Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review

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REVIEW ARTICLE

Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review

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Abstract Intensive soil fertilization with mineral fertilizers has led to several issues such as high cost, nitrate pollution and loss of soil carbon. Fertilization with organic matter such as compost therefore represents an alternative for sustainable agriculture. Traditional organic amendments such as manures, composts and sewage sludge have been extensively studied in the past. However, applications of biogas digestates and their impacts on the environment and human health are still unexplored. Recent articles report the agricultural potential and conflicting results of digestate performances. As a consequence, the effectiveness of digestate as organic amendment and fertilizer is still under debate. Here we review the legislative, chemical, agronomic and environmental literature on anaerobic digestates. We found that digestates can be considered as organic amendments or organic fertilizers, when properly handled and managed. Indeed we further show that anaerobic digestates have a higher potential to harm the environment and human health than undigested animal manures and slurries. The main points are the following: (1) Most solid digestates comply with the European organic matter minimal requirement for an organic amendment; (2) the fertilizer values of liquid digestates lie between those of livestock manures and inorganic fertilizers; (3) anaerobic digestates have higher NH_3 emission potential than undigested animal manures and slurries and, consequently, pose a greater risk to the broad environment; (4) high Cu and Zn concentrations in digestates from co-digestion of pig and cattle slurry feedstock could jeopardize the sustainability of agricultural soils and (5) high Mn concentrations in digestates can induce Mn toxicity in agricultural soils, upon repeated applications.

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Content

1 Introduction

The anaerobic digestion process, also termed biogas process or biomethanation, was highlighted for the first time in 1776 by Alessandro Volta (cited in Ahring 2003). Ever since, it has been utilized mainly for biogas production from animal manure and/or household wastes and for waste treatment (Angelidaki et al. 2003; Tani et al. 2006; Tambone et al. 2009). The popularity of the biogas process has grown since the 1970s, amidst rises of energy prices and worries about the detrimental impact of fossil fuels on global warming. Today, biomethanation has expanded significantly across the world, mainly in Europe where more than 4,000 farm-scale anaerobic bioreactors are found in Germany alone (Weiland 2010).

There are mainly seven lines of exploitation of anaerobic digestion: (a) treatment of municipal sewage sludge, (b) treatment of industrial wastewater from agro-food and fermentation industries, (c) treatment of livestock waste, (d) treatment of the organic fraction of municipal solid waste, (e) co-digestion of livestock wastes and the organic fraction of municipal solid waste, (f) treatment of energy crops and (g) co-digestion of animal slurries with energy crops. These processes successfully convert biowastes into two economically useful by-products: a renewable energy source (biogas) and a potential fertilizer and soil amendment: the anaerobic digestate (Fig. 1). The former is a gas mixture dominated by methane (Chynoweth and Isaacson 1987; Ahring 2003), and the latter is an organic matrix with agronomic properties (Tietjen 1975; Arthurson 2009; Gell et al. 2011). In recent times, emphasis has been put on the sanitizing aspect of anaerobic digestion with respect to its effect on pathogens or other infectious elements (Luste and Luostarinen 2010; Masse et al. 2011). Thus, producing a safe anaerobic digestate suitable for agricultural land application has become as important as producing the maximum yield of biogas. However, the preponderance of efficiency criteria for methane production can lead to a shorter hydraulic retention time of the material in the digester than the time necessary for full stabilization of the digestate. As a consequence, the end-product digestate may entail issues such as odour emission, toxic organic compounds, pathogens and phytotoxicity.

Unlike manures, composts and sewage sludge which have been extensively studied in the past (Diacono and Montemurro 2010; Hatfield and Stewart 2002; Iakimenko et al. 1996; Williams et al. 1985), research on digestates has yet to reach its full capacity. The bulk of research on anaerobic digestates has been devoted to the evaluation of their stabilities with the objective to reduce their pathogenicity, foul odours and putrescibility (Kirchmann and Bernal 1997; Gomez et al. 2005, 2007; Sanchez et al. 2008; Drennan and Distefano 2010). There has been limited research on the chemical, biochemical and biological properties that would underline digestate agricultural functions (Teglia et al. 2011a). Thus, many question marks pertaining to digestate agronomic functions remain unanswered. This situation is evidenced by cases of conflicting results recently highlighted in a review by Möller and Müller (2012). Moreover, few studies have assessed the impacts of soil applications of digestates on the broader environment (air, soil, water). However, while present knowledge is far from complete, a more comprehensive understanding of the agronomic properties of digestates and their effects on soil and the environment is beginning to emerge. In an attempt to provide answers to lingering questions about anaerobic digestates effectiveness as organic amendments and/or organic fertilizers, this paper successively addresses their amending and fertilizer properties. These properties are then validated through short- and mid-term soil and field crop research findings. Throughout, comparative analysis between anaerobic digestates, animal manure and inorganic fertilizers properties is used to make key inferences. Moreover, this review explores potential environmental impacts of two prominent gases, ammonia and nitrous oxide, emitted by anaerobic digestates upon soil application. In the absence of direct research data, potential environmental issues related to soil contamination by heavy metals, surface and ground waters pollution are inferred from the literature analysis on soil applications of animal slurries. Finally, critical research themes for sustainable soil applications of digestates are highlighted at the end of this review.

2 Digestates amending properties and effects on soil properties

2.1 Amending properties

There is a wide range of anaerobic digestates whose composition and aspect depend upon the type of biomass inputs (feedstock) used and the configuration of the digester. Thus, spectroscopic techniques have recently demonstrated that

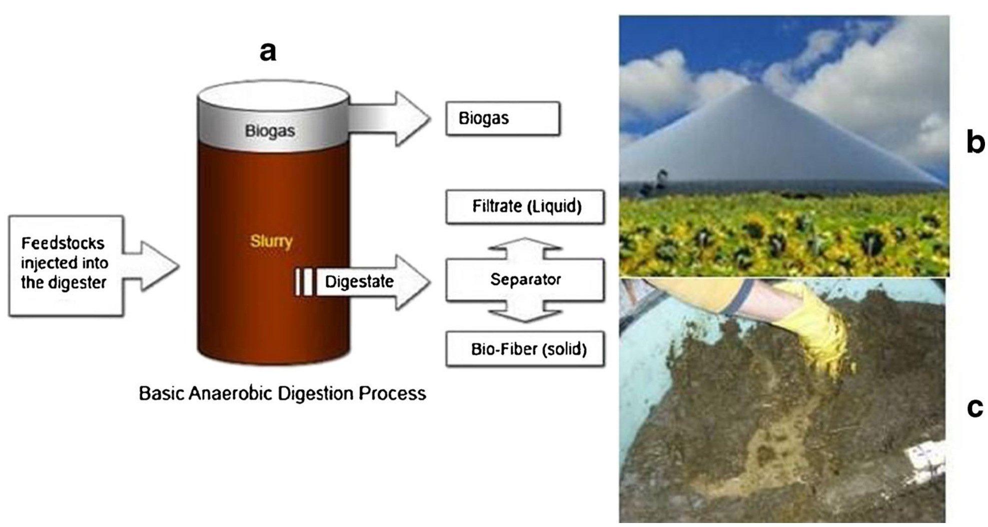

Fig. 1 Basic anaerobic digestion process (**a**) and its two by-products: biogas (**b**) and whole anaerobic digestate (**c**) (adapted from: Phase 3 Developments & Investments, LLC (**a**), 2degreesnetwork.com (**b**) and sustainableexperts.com (**c**))

anaerobic digestates inherit the chemical attributes of the feedstock from which they are produced (Provenzano et al. 2011). Various types of feedstock and combinations of feedstocks have been reported, among others, cattle manure (Gomez et al. 2007), livestock manure and agricultural residues (Amon et al. 2007; Tambone et al. 2010), organic solid wastes and sewage sludges (Gomez et al. 2007; Murto et al. 2004), dairy manure and biowastes (Paavola and Rintala 2008), food wastes and landscape wastes (Drennan and Distefano 2010) and potato and sisal pulp wastes (Parawira et al. 2004; Mshandete et al. 2005). The variability in the biochemical properties of anaerobic digestates is considerable, reflecting the diversity of the biomass input (Teglia et al. 2011b; Furukawa and Hasegawa 2006; Voća et al. 2005; Rivard et al. 1995; Möller et al. 2008). Thus, several aforementioned studies show variation intervals of organic matter content (38–75 %), cellulose/lignin ratio (0.22–1.75), oxygen uptake rate (1,129–3,774) and C/N ratio (6.2–24.8) (Table 1).

