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Assessment of Alternative Phosphorus Fertilizers for Organic Farming:

Compost and Digestates from Urban Organic Wastes

Organic wastes from urban areas include organic household wastes, food processing residues and catering wastes. These so called "Urban Organic Wastes" are important potential sources for nutrient recycling back to agriculture. Main waste treatment options for these sources are composting and anaerobic digestion. Both differ in the process performance – regarding for example emissions or energy balances – and in the characteristics of the final fertilizer product. This fact sheet describes the most important aspects of compost and digestates from urban organic wastes for use in organic farming.

Introduction

The phosphorus balances in arable organic farming systems are very often negative. This indicates the need for the implementation of strategies for their sustainable replenishment in order to avoid long term reduction of soil fertility of organically cropped fields. Phosphorus in organic wastes accounts for a relevant portion of the potential P resources for recycling in European societies.

In urban areas, different sources of organic (degradable) wastes are available, which all together can be referred to as Urban Organic Wastes (UOW):

- Green (biodegradable) waste from gardens or park areas, such as grass or flower cuttings, foliage and hedge trimmings;
- Source separated food waste from private households;
- Food waste from retail, often with high proportions of plastic and often including waste defined according to Regulation (EC) No 1069/2009 (animal by-products);
- Organic waste from food processing;
- Food waste from catering and institutions, including waste defined according to Regulation (EC) No 1069/2009 (animal by-products).

UOWs are usually processed by composting, anaerobic digestion (AD) or incineration. In some cases, materials are still deposited in landfills.

This fact sheet was realised with financial support of the project IMPROVE-P.

IMPROVE

Composting in heaps and containers are two commonly used methods for composting urban organic wastes. Unlike the composition of the raw material, the composting method does not have an influence on the nutrient composition of the final product.

Source separated bio-wastes, herbaceous green waste and food waste in general are well suited for both composting and anaerobic digestion, whereas feedstocks high in lignin are better suited for treatment by composting or for incineration.

Regarding the use in organic farming systems, a central point from the regulation point of view is the compilation of permitted fertilizer sources in Annex 1 of regulation (EC) No 889 / 2008 on organic farming. The EU regulation only mentions source-separated organic household waste, and does not explicitly include several feedstocks commonly used as co-substrates in compost piles or anaerobic digestion plants, e.g. catering wastes, retailer wastes, food processing waste etc. This is giving room for contradicting interpretations in the EU member states.

Recycling processes

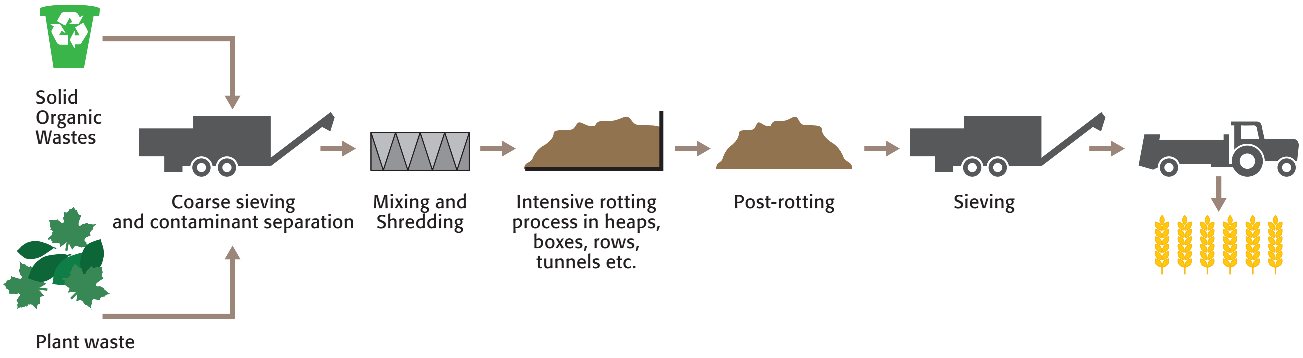
Composting and anaerobic digestion are well known technologies[1]. In the composting process organic material is broken down under the influence of atmospheric oxygen by heterotroph organisms. Modern, methodical composting is a multi-step, closely monitored process with measured inputs of water, air, and carbon- and nitrogen-rich materials. The decomposition process is aided by shredding the plant matter, adding water and ensuring proper aeration by regularly turning the mixture. In professional plants temperatures are maintained above 60 °C over several days, which results in a hygienic product (Figure 1).

Anaerobic digestion is a cascade of processes by which microorganisms break down organic material in the absence of oxygen (Figure 2). Digestate is the residue of the original input material which cannot be used by the microbes in the digesters.

Digestates can either be stored and used as fertilizers, or be separated into a liquid and a solid fraction. Separation will lead to two different fertilizers with contrasting properties: a liquid fertilizer and a solid organic leftover, which either can be used directly as organic amendment, or be composted or dried before field application. As a result of the high total nitrogen (N) as well as NH_4^+-N concentrations in the solid fraction of digestates, a rapid composting process will easily occur where large proportions of N (up to 50–60 %) will be lost as ammonia or nitrous oxide [7] after the separation procedure.

Both methods break down most of the easily degradable organic matter (OM) and stabilize the material, meaning that it can be stored without rapid decomposition causing odor and other nuisances.

Figure 1: Standard process for composting of urban organic wastes



In biogas plants not only urban organic wastes can be fermented, but also other organic wastes, solid manure and slurry.

Solid digestates may be composted, but result in high nitrogen losses.

