Use of fertilizing residues by agricultural activities in LCA studies

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ABSTRACT

This work is a review of Life Cycle Assessment (LCA) studies dealing with agricultural use of fertilizing residues (FR). The majority of the studies were dedicated to LCA of waste and wastewater treatment systems and, in few cases, to agricultural productions. In most of the studies on LCA of waste and wastewater treatment, FR spreading induces toxicity due to heavy metals and global warming and atmospheric pollution because of emissions of nitrogen compounds. When a livestock is studied, FR spreading is generally a minor contributor to the impact compared to livestock building and animal manure stocks. The fertilizing effect of FR is taken into account by substitution of mineral fertilizers. Substitution of mineral fertilizers is the main driver of the environmental assessment result. Unfortunately, the substitution is not always explained or presented in the different studies, which makes interpretation of the results difficult. This variability of system boundaries also affects the results.

Keywords: Field application, Residues, Waste treatment, Wastewater treatment, Biosolids.

1. Introduction

Human waste and animal manures have always been used for agricultural production, but intensive farming and the increase of wastewater treatment capacity put this issue forward. Severe environmental burdens are due to intensive manure production (Mallin and Cahoon 2003), and toxicity of heavy metals contained in biosolids are often highlighted (Benítez et al. 2001).

Agricultural use of fertilizing residues (FR) is represented in several ways in Life Cycle Assessment (LCA) studies. This work is a review of LCA studies dealing with agricultural use of FR to show current LCA practices (key parameters, modeling choices for emissions and substitution) and main results of theses works. The review is presented per FR type: biosolids, organic part of municipal wastes, animal manures, digestates, and biochars.

2. Methods

The collection of articles for this review has been carried out in two steps. First, two queries have been made on the Web of Science (Thomson Reuters 2014) and CAB Abstracts (Cabi 2014) :

- Query dedicated to FR terms: "*waste*" or "residu*" or "sludge*" or "sewage*" or "biosolid*" or "*compost*" or "digestate*" or "anaerobic digest*" or "manure*" or "slurr*" or "effluent*" or "sediment" or "ash*" or "biochar" or "struvite" or "dredg*" or "by-product*" or "by product*" or "abattoir" or "dairy" or "whey" or "bone" or "ossein" or "feather" or "exogenous organic matter" or "organic amendment*".
- Query dedicated to LCA terms: "life cycle analysis" or "life cycle assessment" or "LCA" or "life cycle management" or "LCI" or "life cycle inventor*" or "impact assessment".

These queries crossed title and abstract fields in the database (FR terms in title field and LCA terms in abstract field, and vice versa) and yielded in 2229 references. To reduce the size of this set, a manual selection has been performed by scanning the abstracts to remove references

- not dealing with LCA,
- dealing with waste treatment without agricultural use (*e.g.* biosolid incineration, organic waste landfilling),
- dealing with agricultural production without FR use.

One hundred references have been selected with this approach, which are included in this study.

3. Results

The main part of the article collection is composed of recent articles from the last decade, with an overall time frame from 1998 to 2013. Figure 1 presents a word cloud built from titles of the articles. It shows that the collected articles mainly focused on waste and associated treatment (e.g. words like “waste”, “wastewater”, “municipal”, “solid”, “treatment” and “composting”). The word cloud underlines also the aim of LCA as environmental assessment of the system (“environmental”, “systems”, “greenhouse”, “emissions”, “evaluation”, “study” …). Agricultural words (“organic”, “production”, “application” and “farming”) appear, but with low occurrences.

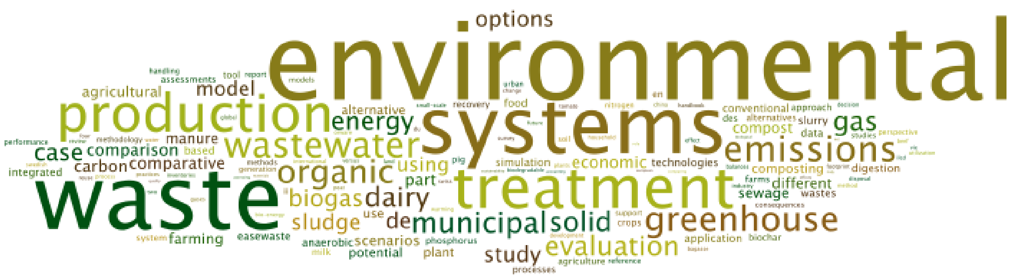

Figure 1. Word cloud from titles of the articles (words of the LCA query have been removed for better readability); The cloud was generated using the Wordle website (www.wordle.net).

4. Discussion

4.1. Overview

Few publications are dedicated only to FR uses. The main part of the literature is composed of environmental assessment of waste treatment, where agricultural use of FR is only a part of the studied system. Table 1 gives an overview of the important parameters of these publications.