A soil amendment is any material which, upon addition to the soil, would improve or maintain its physical, chemical or biological properties. Organic matter content is the main indicator that defines the status of soil amendment according to the European Committee for Standardization (AFNOR: FD CR 13456 2001). Carbon and nitrogen are the most important constituents of any organic material (Jenkinson et al. 1990; Michalzik et al. 2001; Thornton and McManus 2002). Their relative ratios with respect to their respective mineral and organic forms will influence their agronomic use (Havlin et al. 1990). Some solid digestates show a greater mineral nitrogen fraction (51–68 % total N) relative to the organic fraction (Paavola and Rintala 2008; Tambone et al. 2009; Tambone et al. 2010) suggesting that their best use would be as fertilizers. In contrast, other type of solid digestates have displayed a lower mineral nitrogen fraction (24–36 % total N) relative to the organic fraction (Teglia et al. 2011b) suggesting that these digestates have a higher potential of valorization as organic amendment. There is little research on the biochemical fractionation of digestate organic matter. This kind of biochemical analysis is used to characterize the structural nature of the organic matter added to soil through amendment. However, variations from 0.22 to 1.75 of the cellulose/lignin or (cellulose + hemicellulose)/lignin ratios of various types of digestates have been reported (Tambone et al. 2009; Teglia et al. 2011b). These ratios have been suggested to be an indicator of the degree of humification of the organic material, since the microorganism-mediated decomposition of cellulose, hemicellulose and lignin leads to the synthesis of humic substances (fulvic acids and humic acids). Humic acids contribute to soil buffer and cation exchange capacities. A value of 0.5 has been suggested to be the threshold that distinguishes between fresh and mature wastes (Komilis and Ham 2003). However, a poor correlation between these biochemical ratios and the state of biodegradation of the organic wastes has been reported (Buffiere et al. 2006; Teglia et al. 2011a), which

Table 1 Biochemical properties of typical anaerobic digestates reported in the literature

Parameters	Value range	References
DM (%)	1.5–45.7	Svoboda et al. 2013a, b; Teglia et al. 2011a, b; Gutser et al. 2005
OM (% DM)	38.6–75.4	Teglia et al. 2011a, b; Möller et al. 2008; Voća et al. 2005
Total N (% DM)	3.1–14.0	Fouda 2011 ; Möller et al. 2008; Voća et al. 2005
Total N (% FM)	0.12–1.5	Gutser et al. 2005; Kluge et al. 2008; Poetsch et al. 2004
Total NH_4^+ (% FM)	0.15–0.68	Svoboda et al. 2013a, b; Ökologischen and Bodenschutz 2008
NH_4^+ (% Total N)	35–81	Gutser et al. 2005; Möller et al. 2008; Martin 2004
Total C (% DM)	36.0–45.0	Möller et al. 2008
C/N	2.0–24.8	Gutser et al. 2005; Fouda 2011; Möller et al. 2008
Total P (% DM)	0.2–3.5	Teglia et al. 2011a, b; Pötsch 2004; Voća et al. 2005
Total P (% FM)	0.04–0.26	Möller et al. 2010; Ökologischen and Bodenschutz 2008; Kluge et al. 2008
Total K (% DM)	1.9–4.3	Möller et al. 2010; Pötsch, 2004; Voća et al. 2005
Total K (% FM)	0.12–1.15	Möller et al. 2010; Ökologischen and Bodenschutz 2008
Total Mg (% FM)	0.03–0.07	Kluge et al. 2008; Voća et al. 2005
Total Ca (% FM)	0.01–0.023	Pötsch 2004; Kluge et al. 2008; Voća et al. 2005
Total S (% FM)	0.02–0.04	Kluge et al. 2008
CEL/LIGN	0.22–1.71	Tambone et al. 2009; Teglia et al. 2011a, b
CEC (meq/100 g)	20.3–53.4	Teglia et al. 2011a, b
OUR_{max} (mg O_2/h/kg OM)	1,129–6,187	Teglia et al. 2011a, b
pH	7.3–9.0	Chantigny et al. 2008; Kluge et al. 2008; Möller et al. 2008; Fouda 2011

OM organic matter, *DM* dry matter, *CEL/LIGN* cellulose/lignin, *CEC* cation exchange capacity, *OUR* oxygen uptake rate would make them unreliable as stability indicators. There is a general agreement in the literature that the content in humic substances (humic and fulvic acids) of organic materials is indicative of their biological maturity, safe and successful impact in soils as organic amendment (Hachida et al. 2009; Campitelli and Ceppi 2008; Teglia et al. 2011a, b). Despite insufficient amount of data relative to the structural fractions of digestate OM, the organic matter levels of typical digestates are in agreement with the European minimal requirement for organic matter (20 % of the dry matter of the material), which would describe most, if not all, solid digestates referred to in the literature as soil amendment according to European standards (AFNOR: FD CR 13456 2001).

2.2 Effects on soil properties

The long-term impact of anaerobic digestates on soil properties remains an unexplored field of research. A 4-year field trial by Odlare et al. (2008) in eastern Sweden showed that soil chemical properties hardly change in the short term when soil is amended with organic wastes, including digestates. However, relative to other treatments (pig manure, cow manure, compost, inorganic fertilizer), soils treated with liquid digestate from household wastes displayed the highest microbial biomass, nitrogen mineralization rate and potential ammonia oxidation. These results corroborated Tiwari et al.'s (2000). Microbial biomass (Doran and Parkin 1994) and potentially mineralizable nitrogen (Wienhold et al. 2004) are the most commonly suggested biological and chemical indicators for soil quality. An incubation study (Canali et al. 2011) revealed that anaerobic digestates from wine industry mineralized nitrogen at a higher rate than their compost counterparts, which is not always the case as Larsen et al. (2007) reported a significant nitrogen immobilization in the case of anaerobic digestates from bark chips and organic kitchen wastes. However, Canali et al. (2011) observed that nitrogen mineralization of organic products ranked inversely with respect to their C/N ratio. Since the feedstock inputs lose their C, as CO_2 and CH_4, through the anaerobic digestion process, anaerobic digestates generally have a lower C/N ratio than their aerobic compost counterparts. Earlier incubation research work (Loria and Sawyer 2005) on digested swine manure described the dynamics of N and P in amended soils. Raw and digested swine manure produced similar rates of conversion of NH_4^+ to NO_3^-, net organic N and increase in soil test P (STP). At the end of the 112-day incubation period, an average P recovery of 21 % of the applied P was estimated, from routine STP methods, in soil amended with digestates. By the same period of time, maximum net extractable inorganic N, predominantly NO_3^--N, averaged 20 % less than total applied N for both raw and digested manure. The authors concluded that swine digestate was a valuable nutrient resource that producers could use for crop production and should be managed the same way as raw swine manure. Field trials showed similar residual NO_3^- levels on soils fertilized with swine liquid digestate, raw liquid swine manure and mineral fertilizers (Chantigny et al. 2007). Regarding soil physical properties, field experiments by Garg et al. (2005) showed that the amendment of soils with liquid digestate from agricultural waste reduced bulk density and increased saturated hydraulic conductivity and moisture retention capacity of soils. Möller et al. (2008) showed that after 3 years of amendment, the average soil mineral nitrogen content in a rotation of spelt, winter rye and spring wheat was 36 % (89.2 kg N ha^{-1}) higher in fields that were amended with digested cattle slurry than those amended with farmyard manure.