During composting, the energy contained in the degraded OM as well as 43–62% of the nitrogen is lost[3][4]. In contrast, during anaerobic digestion most of the energy contained in the degraded OM is transformed into biogas. At the same time, the N is conserved, predominantly as digestate ammonium (NH_4^+). However, the remaining digestate usually has a high water content, which makes it expensive to handle and spread in the field. Digestate composting or drying is related to high N losses. Up to 90% of the ammonium N might be lost, if not removed from the air stream[2][5].

With both treatments, most weed seeds lose their ability to germinate and the pathogen load is largely reduced[6][7][8].

Available amounts

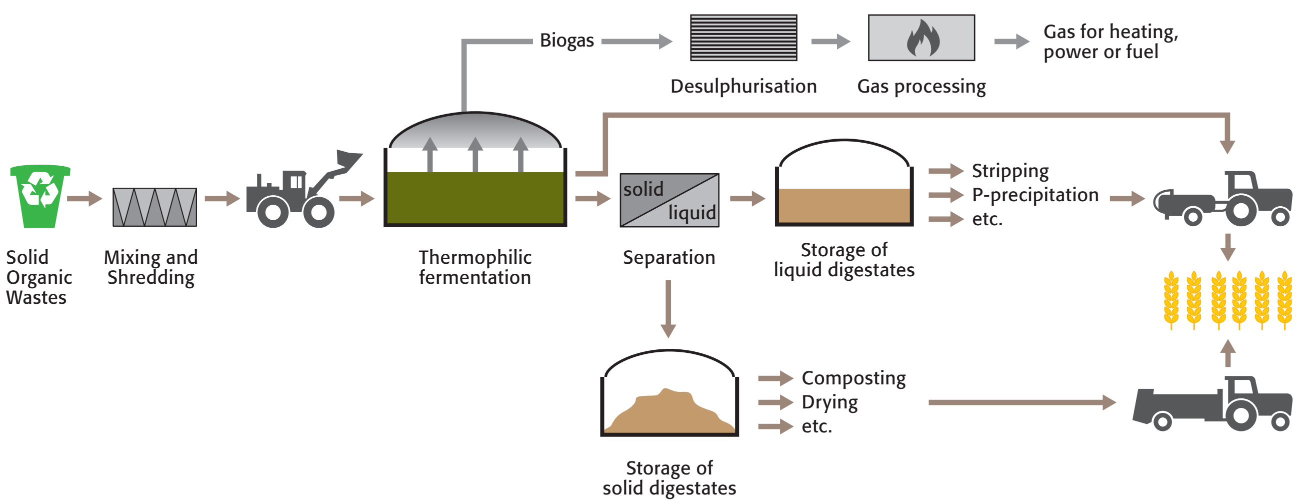
In many countries of Europe, UOW production amounts to approximately 100 kg per person and year[9][10][11][12]. This is equivalent to 40% of the total municipal solid waste mass. Only 30% of biowaste across Europe is collected separately and recycled as organic fertilizer[12]. As shown for the six countries participating in the CORE Organic "Improve-P" project (Table 1 on page 4), significant amounts of UOW are available for producing composts and/or digestates, and more or less efficiently utilised for this purpose.

Nutrient contents and characteristics

The dry matter (DM) content of mature composts ranges between 50 and 75%, while in liquid digestates it falls between 2% and 12% of total mass (Table 2 on page 5). The DM content of the solid fraction of digestates – after a liquid-solid separation – ranges between 20% and 30% for non-dried solids, and between 60% and 86% for dried digestates. The main component of a mature compost DM is ash (mainly sand, silt and clay), whereas in digestate, a larger proportion of the DM is organic matter (OM) (Table 2). Digestates in general contain much higher concentrations of nutrients (N, P as well as K) than composts on a DM basis.

The nutrient spectra of liquid and solid end products from treatment of UOW – respectively the relation of N, P and K to each other – can differ largely. The nutrient spectra of solid end products, including composts as well as solid digestates and the composts made of it, is characterized by low levels of total N due to the high N volatilization losses during treatment[13]. This results in fertilizers with a low ratio of ammonium to total N and relatively high P concentrations, leading to P accentuated fertilizers with a narrow N/P-ratio between 3.5 and 4.5. This can lead to excess applications of P to the soil when compost is applied to meet N requirements[14]. Liquid digestates are characterized by

Figure 2: Standard process for anaerobic digestion of urban organic wastes



To ensure a consistent quality of composts and digestates different analytical and testing methods are used such as analysis of organic and inorganic ingredients and plant tests.

high levels of N, as well as a high ratio of ammonium to total N. As the anaerobic digestion treatment itself has only minor effects on the ratios of nutrients, the nutrient spectra in the final product are often better matched to the crop needs. The N/P-ratio of liquid digestates can vary between 4 and 20.

P concentration and P speciation

On a dry matter base, the mean P concentration in liquid digestates is much higher than in solid digestates, whereas composts show the lowest P concentrations (Table 2). The very high P concentration in digestates of catering wastes and retailer leftovers is a consequence of the high P concentration in the feedstocks and their high organic matter bio-degradability.

In composts as well as in digestates, the major part of the P (>55 %) is present in inorganic forms [15] [16] [17] [18] [19]. Both treatments reduce the ratio of easily soluble P forms including water soluble P to total P[19] [20]. The inorganic P is present as a continuum of P species – some of them are very rapidly exchangeable with inorganic P in the solution, while a majority of them are slowly exchangeable [17] [18]. The P species in alkaline composts are dominated by relatively insoluble calcium phosphates [15] [17] [18], e.g. in the form of condensed calcium phosphates such as apatites or octocalcium phosphates [18]. In neutral or acidic composts, which contain high inputs of animal processing residues, Fe- and Al-species can control the inorganic P concentration in solution [16].

