Fig. 7 Range of heavy metal contents (Cd, Ni, Pb, Cu, Zn, Cr) in digestate, digestate compost and biowaste compost, presented as boxplots with maximum, minimum, median and 25% and 75% quantile; limit values for class "A+" composts according to the Austrian Compost Ordinance indicated by the black line.

Table 3 Tukey HSD test for differentiation of materials in terms of heavy metal contents (type 1 error probability: 0.05); in brackets the confidence intervals (type 1 error probability: 0.05).

Cd (ppm)			Cu (ppm)			
	group			group		
material	2	1	material	2	1	
FMix	[0.0;0.2]		FMix	[8;30]		
BC	[0.1;0.2]	[0.1;0.2]	BC		[16;55]	
D		[0.2;0.5]	D		[43;91]	
DC		[0.1;0.6]	DC		[68;113]	
Ni (ppm)			**Zn (ppm)**			
	group			group		
material	2	1	material	2	3	1
FMix	[2;4]		FMix	[46;91]		
BC		[3;25]	BC		[66;200]	
DC		[15;19]	DC			[200;257]
D		[6;33]	D			[179;289]
Pb (ppm)			**Cr (ppm)**			
	group			group		
material	2	1	material	2	1	
FMix	[0;27]		FMix	[4;8]		
BC		[0;66]	BC		[0;42]	
D		[22;50]	DC		[25;34]	
DC		[33;47]	D		[8;58]	

Biowaste compost features lower zinc contents. Regarding the other heavy metals no significant difference is found between digestates and biowaste composts. The digestate compost exceeds the "A+" limit values for copper and zinc. Limit values for "A" compost quality were not exceeded by any compost sample.

Lab-scale experiments

Compost organic matter plays a crucial role in soils (Glab *et al.* 2009). The amount of humic acids was determined as they mainly contribute to the favorable properties and are therefore a main criterion for compost quality (Smidt *et al.* 2008b). Different mixtures of digestate (D) with different materials were tested in lab-scale experiments in order to find out the impact of different input materials and bulking agents on humification. The first lab-scale composting experiment was carried out with digestate and different portions of fresh biowaste or different portions of the oversize fraction (mainly wood particles) of the screened mature compost (mixtures 1:1, 1:3, 3:1). The favorable mixing ratio of 1:1 (digestate/bulking agent) was kept in the second composting experiment that was carried out with 2-week (Bio 2w) and 4-week (Bio 4w) composted biowaste and the oversize fraction of the screened mature compost (all mixtures 1:1). Biowaste was used as a reference.

The development of humic acid contents during the 42-day composting process is presented in **Fig. 8**. After 2 weeks of composting, humic acids become more stable and quantification by the photometric measurement leads to reliable results. Therefore the humic acid content of day 14 is presented as the first one. The mixture with the oversize fraction of the screened mature compost led to the highest values of humic acid contents. Wood particles improve the pore volume and allow a greater access to air which is extremely important for digestates with a tight consistency.

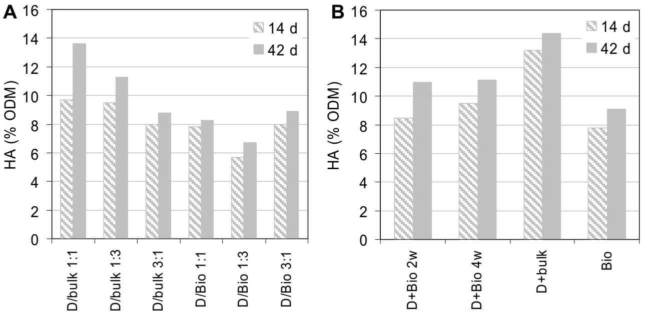

Fig. 8 Development of humic acid contents (shown 14 days and 42 days) in lab-scale composting experiments of digestates (**A**) with different portions of bulking agents, (**B**) with biowaste compost of different ages.

CONCLUSIONS

Composting of digestates is a useful strategy in biogenic resource management which contributes to close the cycle. The production of composts for soil amelioration is considered to be an additional benefit besides energy generation by anaerobic digestion. Nevertheless, eco-balances of anaerobic digestion and subsequent processes are necessary to assess the benefits and the disadvantages. Due to the increasing amount of residues large areas or long transports are necessary to apply the material on soils. Moreover, temporary storage in lagoons causes relevant gaseous emissions. From the environmental point of view this topic requires more attention in the future. The fate of nitrogen also demands additional investigations. The main question focuses on nitrogen losses and how to reduce them by adequate process operation in order to minimize the losses and to maintain the nitrogen level in composts. Fixing of nitrogen in humic substances might be an interesting target. It is evident that the contamination of the input material by heavy metals also affects the compost quality. Therefore quality assurance should be provided by the collection system which seems possible in view of the input materials used for anaerobic digestion. Humification of digestates during composting can be improved if an appropriate mixture is used. The remaining microbial activity of digestates and suitable bulk materials play a crucial role. In a more comprehensive consideration all stages of the biogenic material cycle have to be taken into account. Energy out of biogas is not the only product of this process. Both digestates and composted digestates can be considered as valuable products. In the context of a complete eco-balance several questions have to be answered in the future: available areas for the application and the related transport distances, losses of relevant gaseous emissions during storage of digestates in lagoons or nitrogen losses during the composting process.

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