With the very few exceptions of cases involving feedstock with very high C/N ratio, the literature on the short-term effects of digestates on soil properties has consistently noted the improvement of the quality of soils amended with anaerobic digestates. This situation is evidenced by the increase in microbial biomass and N, P contents. Even though data on the impact of digestates on soil physical characteristics are scarce, the work of Garg et al. (2005) highlights the potential of digestates in reducing soil bulk density and increasing its hydraulic conductivity. These findings corroborate the results on the amending properties of typical anaerobic digestates analysed in the previous section, and they strongly indicate that anaerobic digestates can be considered as effective organic amendment materials.

3 Fertilizer properties and effects on crops

3.1 Fertilizer properties of anaerobic digestates

The nutrient content of anaerobic digestates of all types depends primarily on the nature of the feedstock and the digestion process (Alburquerque et al. 2012; Provenzano et al. 2011). A string of studies conducted by Al Seadi and Moller (2003), Damgaard et al. (2001) and Möller et al. (2010) show that when biogas residues are de-watered, solid fractions of digested cow slurry, pig slurry and mixed manures display significantly higher concentrations in phosphorus, total and organic nitrogen (Table 2), whereas liquid fractions tended to have higher concentrations in available nitrogen. A similar body of work from Tipping (1996) and Zaoui (1988) shows that digested broiler litter liquor has twice as much total nitrogen as the digested dairy slurry liquor, whereas P and K concentrations in the latter were 41 and 168 % higher than in the former, respectively (Table 3). In light of these results and those regarding the organic matter content (previous section), the outline of two facts emerges: (a) The solid fraction (solid digestate) has a greater potential as soil amendment than the liquid fraction, whereas the latter has a greater potential as fertilizer than the former; (b) the nature of the source material

Table 2 Dry matter, nitrogen and phosphorus contents in whole, solid and liquid fractions of co-digested wastes and mono-digested cow and pig slurries (adapted from EA 2009)

Parameter	Digested cow slurry			Digested pig slurry			Co-digested cow (30 %), pig (50 %), biowaste (20 %)		
	Whole	SL	SF	Whole	SL	SF	Whole	SL	SF
Dry matter (%)	7	3.1	23	5	1.5	30	4	1	30
Total N (kg/tonne)	5.47	4.6	9	5.05	4.36	9.56	5.15	4.49	12.5
Available N (kg/tonne)	3.29	3.3	3.3	3.78	3.79	3.72	4.12	4.13	4.0
Organic N (kg/tonne)	2.18	1.3	5.7	1.27	0.57	5.84	1.03	0.36	8.5
Phosphate (kg/tonne)	1.02	0.2	4.2	1.21	0.56	5.49	1.16	0.37	10.0

SL separated liquor, *SF* separated fibre

(feedstock) is one of the major determinant of the qualitative value and the potential use of the end-product (digestate). Thus, for example, liquid digestate derived from dairy feedstock would be more suitable for crops that require relatively high amounts of P and K such as leguminous plants (Israel 1987; Bethlenfalvay and Yoder 1981; Robson et al. 1981) or crops at the reproductive or blooming phase (Clemens and Morton 1999; Poole and Sheehnan 1980). Conversely, liquid digestate derived from broiler litter would be more suitable for cereal crops, vegetables and grasses, which are crops with high N demand (Nkoa et al. 2001; Marschner 1995). Differing European standards exist with respect to N, P, K requirements for organic fertilizers. Thus, for an organic fertilizer to meet French standards, total N, K_2O and P_2O_5 must be greater than 3 % in fresh weight, respectively (AFNOR: FD CR 13456 2001). German standards, on the other hand, specify that nutrient contents on a dry matter basis must be greater than 0.5 % (N), 0.3 % (P) and 0.5 % (K_2O) (Siebert 2008). In the current Spanish legislation for fertilisers (PRE/630/2011 2011), anaerobic digestates cannot be considered balanced fertiliser products, and they must be complemented with mineral fertilisers. The British standards (BSI. PAS 110 2010) do not specify any nutrient limit for anaerobic digestates, although a number of parameters such as dry matter, organic matter, pH, salt content, total nitrogen, P, K, Ca, Mg, S, NO_3^-, NH_4^+, micronutrients, Cl and Na should be declared. It is

Table 3 N, P, K and S concentrations in digested municipal solid wastes, dairy cow and broiler litter slurries (adapted from EA 2009)

Parameter	Digested dairy slurry liquor (g/m^3)	Digested broiler litter liquor (g/m^3)	Municipal solid waste digestate (% DM)
Total N	2,500	5,544	0.84
P_2O_5	2,800	1,980	0.3
K_2O	5,300	1,980	1.3
S	80	–	0.2

DM dry matter

noteworthy that several anaerobic digestates evaluated in the literature comply with the French standards (Tambone et al. 2010; Teglia et al. 2011a, b; see also Table 2), whereas some do not meet the German standards (E. A. 2009). Regardless of the standards, several authors have concluded lately, following chemical and biological analysis that various anaerobic digestates derived from chicken manure, pig manure, Sudan grass and organic household wastes were valuable fertilizers suitable for agricultural production (Weiland 2010; Birkmose 2009; Amon et al. 2007; Voca et al. 2005).

3.2 Effects on crop growth and yield

A few conflicting results pertaining to the effect of anaerobic digestates on crop yields have been recently reported in the literature (Möller and Müller 2012). The effect of anaerobic digestates on crops can be analysed a posteriori with respect to three types of control: unfertilized, undigested feedstock and mineral fertilizers. Thus, digestate research results can be grouped into three categories of performances: (a) performances similar to the unfertilized control (Svensson et al. 2004; El-Shakweer et al. 1998), (b) performances similar or higher than undigested feedstock (Möller et al. 2008; Chantigny et al. 2007; Loria et al. 2007; Mattila et al. 2003; Esteban and Sawyer 2005; Rubaek et al. 1996) and (c) performance equal or better than mineral fertilizers (Ahmad and Jabeen 2009; Chantigny et al. 2008; Tiwari et al. 2000).