The biogas process leads to a transformation of organic forms of P into inorganic forms. Simultaneously, the pH of the digestate increases [19]. Raising the pH moves the chemical equilibrium toward the formation of phosphate ($HPO_4^{2-} \rightarrow PO_4^{3-}$) and subsequent precipitation as calcium- or magnesium-phosphate (e.g. $Ca_3(PO_4)_2$) [21] [22]. Simultaneously, the binding form of other elements such as iron (Fe) may also be influenced by anaerobic digestion, affecting P turnover and precipitation processes [29]. The fraction of dissolved P, mineralized during AD, associates with suspended solids [22] [19]. Therefore, the water-extractable P-fraction may decrease substantially during AD [19].

Table 1: Availability of different kinds of urban organic wastes (excluding sewage sludge) in different European countries

	Sources [Mg or tonnes per year]			Fertilizer amounts produced [Mg or tonnes per year]		Nutrient amounts [Mg per year]			Data based on and adapted from:
	Green wastes	Household bio-wastes	Catering wastes [1]	Composts	Digestates	N	P	K	
Austria	728,500	752,100	140,500	164,000	420,000–450,000				[24] [25]
Denmark	410,000	245,000	9,800			2,689	450	4,205	[26]
Germany	5,000,000	4,000,000	358,000	5,000,000	430,000				[9] [10] [12] [27]
Norway	160,000	250,000 – 270,000	25,000 – 30,000	112,000	45,000				[28]
Switzerland	213,977	397,385	152,840	517,165 m^3	362,000 t liquid digestate, 142,150 m^3 solide digestate				[29]
United Kingdom	7,000,000 to 8,300,000			2,740,000	113,000				[11] [12]

[1] *including organic leftovers of retailers*

Due to their high ammonium contents, liquid digestates should be applied to N demanding crops using special devices to avoid major ammonia losses.

The substrates used for organic gardening are largely made from compost. It provides a high proportion of the plants´ phosphorus and potassium needs.

P bioavailability and influencing factors

Phosphorus in composts and digestates can be considered as 100 % plant available in the long term [30] [31] [19]. About 10 to 50 % of total P in municipal compost is available for plant uptake in the first two years after application [32] [33] [34] [35] [36] [37]. The apatite and octacalcium phosphates fraction will have a low availability to plants in neutral and alkaline soils [38]. *Frossard et al.* [18] found a strong positive correlation between the total N concentration in composts and the inorganic P in solution, suggesting that the total N concentration can be used as a predictor for rapidly plant-available P. However, plant bioavailability of compost P can be affected by the feedstock (substrate) and the biological stability of the compost, with stable compost having lower levels of water-soluble P [37]. For digestates, most available results from field experiments indicated no effects of AD on P availability [39] [40] [19].

Other nutrients, their speciation and plant bioavailability

Composts and digestates contain all nutrients needed by crops for growth. In addition to phosphorus (P) and nitrogen (N), potassium (K) and sulfur (S) are of major interest from an agronomic point of view. Composts show low N and ammonium concentrations, and low (<0.1) ammonium to total N ratios [41] [42] [14]. The N fertilizer value of composts in the year of application can range between -15 % (net immobilization) and +15 %, with 5 % of the total applied N amounts taken up in aboveground plant material as a mean value [33] [43] [42] [44]. In the following years a net mineralization of 2 % to 8 % of the remaining N can be assumed [45] [33] [41]. In a long-term perspective (20–40 years), approximately 40 % of the N supplied as composts will become plant available [46] [30].

Table 2: Dry matter content (DM, as % fresh matter) and macronutrient concentration (% DM basis) of composts and digestates certified by the German compost association [1]

	DM	OM	N	P	K	S	Mg	Na
Green waste compost	62.6 (52–74)	36.9 (23–51)	1.15 (0.7–1.6)	0.22 (0.14–0.32)	0.85 (0.4–1.3)		0.44 (0.19–0.79)	
Household waste compost allowed for use in Organic Farming	64.5 (52–78)	39.5 (26–54)	1.45 (0.9–2.0)	0.31 (0.18–0.44)	0.98 (0.6–1.4)		0.45 (0.22–0.72)	
Household waste compost including other feedstocks not specified in EU regulation [2]	64.0 (52–77)	39.5 (26–52)	1.53 (0.9–2.0)	0.36 (0.18–0.49)	1.10 (0.6–1.5)		0.51 (0.22–0.74)	(0.037–0.39)
Liquid household waste digestate allowed for use in Organic Farming [3]	12.0 (5.0–20.5)	58.1 (42–78)	4.47 (2.3–6.9)	0.68 (0.36–1.23)	3.24 (1.48–6.57)		0.65 (0.42–1.06)	(0.06–0.36)
Liquid household waste digestate including other feedstocks not specified in EU regulation [2]	5.20 (2.3–9.1)	59.5 (45–73)	12.1 (4.5–19.1)	1.17 (0.55–3.15)	4.31 (4.5–8.7)	(0.3–0.9)	0.44 (0.16–0.73)	(0.09–6.4)
Liquid digestate of catering and retailer organic wastes (no certification for use in Organic Farming)	3.34 (1.9–7.1)	56.5 (48–80)	16.3 (4.93–26.5)	2.21 (1.03–3.14)	4.49 (2.7–8.7)	0.86 (0.44–2.74)	0.21 (0.08–1.12)	5.6
Solid household waste digestate allowed for use in Organic Farming [3]	45.8 (25–69)	61 (44–87)	1.84 (1.1–2.6)	0.60 (0.24–1.10)	1.20 (0.5–2.0)		0.51 (0.35–0.75)	
Solid household waste digestate including other feedstocks not specified in EU regulation [2]	42.4 (26–84)	58.2 (38–81)	2.87 (1.81–4.86)	0.92 (0.41–1.45)	1.32 (0.35–2.32)		0.59 (0.40–0.87)	