3.2.1 Suboptimal performances of anaerobic digestates and best management practices

Cases of suboptimal performances when anaerobic digestates were used for barley, oat and wheat production have been reported in the literature (Svensson et al. 2004; El-Shakweer et al. 1998). Interestingly, these research works involved questionable agronomic practices such as field surface application or inappropriate storage and management of digestates. Inappropriate storage and/or application of anaerobic digestates can lead to the loss of their fertilizer value or nitrogen use efficiency, through ammonia volatilization, leaching and runoff into surface and ground waters. The mechanisms are well understood: Anaerobic digestion of organic nitrogen results in increased levels of soluble inorganic nitrogen, mainly ammonium (Möller and Stinner 2009) and its equilibrium partner ammonia. The equilibrium relation is dependent on factors such as temperature and pH: The higher the pH and temperature, the higher the production of free ammonia (Angelidaki et al. 2003; Hengnirun et al. 1999). Since most liquid digestate pHs are in the alkaline range, their potential for ammonia loss that is N-nutrient loss is high (see next section). Nutrient nitrogen loss through ammonia volatilization would depend upon variables such as storage conditions (e.g. uncovered slurry tank), methods of land application (Fig. 2) and environmental conditions (heat, wind) during land application (Sommer and Hutchings 2001; Sandars et al. 2003; Holm-Nielsen et al. 2009). For example, manure tanks covered with semi-permeable materials (e.g. straw, Leca granules etc…) can reduce the emission of ammonia by 70 to 80 % (Börjesson and Berglund 2007). The general consensus regarding the methods of application of anaerobic digestates is that injection and incorporation are the methods that minimize the most ammonia volatilization while surface application techniques (splash plate and trail hoses) bring about higher ammonia losses (IEA 2010; Huisjsmans et al. 2002; Wulf et al. 2002a). The drawback of the injection method is its higher cost and greater damage to crops when compared to other methods such as trailing hose, trailing shoe and splash plate. The trailing shoe, a method used on grasslands, appears to be the best alternative when variables such as distribution of slurry, risk of ammonia volatilization, risk of contamination of crop, risk of wind drift and damage to crop are all factored in.

3.2.2 Fertilizer value of anaerobic digestates

The fertilizer value of anaerobic digestates can be assessed directly from the relative proportion of the amount of mineral fertilizer necessary to obtain the same yield of crop, or through field performance comparisons with universally recognized organic (Lafleur et al. 2012; Gong et al. 2011; Hasegawa et al. 2005; Adeli et al. 2005; Burns et al. 1987) or inorganic commercial fertilizers. A few authors have calculated the fertilizer value of anaerobic digestates. Gutser et al. (2005) compared the characteristics of 15 sources of organic fertilizers (Table 4). They found that anaerobically co- and mono-digested feedstocks had the fifth and sixth highest fertilizer values (50–70 and 40–60 %, respectively), just behind sources such as urine, poultry slurry, dried poultry excrements and meat/blood/bone meal and interestingly ahead of traditional sources such as cattle slurry, solid manure, sewage sludge, green manure and biocompost. Similar results were reported by Herrmann et al. (2013): Anaerobic digestates obtained from the co-digestion of animal slurries and maize ensilage displayed a relative nitrogen fertilizer value 30 % higher than those of cattle and pig slurries. With respect to field performances, many authors have shown that anaerobic digestates have similar or greater crop performance than corresponding undigested animal manures and slurries (Bachmann et al. 2011; Möller et al. 2008; Chantigny et al. 2007; Loria et al. 2007; Mattila et al. 2003; Esteban and Sawyer 2005; Rubaek

Fig. 2 Four typical methods of digestate application: splash-plate surface application (**a**), injection (**b**), trailing hose (**c**) and trailing shoe (**d**) (adapted from: Claudia Wagner-Riddle's University of Guelph team (**a**), extension.org (**b**), commons.wikimedia.org (**c**) and abbeymachinery.com (**d**))

Table 4 Fertilizer properties of typical organic materials (Gutser et al. 2005)

Organic material	N content	Dry matter (%)	NH_4^+ (% total N)	C/N	Biodegradability	Fertilizer value (%)
Legume coarse meal	40–60 kg t^{-1}	95	0–5	10–13	High	35–45
Horn/feather/leather meal	130 kg t^{-1}	95	0–5	3–4	High	50–70
Brewery/distillery residues	3 kg m^{-3}	6	0–5	8–10	High	30–35
Meat/blood/bone meal	75–120 kg t^{-1}	95	5–10	3–5	Very high	60–80
Green manure	10–35 kg t^{-1}	100	0–10 (NO_3^--N)	10–30	Low medium	10–40
Biocompost	6 kg m^{-3}	60	0–15	13–20	Low	0–20
Solid manure	6 kg m^{-3}	25	5–20	12–15	Low	10–20
Sewage sludge (high DM)	4–5 kg t^{-1}	25	5–20	6–8	Medium	15–30
Dried poultry excrements	30 kg t^{-1}	55	5–30 (uric acid)	5	High	60–70
Sewage sludge (low DM)	1–2 kg m^{-3}	5	30–40	3–5	Medium	45–55
Cattle slurry	4 kg m^{-3}	7.5	40–60	8	Low	35–45
Digestate from plant biomass	2–3 kg m^{-3}	8	35–60	5–8	Low	40–60
Digestate with co-fermentation	3–15 kg m^{-3}	5	45–70	2–5	Low	50–70
Poultry slurry	10 kg m^{-3}	15	60–80	4	Medium	70–85
Urine	4 kg m^{-3}	2	80–90	1–2	–	90–100

DM dry matter

et al. 1996), which factually demonstrates their high fertilizer value.

Relative to mineral commercial fertilizers, numerous studies across the world have shown that anaerobic digestates were at least as effective as mineral fertilizers. Thus for instance, in vegetable production, a digestate derived from household wastes was shown to be a quick-release nitrogen fertilizer comparable to inorganic synthetic fertilizer and did not cause contamination by coliform groups, *Escherichia coli*, faecal *streptococci* and *vibrio parahaemolyticus* in the soil and on spinach (*Spinacia oleracea L.*) and Komatsuna (*Brassica rapa* var. *perviridis* L. H.) leaves (Furukawa and Hasegawa 2006). Similarly, liquid digestates from swine slurries were found as good nutrient sources as chemical fertilizers to water spinach (*Ipomea aquatica Forssk*.) (Lam et al. 2002), cucumber (*Cucumis sativus* L.) and tomato (*Lycopersicon esculentum* Mill.) grown in pig–biogas–vegetable greenhouse systems (Qi et al. 2005).

Regarding cereal and cash crops production, a recent work by Haraldsen et al. (2011) on barley fertilization has established that a liquid anaerobic digestate, from source-separated household wastes, had the same performance as the mineral NPK fertiliser Fullgjødsel®, which led the authors to recommend the digestate for cereal production. It has been reported that substantial amounts of synthetic mineral nitrogen could be replaced by biogas slurries in wheat cropping Tiwari et al. (2000). Likewise, liquid digestates derived from cattle manure had similar results to chemical fertilizers, when they were spread into fields of timothy (*Phleum pratense* L.) and legumes, wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L.) and potato (*Solanum tuberosum* L.) (Civil Engineering Research Institute of Hokkaido 2003).

In India, a liquid digestate from cow manure had been incorporated into the organic farming system where it is associated with an on-farm product *Panchavgaya* (a concoction of five cow products: dung, urine, milk, curd and ghee). Somasundaram et al. (2007) reported that this combination outperformed synthetic mineral fertilizer in corn and sunflower (*Helianthus annus* L.) production. These results were confirmed by Ahmad and Jabeen (2009) when they reported an improvement of the growth and development, as expressed by height, leaf area index and yield, of sunflower plants fertilized with a liquid digestate from cow dung. Chantigny et al. (2008), after studying the yield and nutrient export of maize fertilized with liquid digestate from swine manure, concluded that when side-dressed to corn and immediately incorporated, liquid digestates from swine manure had the same fertilizer value as mineral fertilizer. Regarding nutrient uptake, Chantigny et al. (2007) showed that nitrogen uptake by forage crop grown on soils amended with swine liquid digestates was similar to that observed with inorganic synthetic fertilizers, but was lower with raw, decanted and filtered liquid swine manures.

The pattern of the effect of digestates on crop growth and yield observed from various studies across the world is consistent and clear. Not only chemical compositions of anaerobic digestates fit most European legal definitions of an organic fertilizer, their field-validated fertilizer values lie between those of two universally accepted fertilizers: raw manure and commercial inorganic fertilizer. Therefore, anaerobic digestates can be regarded as effective organic fertilizers when appropriate storage and application methods are employed. However, in many instances, good field performances of digestates appear to contradict national standards that define organic fertilizers such as German's. This type of contradiction can be resolved by redefining the concept of organic fertilizer so that it is based on their fertilizer value.

4 Environmental risks associated with land applications of anaerobic digestates

Biogas and anaerobic digestates are the two by-products of anaerobic digestion. Each poses a threat to one or several components of the broader environment. Leakage of methane and carbon dioxide, two greenhouse gases (GHG), from the digester can contribute to global warming, whereas anaerobic digestates can directly impact soils, water bodies and the atmosphere. Since the initial feedstocks have been depleted of most of their easily degradable carbon during digestion, nitrous oxide is the only significant GHG that can be potentially be released by anaerobic digestates. Inappropriate storage or application of anaerobic digestates can lead to gaseous nitrogen emission (ammonia and nitrous oxide) and/or nutrients leaching and runoff into surface and ground waters (Fig. 3).

4.1 Risks of atmospheric pollution

During the anaerobic digestion process, a large fraction of carbonaceous compounds are converted to methane and carbon dioxide, which are collected as biogas. As a result, the proportion of carbon decreases in the biogas residues while that of nitrogen increases in the form of NH_4-N, hence a lower C/N ratio (Gutser et al. 2005; Svensson et al. 2004). Concomitantly, fatty acids are degraded and calcium ions released from the degradation of organic matter leading to digestate pH increase (Weiland 2010). High pH and NH_4 concentration are conditions that favour NH_3 emission.

4.1.1 Ammonia emission and fallout

Ammonium and its equilibrium partner ammonia are found at higher concentrations in liquid digestates (Alburquerque et al. 2012; Kaparaju et al. 2012; Möller and Stinner 2009). Factors such as temperature and pH can alter this equilibrium and hence determine which form is released into the environment, or which component of the environment (air, soil and water) is affected.

Agricultural and environmental significance of ammonia emission Ammonia (NH_3) volatilization has been estimated to account for 15 % of the total applied nitrogen (Sommer and Hutchings 2001; Matsunaka et al. 2006; Möller and Stinner 2009; Terhoeven-Urselmans et al. 2009). NH_3 emission inventories from several countries have shown that agriculture produces approximately 90 % of the total emission of NH_3 to the atmosphere (Misselbrook et al. 2000; Buijsman et al. 1987). It is estimated that emissions from agriculture range from 186,000 to 405,000 Mg NH_3-N year^{-1} in UK alone (Buijsman et al. 1987; Ryden et al. 1987; Kruse et al. 1989; Jarvis and Pain 1990; Asman 1992). Asman and Van

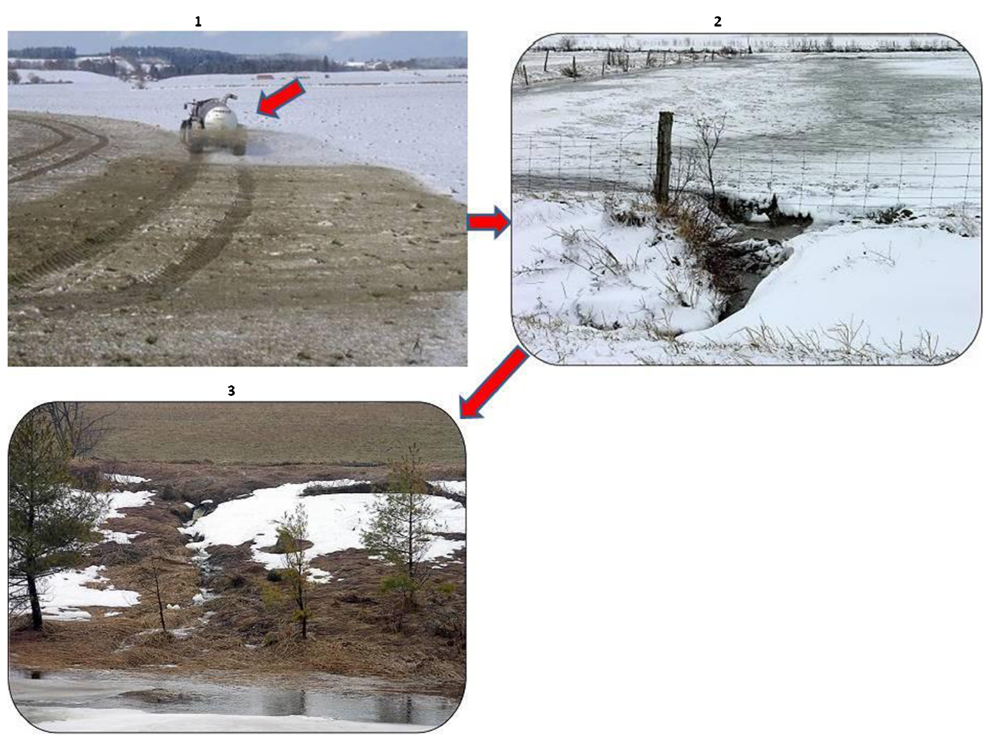

Fig. 3 Sequence of events leading to the pollution of a surface water body following an inappropriate application of anaerobic digestate. *1* Winter surface application of anaerobic digestates, *2* runoff during spring thaw and *3* discharge of nutrients in a water body (adapted from: CPEPESC (*1*); OMAFRA (*2* and *3*))

Jaarsveld (1990) estimated that 80 to 90 % of total ammonia emitted from livestock operations is redeposited within 10 km of the source, while about 20 % is returned to earth within 1 km. The remainder is dispersed into the atmosphere, sometimes over hundreds of kilometres. Acid rains that result from atmospheric deposition of ammonia contribute to the acidification of terrestrial and aquatic ecosystems as well as the eutrophication of surface water bodies (Fangmeier et al. 1994; Erisman and Monteny 1998; Dragosits et al. 2002; Krupa 2003; Sanderson et al. 2006).

Ammonia emissions are a major air quality concern at national, regional and global levels (NRC 2002). Ammonia gas, once emitted, reacts and neutralizes atmospheric gaseous H_2SO_4, HNO_3 and HCl to form soluble ammonium aerosol salts NH_4SO_4, NH_4NO_3 and NH_4Cl in the sub-micron size range (McMurry et al. 1983; Warneck 2000), which, depending on the relative humidity in the atmosphere (Tang and Munkelwitz 1977; Tang 1980), may be deposited back onto earth. Beside surface water eutrophication and ecosystem acidification mentioned above, the negative environmental impact of ammonia deposition also includes phytotoxicity (Van der Eerben et al. 1998; Pitcairn et al. 1998) and the reduction of plant biodiversity (Goulding et al. 1998). Soils surrounding ammonia emission sources can sorb NH_3 (Hao et al. 2005, 2006), which could complicate fertilizer and manure application recommendations for crop production.

In addition to its effects on soil systems and plants, ammonia-derived particulate matter with a diameter of 2.5 microns or less, known as PM2.5, can penetrate deep into the lungs and cause serious health issues such as respiratory and cardiovascular problems. They also contribute to the formation of haze. Thus, for example, in the USA, haze has reduced natural visibility from 90 miles to between 15 and 25 miles in the east and from 140 miles to between 35 and 90 miles in the west (EPA 2004).