[1] *in parentheses: 10 and 90 % fractile of values*

[2] *e.g. catering wastes, leftovers of retailers, etc., not allowed for use in Organic Farming*

[3] *provided that the single contents for potentially toxic elements are within the threshold values set by the Reg. (EC) 889/2008 (see table 3)*

As previously stated, the nitrogen losses during the anaerobic digestion process are minor. Therefore, liquid digestates from urban areas have relatively high N concentrations ranging between 2.3 % and 27 % on a dry matter base. The ammonium to total N ratio of liquid digestates ranges between 0.35 and 0.75 [14]. The fertilizer value of total N in liquid digested household waste is comparable with cattle slurry [47] [48]. Composted solid digestates have an N fertilizer value similar to composts, and dried solid digestates have a very low N fertilizer value due to N losses during the drying process and the buildup of heterocyclic N compounds (melanoids).

The K fertilizer value of composts and digestates is similar to mineral K fertilizers [32], as K does not become part of structural components in organic molecules. Due to the high water solubility of K, leaching losses may occur in composts which are not covered adequately to protect them from rainfall [44]. Composts as well as digestates also contain S [49]. Since S is transformed into gaseous H_2S under anoxic conditions, both treatments lead to S losses. These losses are probably higher for digestates than for composts due to the strong anoxic environment in digesters. The available database on S concentrations and S efficiency after field application is weak for both products.

Organic matter contents and effects on soil organic matter

Both, anaerobic digestion and composting decrease the total amounts of organic matter supplied to the soil, because easily degradable compounds are lost during the process [50] [51]. The process of anaerobic digestion decomposes only compounds degradable under anoxic conditions, whereas during composting compounds degradable under anoxic as well as oxic conditions are decomposed or transformed. Therefore, composting affects almost all kind of organic compounds leaving even less total amounts of organic matter for field application as compared with if the same amount of substrate was digested. The main components of compost OM are lignin, carbohydrates, and long-chain aliphatic structural groups [52], whereas the main components of digestate OM are lignin as well as cellulose, with minor values for hemicellulose (own unpublished data), meaning also a high recalcitrance of the OM components in digestates [51]. Since more lignified materials, with less P, are preferentially composted, the average OM content per unit P is usually much higher in composts than in digestates, liquid digestates in particular show low OM / P ratios. No data are available comparing the direct effect – resp. the output of the provided organic matter – and the indirect effect – resp. the impact on plant growth – of composts and digestates derived from equivalent amounts of treated residues on the amounts and the quality of soil humus.

Soil liming effects

Most organic amendments including composts and digestates decrease the soil acidity [14]. Usually organic amendments have a surplus of cations (e. g. K^+, Ca^{2+}, Mg^{2+}, Na^+, NH_4^+) over anions (e. g. $H_2PO_4^-$, SO_4^{2-}, Cl^-), which are compensated for by bicarbonate (HCO_3^-), carbonate (CO_3^{2-}) or organic acids [53] [36]. For example, in composts as a mean 8 % of the carbon is carbonate-C [54]. The decomposition of organic acids as well as of carbonates to CO_2 in the soil are proton consuming processes (e. g. [55]) leading to a decrease of soil acidity (“liming”). The treatment procedures themselves do not directly influence the “liming” properties of digestates or composts.

Salinity

The salt concentration of composts is usually much lower than for digestates. However, the salt concentration is usually measured indirectly, by electrical conductivity. Sodium chloride (NaCl), which is a common salt in food waste, as well as all other cations and anions contribute to the conductivity, but also organic acids are present in the fertilizer. Therefore, the “salt concentration” is not necessarily a strong indicator for the risk of long-term soil salinization by application of organic fertilizers. This characteristic should be used and interpreted carefully, if the aim is to avoid soil salinization. A high salt concentration can also mean a high overall nutrient concentration. To assess the potential effects on soil salinity, sodium (Na) and chlorine (Cl) concentrations are useful. The database for the concentrations of Na and Cl in organic amendments is very weak.

Other effects

Both, composts and digestates improve the soil physical properties by reducing the soil bulk density, increasing the saturated hydraulic conductivity, moisture retention capacity of soils [51] [36] [42] and the aggregate stability [56] [57] [51] [36] [42], compared to an untreated control. Both kinds of amendments also increase the soil biological activity [58] [51] [50] [36] compared to an untreated control. However, for both treatment procedures the effect on characteristics describing the soil biological activity is usually a decrease by the composting or digestion compared to an untreated feedstock applied directly (see compilation provided by [51]). There is only a single study available directly comparing the effects of digestates or composts from similar feedstocks from UOWs under field conditions: Digestates and composts had similar values for the investigated soil microbial indicators (e. g. proportion of active microorganisms substrate induced respiration, potential ammonia oxidation rate and nitrogen mineralization capacity) irrespective of applied N dose (50 and 100 kg N ha^{-1} yr^{-1}) [59]. Since the production of 50 kg compost N may roughly need the same amount of feedstock as the production of 80–100 kg digestate N, also the comparison of these two treatments is relevant. They neither differed significantly for the soil microbial indicators. The long term evolution of the soil organic matter content under digestates vs. compost application has not yet been studied.

It is often stated that composts sustain disease suppressiveness in potting substrates as well as in soils, an effect not yet investigated for digestates [60] [61]. However, under field conditions, conflicting results seriously hinder practical recommendations, and often a material suppressive to one pathogen can be ineffective or even conducive to other pathogens [61]. The effect of composts on disease suppression or on increase of disease incidence will also depend on their maturity level [60], increasing the difficulties in the practical management.