Ammonia emission from anaerobic digestates Ammonia emission from anaerobic digestates is affected by management and environmental factors such as storage conditions, methods of application, concentrations of ammonia in the digestate, pH, temperature, air velocity, surface area and moisture (Sommer and Hutchings 2001; Sandars et al. 2003; Holm-Nielsen et al. 2009). Given the higher NH_3/NH_4 concentration and pH in anaerobic digestates relative to livestock manures (Haraldsen et al. 2011; Möller et al. 2008; Chantigny et al. 2008) and the intensification of biogas production across the world, biogas plants and associated crop fields are expected to be major sources of emission of ammonia. For illustration, field experiments (Misselbrook et al. 2000) show that NH_3 emission from land application of cattle and pig slurries range from 15 to 60 % of the total ammoniacal nitrogen applied, which values for dairy cows and all other cattle were estimated between 2.25 and 1.75 kg m^{-3} slurry, respectively (MAFF 1995). NH_3 emissions from poultry manure spread onto land were estimated at 45 % of ammoniacal and uric acid nitrogen applied (Nicholson et al. 1996; Chambers et al. 1997). In theory, these emissions factors are expected to be higher in lands spread with biogas digestates because of their higher pH and NH_3 contents. In fact, several studies have found similar (Chantigny et al. 2004; Pain et al. 1990) or higher emissions than raw manures (Ni et al. 2012; Gericke 2009; Amon et al. 2006; Wulf et al. 2002a). In contrast, Rubaek et al. (1996) reported lower emissions with digested than with raw manure. Specifically, NH_3 emissions after anaerobic digestates application were estimated between 7 and 24 % of applied NH_4-N as opposed to 3 to 8 % for animal slurries (Gericke 2009). Wulf et al. (2002a) have precisely quantified these emissions at about 350, 275, 160 and 50 mg NH_3-N m^{-2} h^{-1} within the first 10 h following application of liquid digestate through splash plate, trailing shoe, harrow and injection methods, respectively. Ten years later, Ni et al. (2012) quantified and compared the NH_3 emission rates of anaerobic digestates, cattle and pig slurries applied through the trailing hose method at 120 and 80 kg NH_4^+-N ha^{-1}. They found that 20 h after the application, digestates out-emitted cattle and pig slurries (Fig. 4).

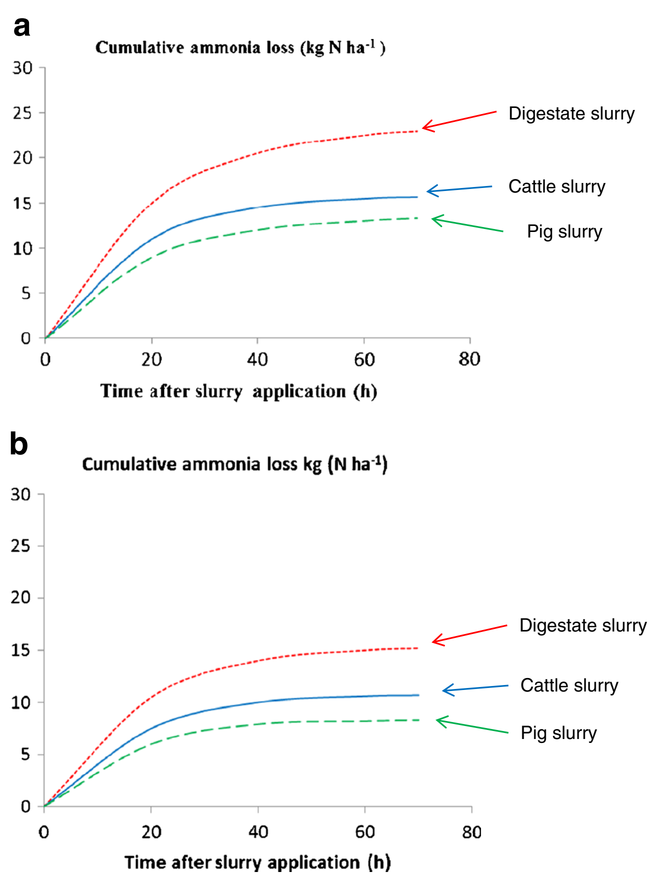

Fig. 4 Cumulative ammonia loss by digestate, cattle and pig slurries spread onto land under identical conditions. **a** 120 kg NH_4-N ha^{-1}; **b** 80 kg NH_4-N ha^{-1} (adapted from Ni et al. 2012)

4.1.2 Nitrous oxide emission

Besides ammonia, nitrous oxide (N_2O) may also be significantly emitted following field applications of anaerobic digestates (Vallejo et al. 2006; Wulf et al. 2002b).

Environmental and agricultural significance of N_2O emission Nitrous oxide is one of the most important greenhouse gases and ozone-depleting chemical compounds released on earth (Ravishankara et al. 2009; Metz et al. 2007). Its global warming potential is 310 times higher than that of carbon dioxide (Börjesson and Berglund 2007). Soils in general contribute more than half of the world's emission, and agricultural soils in particular account for about half of total soils emissions (Denman et al. 2007). Here, the main contributing factors are high nitrogen inputs, intensive cropping systems, edaphic and climatic variables (Mosier et al. 1998a, b). Specifically, episodic N_2O emission bursts related to the process of freezing and thawing of agricultural soils can account for up to 73 % of the annual soil N_2O emission budget (Lemke et al. 1998; Wagner-Riddle et al. 1997).

Spring-thaw emission bursts are attributable to the physical release of N_2O entrapped under frozen surface layers during winter and the new production of N_2O at the onset of thaw (Risk et al. 2013). In soils, nitrous oxide can be produced through three biochemical and one chemical pathways depending upon the availability of oxygen or the soil pH. The biochemical pathways are those of the nitrification and denitrification processes. In oxygen-saturated soils, N_2O can be produced though the oxidation of hydroxylamine (NH_2OH), an intermediate step of nitrification (Sutka et al. 2003). In hypoxic soils, nitrifying bacteria (*Nitrosomas*, *Nitrosococcus*, *Nitrobacter*, *Nitrococcus*) may reduce nitrite (NO_2^-) to N_2O (Wrage et al. 2001). In anoxic soils, N_2O can be released during denitrification when denitrifiers (*Paracoccus*, *Pseudomonas*, *Thiobacillus*) reduce nitrate (NO_3^-) to dinitrogen (N_2). Finally, in acidic soils, N_2O can be formed by chemodenitrification (Goodroad and Keeney 1984).

Nitrous oxide emission from anaerobic digestates In general, NH_3 emissions tend to be higher with digested than undigested slurries. On the contrary, N_2O emissions from digested materials are generally lower than emissions from undigested feedstock. It has been hypothesized that this is the result of lower contents in easily degradable C in digested feedstock, hence less energy source for denitrifiers (Vallejo et al. 2006; Rochette et al. 2000). Thus, several comparative studies have shown lower N_2O emissions on land spread with digested slurries (Collins et al. 2011; Chantigny et al. 2007; Amon et al. 2006; Vallejo et al. 2006; Petersen 1999). Specifically, Börjesson and Berglund (2007) reported an average reduction of N_2O emissions from 40 (undigested) to 25 g (digested) N_2O per tonne of manure applied. Beside the aforementioned soil characteristics that influence N_2O emission, soil texture is a determinant as well. Thus, Chantigny et al. (2007) reported a 54–69 % lower N_2O emission with the digested than with undigested manure in a loam soil, as opposed to a 17–71 % lower emission in a sandy loam. As far as best management practices are concerned, it is generally accepted that spring applications of manures and slurries mitigate runoff and leaching of nutrients. It appears that spring (post-thaw), unlike fall (pre-thaw), applications would mitigate nitrous oxide emissions via the reduction of the amount of substrates necessary for the accomplishment of N_2O-related freeze–thaw processes. Beside the time of application, agricultural practices that enhance soil aeration and good drainage would also mitigate N_2O emissions following the application of anaerobic digestates.