Composts can be used for soil restoration and soil remediation [62]. Digestates are less suited for this purpose due to their high nutrient concentration, which can lead to over-fertilization with N and other nutrients when applied at rates suitable for soil restoration.

Pollutants

Potentially toxic elements (PTEs) and their soil accumulation risk

Accumulation of PTEs is a common concern related to composts and digestates from urban organic wastes (UOWs) [63] [64] [44] [14]. PTEs can accumulate in soils after long-term application of treated urban wastes [64]. The concentrations of PTEs in composts obtained from source-separated waste systems are markedly lower than in composts obtained from mechanically separated organic waste [64] [65], supporting the stipulation that only UOW from source-separated collection systems are acceptable in organic agriculture (see Regulation (EC) No 889/2008).

Some UOW composts and digestates may fail the current thresholds for potentially toxic elements. These elements, e.g. zinc, may not only originate from the organic waste, but also from mechanical treatments such as compost mixing. Nevertheless, the mean of the specific cadmium (Cd) concentration per unit P in all composts and digestates studied by Möller and Schultheiss [14] was lower than for rock P, which is a permitted fertilizer in organic agriculture (Table 3).

Table 3: Concentration of (potentially) toxic elements in composts and digestates certified by Bundesgütegemeinschaft Kompost, the German compost association (mg kg^{-1} DM) *(data compiled by Möller & Schultheiss 2014)* 1)

	Cu	Zn	Pb	Cd	Cr	Ni	Hg	mg Cd kg^{-1} P	HMP 2)	HMN 3)
Threshold values according to Reg. (EC) 889/2008 on Organic Farming	70	200	45	0.7	70	25	0.4	32.8 6) 206 7)	–	–
Green waste composts	34.4 (22.3-50.0)	154 (106-**213**)	32.4 (17.0-**50.7**)	0.40 (0.19-0.70)	22.8 (12.0-35.9)	13.8 (5.70-23.5)	0.11 (0.05-0.16)	184	31.7	0.72
Household waste composts allowed for use in Organic Farming	40.5 (26.8-56.6)	150 (114-184)	27.9 (18.2-38.0)	0.35 (0.20-0.51)	21.5 (13.4-30.5)	12.2 (6.29-18.9)	0.10 (0.05-0.16)	113	20.6	0.53
Household waste composts including other feedstocks not specified in EU regulation 4)	54.2 (26.8-**80.9**)	**213** (114-**280**)	44.8 (18.2-**67.0**)	0.46 (0.20-0.70)	28.1 (13.4-42.2)	17.5 (6.29-**27.8**)	0.11 (0.05-0.17)	128	25.1	0.69
Liquid household waste digestates allowed for use in Organic Farming 5)	49.2 (27.6-**76.8**)	200 (139-312)	20.1 (3.0-33.2)	0.41 (0.20-0.62)	18.9 (5.20-29.6)	12.6 (6.94-18.0)	0.10 (0.05-0.14)	60.3	10.2	0.19
Liquid household waste digestates including other feedstocks not specified in EU regulation 4)	81.5 (32.1-**131**)	348 (170-**554**)	10.0 (2.00-32.0)	0.40 (0.19-0.69)	16.7 (6.50-29.0)	15.0 (6.36-**28.0**)	0.10 (0.03-0.19)	24.7	5.7	0.12
Liquid digestates of catering and retailer organic wastes (no certification for use in Organic Farming)	40.0 (10.1-**176**)	177 (115-**338**)	3.85 (1.03-24.4)	0.33 (0.05-**1.25**)	7.56 (4.13-22.7)	9.45 (3.69-23.6)	0.07 (0.02-0.33)	15.3	2.5	0.06
Solid household waste digestate allowed for use in Organic Farming 5)	24.1 (7.50-38.3)	102 (46.0-177)	14.7 (1.88-34.0)	0.23 (0.03-0.38)	19.0 (3.40-40.2)	8.81 (2.50-16.8)	0.07 (0.01-0.18)	38.3	7.4	0.28
Solid household waste digestates including other feedstocks not specified in EU regulation 4)	42.5 (19.2-65.0)	193 (89.2-**287**)	25.7 (3.00-48.8)	0.44 (0.15-**0.88**)	21.1 (8.28-40.4)	16.4 (4.30-**31.0**)	0.09 (0.01-0.14)	47.8	8.7	0.36

1) in parentheses: 10 % and 90 % fractile of values

2) HMP – Heavy metal-P-Index

3) HMN – Heavy metal-nutrient-Index

4) e.g. catering wastes, leftovers of retailers etc., no certification for use in Organic Farming

5) provided that the single contents for potentially toxic elements are within the threshold values set by the Reg. (EC) 889/2008

6) German Fertilizer Ordinance from 2004

7) threshold value for aluminium-calcium phosphates and soft ground rock phosphate according to Reg. (EC) 889/2008.

It is often stated that – when using high quality composts, such as those specified by the EU Regulation on organic farming – the risk of soil PTE accumulation is minimal (e.g. [64] [44]). Figure 3 gives an example for the calculated Cd accumulation scenario for different composts and digestates. It shows the potential accumulation after continuous application of 4 kg P per ha and year on the soil Cd concentrations. The precautionary value defined by the German Soil Protection Ordinance (Bodenschutzverordnung) is dependent on soil type, and ranges from 0.4 mg Cd kg^{-1} for sandy soil to 1.5 mg Cd kg^{-1} for a clay soil. The results indicate a higher Cd soil accumulation risk for composts than for digestates.

Figure 3: Soil cadmium accumulation scenarios depending on fertilizer use (assumptions: yearly P input of 4.0 kg ha^{-1}, soil pH: 7.0) *(Weissengruber & Friedel, pers. communication)*.

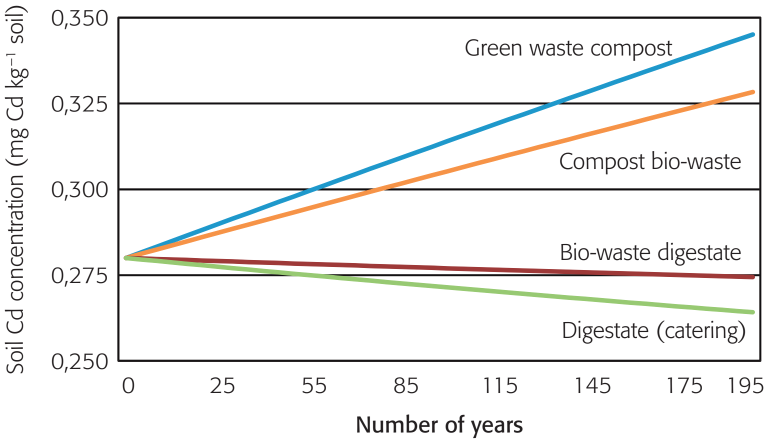
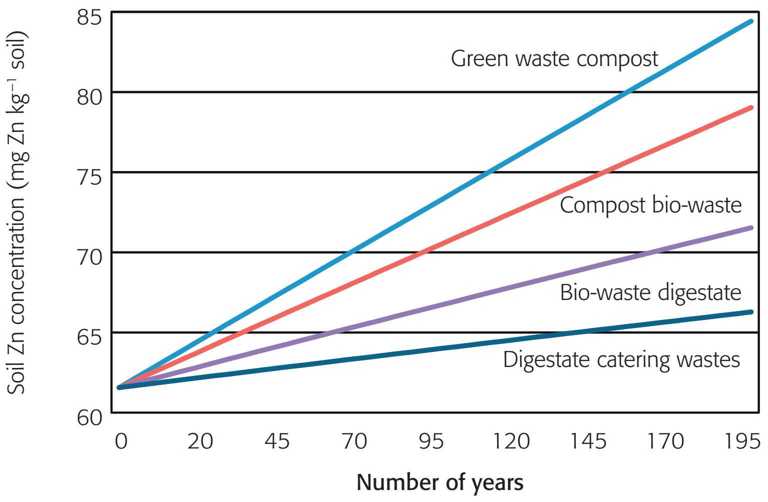


Figure 4: Soil Zinc accumulation scenarios depending on fertilizer use (assumptions: yearly P input of 4 kg ha^{-1}, soil pH: 7.0) (Weissengruber & Friedel, pers. Communication).



The Zn concentration of digestates allowed for use in organic farming is higher than for composts, and often beyond the threshold values allowed by the Regulation (EC) No 889/2008 (Table 3). However, similar to what is shown for Cd in Figure 3, the Zn soil accumulation risk is much lower for digestates than for composts (Figure 4). These facts demonstrate a central weakness in the current regulation by setting fixed PTE values on a dry matter basis as threshold values. A more logical solution would be, to relate PTE thresholds to nutrient concentrations, for example by calculating indices. Such an index is the heavy metal/nutrient relationship (HMN). It is an index for the potentially toxic element load (weighted according to their respective potential environmental impact) related to the plant nutritional value of the fertilizers. Higher values indicate a higher toxic element load relative to the benefit attainable by the fertilizer use. HMN shows a much better correlation to the obtained risk assessment than PTE concentration (Table 3).

Persistent organic pollutants

Fertilizers from organic waste may contain significant amounts of persistent organic pollutants (POP) such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) [66]. Composting degrades some of the persistent organic pollutants more effectively than anaerobic digestion [66] [67], however a clear understanding of how these treatments affect organic contaminants is lacking [65]. Concentrations of persistent organic pollutants such as PAHs, PCBs, polychlorinated dibenzodioxins and dibenzofurans (PCDD/F) in high-quality composts may be as low as soil background levels [44]. The POP database for digestates is weak, however the few available studies indicate very low levels of these compounds [68] [69] and Pfundner 2004 cited by [70].

Chemicals added during treatment

Lime is sometimes added during composting, however there is usually no need for other additives. For anaerobic digestion, processing chemicals are sometimes added to improve the performance of the involved microbes, adjust DM content, avoid foaming, and to bind S which – as H_2S – is damaging for biogas incineration equipment. A range of chemicals may be relevant, as shown by the certification standards for digestates in Sweden [71]. The implications for use of such digestates in certified organic agriculture remain to be clarified.