4.2 Risks of nutrient pollution

A major environmental concern with land application of biogas digestates is the potential contamination of surface and ground waters with excess nitrogen and phosphorus. Most studies show that digestates are richer, in terms of nutrient contents, than their respective raw manure counterparts (Haraldsen et al. 2011; Möller et al. 2008; Chantigny et al. 2008; Gomez et al. 2007; Loria and Sawyer 2005). Consequently, environmental issues associated with the production and land applications of manures are equally, perhaps potentially more prominent with anaerobic digestates, in particular, issues such as surface and groundwater pollution and eutrophication of water bodies, which have been documented and linked to the production and use of manure (Mulla et al. 2001; Hubbard and Lowrance 1998; Newton et al. 1994; Odgers 1991).

Nitrogen leaching has received most of the attention from researchers due to the considerable amount of nitrogen in animal manures and slurries. These high N levels are attributable to the low animal N-use efficiency (Oenema and Tamminga 2005). To illustrate, only 20 to 30 % of the nitrogen taken up by dairy cows are converted into meat and milk; the balance is excreted as faeces and urine. The organic N fraction in the excrements is further digested in the bioreactor where the retention times are much longer than in animal digestive tracts. This may explain the higher NH_4-N generally observed in digested as compared to undigested slurries. When anaerobic digestates are applied into soils, NH_4^+ are either absorbed by plant root cells, or adsorbed on negatively charged soil particles, or oxidized to NO_3^- by nitrifying microorganisms. For example, a 4-year field study in Sweden showed that the application of anaerobic digestates increased the rate of potential ammonia oxidation (Odlare et al. 2008), and the analysis on N fractions in leachates obtained from fields treated with anaerobic digestates revealed that nitrate-N was the dominant fraction, and ammonium N (0.3 %) and organic N (6 % of total N) only contributed marginally (Svoboda et al. 2013a; Wachendorf et al. 2006). Due to their negative charges, nitrate are hardly adsorbed onto soil particles, hence their high mobility through the soil and their high polluting potential. Reported results of studies that compared N leaching after applications of digested and undigested slurries vary widely, most likely because of the variability of soil types and factors that govern ammonia and nitrous oxide emissions. Thus, (a) no significant differences in N concentrations were detected in leachates under fields treated with animal slurries and anaerobic digestates (Svoboda et al. 2013a, b; Pötsch 2004); (b) a 5 % higher nitrate N loss was observed in crop rotation treated with digested as opposed to raw slurries (Jørgensen and Petersen 2006); (c) a lower N leaching was reported after application of anaerobic digestates compared to undigested slurry (Jäkel and Mau 1999) and (d) inconsistent results of nitrate N leaching have been observed across years between raw and digested cattle slurries (Brenner and Clemens 2005). From the literature analysis, it can be concluded that anaerobic digestates pose at least a similar threat than animal manures and slurries to water bodies as far nutrient leaching is concerned.

Nutrient leaching potential following application of anaerobic digestates depends upon factors such as fertilisation strategies (e.g. time and methods of application), soil texture (e.g. sandy and clayey soils), topography (risk of runoff; see Fig. 3), precipitations and cropping systems. Best management practices that can be utilized to mitigate nutrient leaching include adjustment of digestate nutrient supply to crop demand and soil tests, synchronization of nutrient release with crop developmental demand, cultivation against slopes, avoidance of fall applications, long time gaps between digestate application and sowing, and applications that precede heavy rains.

4.3 Risk of soil contamination

Land application of anaerobic digestates may introduce into soils physical, chemical and biological contaminants which may jeopardize their long-term agricultural productivity. Physical contaminants include plastics, glasses, stones etc… The focus of this review is on chemical and biological contaminations.

4.3.1 Chemical contamination

Land application of organic wastes is not risk-free, since it may result in the incorporation into the soil of phytotoxic compounds (Boydston et al. 2008; Gough and Carlstrom 1999; Liu and Christians 1994), pathogens (Watcharasukarn et al. 2009; Grewal et al. 2006; Reddacliff et al. 2003; Gantzer et al. 2001) and heavy metals (Alburquerque et al. 2012; Wong et al. 1996; Jacobs 1981). With respect to phytotoxicity of digestates, causal compounds include ammonia (Leege and Thompson 1997; Wong et al. 1983), volatile organic acids (Drennan and DiStefano 2010; Abdullahi et al. 2008; Poggi-Varaldo et al. 1999; DeVleeschauwer et al. 1981), phenolic compounds (Inglet et al. 2009; Gorsuch et al. 1990) and salts (McLachlan et al. 2004). Regarding heavy metals (Ni, Pb, Cr, Cd), several studies (Alburquerque et al. 2012; Schievano et al. 2009; Siebert et al. 2008; Edelmann et al. 2004) have reported lower levels in digestates relative to the standards set by Spanish, British and German legislations (BSI. PAS 110 2010; Siebert et al. 2008). However, agriculturalists and environmentalists should bear in mind that those concentrations of heavy metals within the limits of standards do not preclude the possibility of land contamination in the long run owing to the long-term accumulation over repeated applications. Also of serious concern are the high concentrations in some digestates of some micronutrients such as Cu and Zn (Alburquerque et al. 2012) due to the use of pig and cattle slurry as feedstock. These two elements are used as additives to stimulate livestock growth and prevent pig and cattle diseases. Beside heavy metals, micronutrients as a whole could be a threat to sustainable agriculture. A recent survey across Europe has disclosed the abundance of micronutrients in all digesters, especially those supplied with wastes like blood, kitchen and food wastes (Schattauer et al. 2011). For illustration, Cu and Zn can potentially jeopardize the sustainability of agricultural soils through soil accumulation and interference with the metabolic activities of plants. Thus, although they both play essential metabolic roles as metallic enzyme activators, or cofactor of RNA and DNA polymerase (Zn), in cell growth stimulation (Burgess et al. 1999), they can inhibit plant growth once in excess in the soil solution (Ebbs and Kochian 1997; Pahlsson 1989). Both metals synergistically inhibit the absorption by plants of Fe and Mn.

Speaking of manganese, it is an essential element for plant growth and development. It can, however, be detrimental when available in excess. Concentrations as low as 1 ppm can be toxic to most field, horticultural, flower and forage crops (Morris and Pierre 1947; Berger and Gerloff 1947; Jacobson and Swanback 1932). Excess Mn in the soil solution can interfere with the absorption, translocation and the metabolism of other mineral elements such as Ca, Mg, Fe and P (Clark 1982). Inside plant tissues, excess Mn can inhibit the activities of enzymes and hormones involved in essential Mn-requiring metabolic activities (Horst 1988; Epstein 1961). The overall result of manganese toxicity is a significant reduction of plant growth and development, as well as yield. Mn toxicity in agriculture is often more important than Mn deficiency in many parts of the world. Common determinants of Mn toxicity are poor drainage, soil acidity (pH below 5.5) (Chesworth 1991; Morris and Pierre 1947); soil with high pHs under reducing conditions that result from flooding, compaction or organic matter accumulation (Kamprath and Foy 1971) and high temperature or high light intensity (El-Jaoual and Cox 1998). The concentration of Mn in digestates can be as high as 50–55 ppm (Bischofsberger et al. 2005; Sahm 1981). Repeated long-term applications of digestates onto lands may result in Mn and organic matter accumulation, factors that favour Mn toxicity, especially in soils with low Mn sorption capacity.