Other aspects

Energy consumption

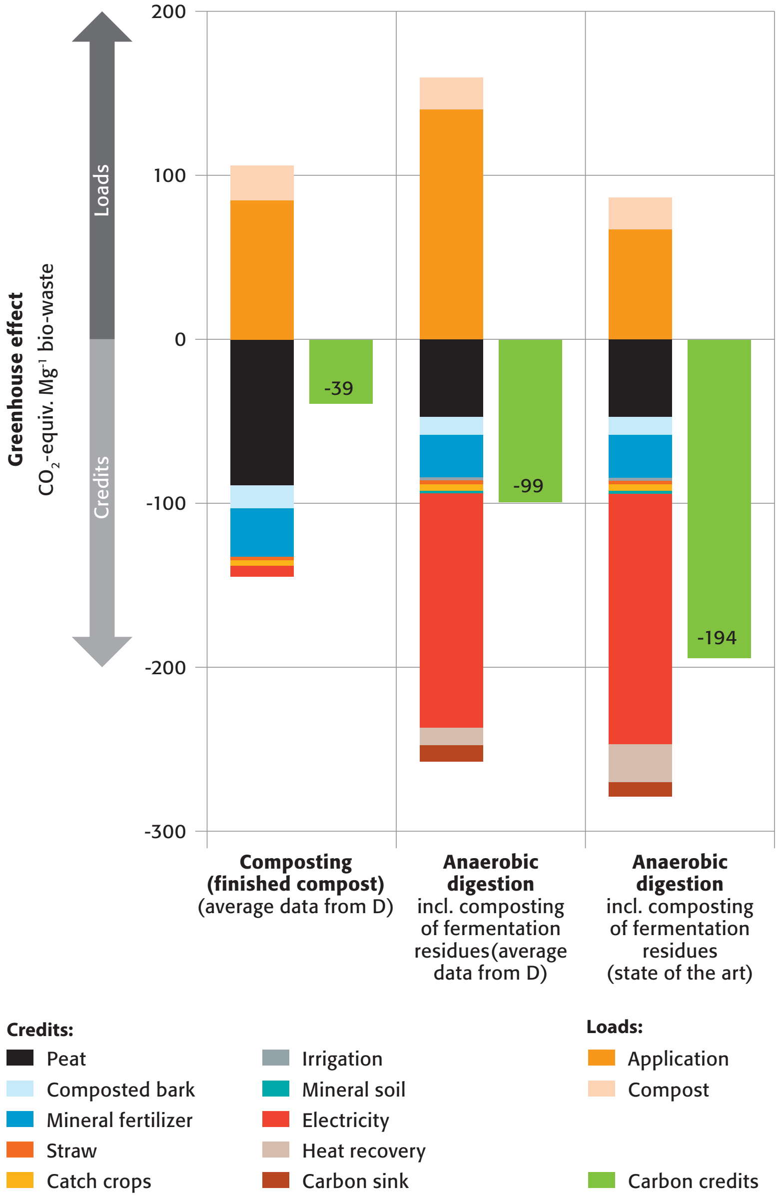
Composting of source separated wastes requires an energy input in the range of 15–80 kWh t^{-1} input material, whereas digestion of an equivalent amount of feedstock requires 30–60 kWh t^{-1} [72]. However, the credits for the electrical energy produced by digestion can account for ~200 kWh t^{-1} input material, indicating a strong surplus of energy for the entire process. This can be further improved if process heating energy is also harvested as a by-product [72]. Utilisation of thermal energy produced during composting is also an option (e.g. [73]), but so far poorly utilized in Europe.

Greenhouse gas emissions

Composting causes direct emissions of greenhouse gases (GHG) and ammonia (NH_3) [74] [19] [75] [7] as well as nutrient losses (N, K) [4] along with some indirect effects on GHG emissions. Digestion may also lead to losses of methane (CH_4), especially linked to leakages and technical problems of the biogas plant. However, in comparison to composting, digestion significantly reduces GHG and NH_3 emissions [76] [24] [77]. For example, according to a German survey, collection and composting of source separated household waste emits ~100 kg CO_2-equiv. Mg^{-1} waste, whereas the emissions related to operations of a biogas plant are much lower (~60 kg CO_2-equiv. Mg^{-1}) and the credits for the produced energy are ~160 kg CO_2-equiv. Mg^{-1} [72] (Figure 5). A comparative life cycle analysis of treatment alternatives for source-separated organic household waste indicated that digestion for biogas production was more beneficial than incineration with energy recovery and composting in decentralized plants without cleaning of emissions [78]. Therefore, composting is related to strong GHG emissions, while AD reduces the overall emissions, and offsets emissions from fossil fuels. Therefore, from an environmental point of view easily degradable UOWs should be treated preferentially via anaerobic digestion and not via composting to reduce nutrient losses and GHG emissions [72] [70] [78] [24].

However, after the treatment, due to the higher N loadings and the high NH_4^+ contents, the storage, management and application of digestates are related to a higher risk of N losses and GHG emissions than composts. For example, open storage of digestates, and composting of solid digestates can strongly affect the overall GHG balance and even turn it negative [24]. Hence, management and field application for digestates is a much bigger challenge than for composts, and inappropriate digestate management can counteract the treatment advantages.

Figure 5: Greenhouse gas emissions caused by composting and anaerobic digestion



Conclusions

Compost and digestates show relatively high direct plant phosphorus availability. Both fertilizers influence positively several soil properties like soil organic carbon, microbial activity and soil pH by providing proton-consuming components during decomposition (e.g. carbonates, organic acids). Anaerobic digestion conserves plant nutrients like nitrogen during the treatment and hence usually has the highest nitrogen fertilizer value, combined with lower global warming potential and a better energy balance in life cycle analyses as compared with composting. Also, the relationship between potentially toxic elements and nutrient concentration is more favorable with digestates. One benefit of composting is a final product that is much easier to store and handle during transport and field application. Nitrogen loss risks during handling and after field application are higher with digestates. Therefore, their application requires highly sophisticated spreading techniques.

Assessment of the suitability for use in organic agriculture

Current status according EU legislation on organic farming

The current EU regulation (EC) No 889/2008 permits source-separated household wastes collected in a closed and monitored collection system as a source for production of organic fertilizers for organic farming from urban organic wastes – provided the fertilizers do not exceed the maximum concentrations of PTEs described in Table 3.

Compliance with organic principles

Recycling and use of nutrients in UOWs as fertilizers in organic agriculture aligns with the organic concept of working in closed nutrient cycles. An evaluation of compost and digestates from UOW used as P fertilizers in organic agriculture should consider at least five aspects:

- The share of nutrients recovered by the process
- The processes and additives applied to obtain the fertilizer
- The potential environmental impact
- The mode of action of the fertilizer in the soil and fertilizing efficiency
- The potential long-term effects on soil contamination and environmental pollution

Regarding nutrient amounts, urban organic wastes comprise important nutrient sources that can easily be recycled to agricultural land. Whereas both composting and digestion are satisfactory with respect to P recovery, digestion is much more efficient in terms of N recovery, provided appropriate post-digestion management that avoids or at least reduces N volatilization losses. Composting is better suited for treatment of woody feedstocks, whereas for anaerobic digestion easily degradable feedstocks low in lignin are required.

Regarding processes and additives, composting and anaerobic digestion are based on natural biological processes, with a minimum input of additives. Hence, both treatment options comply well with organic principles. However, composting is much easier to implement in terms of technical facilities, whereas for AD a cascade of facilities including closed storage and sophisticated field application techniques are necessary to get satisfactory results.

Regarding the potential environmental effect, according to regulation (EC) No 834/2007 about organic production all plant production techniques used shall prevent or minimize any contribution to the contamination of the environment. The differences in GHG emissions described above, favour anaerobic digestion treatment.

Regarding characteristics of fertilizers, composts and digestates differ substantially in their mode of action in the soil and the fertilizing efficiency, mainly for N. According to Regulation (EC) No 834/2007 *"plants should preferably be fed through the soil eco-system and not through soluble fertilizers added to the soil."* Composts have low concentrations of easily soluble N, complying with this objective. The acceptability of digestates as fertilizers in organic agriculture has been questioned, mainly because of the high mineral N content. Digestates have a strong short-term N availability due to their high NH_4^+ concentrations and a high proportion of NH_4^+ to total N. If gaseous N losses during storage and field application can be tackled effectively, the N efficiency of the entire recycling system will be much higher than for composts, showing conflicting issues addressed by the different treatment approaches.

Regarding potential long-term effects, digestates may have higher concentrations of potentially toxic elements on a dry matter base. However, the soil accumulation risk is likely much lower than for composts. To reach a specific amount of nutrients, the low nutrient concentration in composts demands higher application rates on a DM level to reach a specific amount of nutrients than would be required for digestates. This may over-compensate for possibly lower PTE concentrations in composts.

An overall evaluation shows that anaerobic digestion of urban organic wastes has several advantages in terms of nutrient efficiency, environmental performance as well as long term risk of PTE accumulation in soils. Major constraints are the sophisticated techniques needed for production, storage and field application of digestates. From a conceptual point of view, the N fertilizing effect of digestates may be a constraint in terms of their acceptability in parts of the organic agriculture community.

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Imprint

Editors:
Universität Hohenheim
Institute of Crop Science
Fertilisation and Soil Matter Dynamics Group (340i)
Fruwirthstraße 20, D-70599 Stuttgart, Germany
Contact person: Dr. Kurt Möller
kurt.moeller@alumni.tum.de
https://plantnutrition.uni-hohenheim.de/

ETH Zürich
Plant Nutrition Group
Eschikon 33, CH-8315 Lindau, Switzerland
Contact person: Dr. Astrid Oberson
astrid.oberson@usys.ethz.ch
www.plantnutrition.ethz.ch

Research Institute of Organic Agriculture (FiBL)
Ackerstrasse 113, Postfach 219, CH-5070 Frick,
Switzerland
Contact person: Dr. Paul Mäder
paul.maeder@fibl.org
info.suisse@fibl.org, www.fibl.org

Research Institute of Organic Agriculture (FiBL)
Doblhoffgasse 7/10, A-1010 Wien, Austria
Contact Person: Dr. Stefan Hörtenhuber
stefan.hoertenhuber@fibl.org
info.oesterreich@fibl.org, www.fibl.org

Bioforsk
Norwegian Institute for Agricultural and
Environmental Research
Organic Food and Farming Group
Gunnars veg 6, 6630 Tingvoll, Norway
Contact person: Dr. Anne-Kristin Løes
anne-kristin.loes@bioforsk.no
www.bioforsk.no

Universität für Bodenkultur Wien
Institut für Ökologischen Landbau
Gregor Mendel Strasse 33, A-1180 Wien, Austria
Contact person: Prof. Dr. Jürgen Friedel
juergen.friedel@boku.ac.at
www.nas.boku.ac.at/ifoel

Newcastle University
Nafferton Ecological Farming Group
Stocksfield, NE43 7XD, United Kingdom
Contact person: Dr Julia Cooper
julia.cooper@ncl.ac.uk
www.nefg-organic.org

University of Copenhagen
Department of Plant and Environmental Sciences
Thorvaldsensvej 40, DK-1871 Frederiksberg,
Denmark
Contact person: Dr. Jakob Magid, jma@plen.ku.dk
http://plen.ku.dk/english/

Author: Kurt Möller (Institute of Crop Science, University of Hohenheim, Germany)

Reviewers: Astrid Oberson (ETH Zürich, Switzerland), Anne-Kristin Løes (Bioforsk, Norway), Julia Cooper (University of Newcastle, UK), Jacques Fuchs (FiBL), Paul Mäder (FiBL), Iris Wollmann (Institute of Crop Science, University of Hohenheim, Germany)

English editing:
Julia Cooper (Newcastle University)

General editing: Bettina Billmann, Gilles Weidmann (FiBL)

Layout: Brigitta Maurer (FiBL)

Photos:
Jacques Fuchs (FiBL) with exception of photo 2 on page 8 by Bettina Billmann.

FiBL-Order Nr. 1699

Acknowledgement: The partners of the IMPROVE-P consortium gratefully acknowledge the financial support for this project provided by the CORE Organic II Funding Bodies, being partners of the FP7 ERA-Net project, CORE Organic II (Coordination of European Transnational Research in Organic Food and Farming systems, project no. 249667).

For further information see: www.coreorganic2.org. For more information on the project consult the project website https://improve-p.uni-hohenheim.de/.