4.3.2 Biological contamination

Numerous pathogenic bacteria species have been tallied in organic wastes used for anaerobic digestion (Sahlstrom 2003). The risk is higher when manure is included as feedstock, since several outbreaks of gastroenteritis have been linked to livestock operations (Spencer and Guan 2004; Pell 1997). Bacteria such as *Salmonella*, *E. coli*, *Yersinia*, *Campylobacter* and the protozoa *Giardia* and *Cryptosporidium* are the most prevalent pathogenic microorganisms found in manures (Bicudo and Goyal 2003; Hutchison et al. 2005). Other bacteria such as *Clostridium perfringens*, *Listeria monocytogenes* and *Treponema hydrosenteriae* have also been reported as causal agents of human infections related to livestock (Colleran 2000).

Mitigation of the risk of pathogens embedded in the feedstock occurs through integrated or post-sanitation configuration of the anaerobic digestion process (Angelidaki et al. 2003; Olsen et al. 1985; Olsen and Larsen 1987; Masse et al. 2011). Despite the hygienization process, the persistence of pathogenic parasite eggs, bacteria and fungi has been reported in many biogas plants (Plymforshell 1995; Sahlstrom 2003; Schnurer and Schnurer 2006; Slana et al. 2011). Recent studies (Bonetta et al. 2011; Goberna et al. 2011) showed that the hygienic quality of digestate products improved dramatically, relative to the initial cattle manure input, for almost all microbiological parameters but *L. monocytogenes*. In light of the aforementioned results, it appears that there should be a protocol that identifies specific pathogen indicators in order to characterize digestate products.

The microbiological status of the output digestate depends on the quality of the input feedstock and on the configuration features of the digester such as pre-treatment (pasteurisation), digestion temperature, pH, ammonia concentration, hydraulic retention time, among others (Sahlstrom 2003; Ottoson et al. 2008). The persistence of some pathogens in digestates can be explained by the presence of bacteria species capable of forming spores in animal wastes (Snell-Castro et al. 2005). These spore-formers are not eliminated during the anaerobic digestion process (Olsen and Larsen 1987; Sahlstrom et al. 2004; Bagge et al. 2005; Goberna et al. 2009). Regrowth of pathogens and their spores can also occur in storage facilities (Sidhu et al. 2001; Pepper et al. 2006). Stabilization of digestates through post-treatment measures such as curing (Drennan and DiStefano 2010) and composting (Tiquia et al. 1996; Smet et al. 1998) significantly reduces the risk they pose on human health and the broad environment.

5 Research needs

5.1 Relationships between the type of feedstock and the agronomic properties of digestates

For a model of anaerobic digestion in which the end-products biogas and digestates hold similar economic and agro-environmental importance, organic amendment and fertilizer properties of digestates are critical parameters that could ensure agro-ecosystem sustainability while contributing to the reduction of the dependency towards fossil fuels (reduction of mineral fertilizer consumption). With respect to organic amendment properties, defined as attributes of organic materials that could maintain or improve soil physical, chemical and biological properties, little research is available on the relationships between the biomass input used at the onset of the anaerobic digestion process and the output digestate content in organic matter, dry matter, total carbon and humic substances (humic acids/fulvic acids ratio). Such knowledge would allow the preferential selection of feedstock that result, upon anaerobic digestion, in digestates high in organic matter and humic acids which could be ultimately used as soil conditioner to restore eroded, degraded and disturbed land such as quarry pits, mining fields, landfill sites etc…

5.2 Long-term effects of solid digestates on soil physical properties

Unlike classic organic amendments such as manures, composts and sewage sludge, which have been extensively investigated (Khallel et al. 1981; McConnell et al. 1993; Stabnikova et al. 2005; Diacono and Montemurro 2010), little is known about the long-term effects of solid digestates on soil aggregate stability, bulk density, water holding capacity, hydraulic conductivity etc… The organic and dry matter contents as well as cellulose/lignin ratios reviewed in this paper suggest that solid digestates are good candidates for increasing soil aggregation, water holding capacity, hydraulic conductivity and decreasing bulk density. Compounds such as cellulose, lignin and humic substances, which are barely degraded during the anaerobic digestion, are highly reactive and can interact directly with soil surfaces to strengthen the aggregates (Pagliai et al. 1981). Other research questions that can help evaluate the long-term potential of digestates are:

– Long-term effects of land application of digestates on the accumulation and availability of soil nutrients:

What is the time-course of total N, organic C, available P and exchangeable K in soils that have been spread with digestates?

– The cumulative and residual effects of digestate nitrogen on crop growth and quality:

There are little published data available on how nitrogen is released from a single application of digestate or on the accumulated residual effects following repeated applications. This information is pivotal in the reduction of the amount of N fertilizer required where digestates are applied either on a regular basis onto croplands and rangelands, or as large one-off applications for land reclamation. Information on the effect of digestates on crop quality is paramount as well. Relationships between digestate rates and crop quality variables have to be investigated. Examples of such dependent quality variables are lodging of cereals and flax, cereal protein content, leaf/cob ratio in silage maize, change in grassland species composition and quality, high nitrate and potassium content and reduced calcium and magnesium contents of grass, sugar content and sap purity in sugar beet (N, K, Na) and starch content of potatoes.

5.3 Identification of specific pathogen indicators to characterize digestate products

There have been several instances of persistence of pathogenic parasite eggs, bacteria and fungi in biogas plants despite the thermophilic hygienization of the anaerobic process. In particular, *L. monocytogenes* has been detected in some digestates. Negative detection of some pathogens may be due to unsuitable protocols of pathogen indicators, hence the need to identify specific pathogen indicators in order to characterize digestate products.

5.4 Determination of emission factors

Emission factors are defined as the amount of ammonia that volatilize from organic or inorganic sources into the atmosphere. They help estimate the potential adverse impact of the material on the environment as well as the utilization rate of nitrogen by crops. Several field studies have estimated emission factors of various livestock manure (see above). Research on ammonia emission from gas tanks, storage facilities and land applications of anaerobic digestates is needed in order to quantify the environmental risks associated with their use.

6 Conclusion

Research on biogas digestates has intensified during the past decade, yet the question of their effectiveness as organic amendment or fertilizer lingered in the mind of many researchers and research users. This review has shown the high variability within the digestate group of organic materials with respect to their physical and biochemical properties. Their biochemical properties, which are a function of the initial biomass inputs, suit the legal requirements on organic amendments of most European countries. Short-term studies have shown that the application of anaerobic digestates onto soils can have positive effects on their physical properties such as reduction of bulk density, increase in saturated hydraulic conductivity and enhancement of moisture retention capacity. Regarding the fertilizer properties of anaerobic digestates, the past decade of research has shown that their efficacies lie between those of livestock manures and mineral fertilizers, with many instances where digestates equalled mineral fertilizers. It is worth mentioning that the fertilizer efficacy of liquid digestates depends upon factors such as the nature of the feedstock (best results when co-digested), the method of storage and handling (e.g. use of protective floating layers and tight membrane-covered tanks) and the method of field applications (best results with injection and trail-shoe methods). However, because of their higher pH and NH_3/NH_4 contents, anaerobic digestates have a higher potential than livestock manures for emitting ammonia and nitrous oxide into the atmosphere. Hence, they can adversely affect air and water quality, as well as contribute to the global warming process of our planet. Anaerobic digestates also pose a long-term threat to soil health through the accumulation of metal elements, mainly Cu, Zn and Mn. This scenario is particularly within the realm of possibility in cases of anaerobic co-digestion with cattle and pig slurries. Although some research progress has been accomplished, more specific studies are needed to advance knowledge on anaerobic digestates and their contribution to a sustainable and environmentally sound agriculture. These include the linkage between the nature of the feedstock and the amending properties of the anaerobic digestates, the long-term effects of their applications on soil chemical and physical properties, the identification of suitable pathogen indicator protocols for anaerobic digestates and the determination of their specific emission factors.

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