When a system is multifunctional (several products or several services), substitution is often performed (avoided impacts due to avoided product). Consequently, in many cases, an agricultural use of FR is represented by an avoided mineral fertilizer production and use (41/45 references in Table 1). This allows for avoiding impacts due to production (resource consumption, plant pollution, transport …) and emissions after crop fertilization (trace metals to soil, nitrogen compounds emissions).

The key parameter for substitution of mineral fertilizers is the fertilizing effect of the FR, expressed by a Mineral Fertilize Equivalent (MFE) coefficient. But this parameter is often missing (29 references in Table 1). Noted by Heijungs and Guinée (2007) and underlined by Winkler and Bilitewski (2007), one of the main reasons for the variability of LCA results for waste treatment systems is the way how avoided impacts (due to energy or secondary matter productions) are taken into account in the system. Brockmann et al. (2014) provide a simple excel tools for MFE computation.

Emissions from spreading are dealt in three ways: (1) emissions are not taken into account (7 publications) or only partially (e.g. only heavy metals, 4 publications), (2) FR use emissions are represented, but avoided emissions not (13 publications), and (3) the difference between FR use and avoided mineral fertilizer use emissions is applied (4 publications).

4.2. Biosolids

About twenty articles deal with agricultural use of biosolids. Almost all consider the fertilizer role by substitution, but, unfortunately, the MFE value is sometimes missing, described in an internal report or it is referred to an author’s country study. When MFE values are provided (see Table 1), an important variability is observed for nitrogen equivalence, while phosphorus and potassium values are close to one.

Except for some studies (Dennison et al. 1998; Murray et al. 2008), heavy metals emissions to the environment are represented. Several authors underline the importance of this phenomenon and the induced toxicity (Hospido et al. 2004; Houillon and Jolliet 2005; Johansson et al. 2008; Wenzel et al. 2008).

Hospido and coauthors (Hospido et al. 2010) take into account thirteen drug residues in the toxicity assessment through a new characterization factor for the CML method (Muñoz et al. 2009). In this work and with this approach, the authors conclude that the drug residues’ impact is negligible compared to the heavy metals burden.

Table 1. Main characteristics of waste and wastewater treatment LCA studies.

References	FR type[a]	Impacts[b]	Fertilizer substitution	Mineral Fertilizer Equivalent	Carbon storage / organic matter	Field emission (FR use)	Field emission substitution (avoided fertilizer)
(Dennison et al. 1998)	USS	ND	No	NA	No	ND	No
(Murray et al. 2008)	USS	cc + inventory	Yes (N, P)	N: 1 / P: 1	No	No	No
(Hospido et al. 2004)	USS	CML	Yes (N, P)	ND	No	Yes (HM)	No
(Houillon and Jolliet 2005)	USS	eb; cc	Yes (N, P, K, lime)	N: 0.61 / P: 0.7 / K ND	No	No	No
(Wenzel et al. 2008)	USS	EDIP	ND	ND	No	ND	ND
(Johansson et al. 2008)	USS – CUSS	cc, acid. eut	Yes (N, P)	N: USS 0.42; CUSS 0.3 / P: USS 0.7 CUSS 0.035	No	Yes (N_2O, CH_4, NH_3, NO_3^-)	Yes (N_2O, CH_4, NH_3, NO_3^-)
(Beavis and Lundie 2003)	ISS	eut, cc, ph ox, acid, ecotox	Yes (N, P)	Yes (Substituted value)	No	ND	No
(Hospido et al. 2005)	USS	CML	Yes (N, P)	ND	No	Yes (CH_4, HM)	No
(Tarantini et al. 2007)	CUSS	CLM+ tox	No	NA	No	Yes (HM)	No
(Peters and Rowley 2009)	CUSS	eeb, cc, tox, ecotox	Yes (N, P, lime)	Yes (Substituted value)	Yes	Yes (HM)	No
(Hong et al. 2009)	CUSS	cc, acid, tox, lu	Yes (ND)	ND	No	Yes (HM)	No
(Liu et al. 2013)	USS	cc	Yes (N, P)	ND	No	No	No
(McDevitt et al. 2013)	USS	CML + USE-TOX	Yes (ND)	ND	No	Yes (N_2O, leaching)	No
(Lundin et al. 2000)	USS	inventory	Yes (N, P)	N: 0.5 / P: 0.7 – 1	No	No	No
(Pasqualino et al. 2009)	USS	CML	Yes (N, P)	ND	No	Yes (ND)	No
(Foley et al. 2010)	USS	inventory	Yes (N, P)	N: 0.25 – 0.75 / P: 0.25 – 0.75	Yes	Yes (N_2O, NH_3, HM)	Yes (N_2O, NH_3, HM)
(Hospido et al. 2010)	USS	CML	Yes (N, P)	N 0.5 / P 0.7	No	Yes (N_2O, NH_3, PO_4^{3-}, HM, TOC)	No
(Sablayrolles et al. 2010)	USS	acid, eut, cc, oz dep, ph ox, ecotox, tox	Yes (N, P)	Yes (Substituted value)	No	Yes (N_2O, HM, TOC)	Yes (N_2O, HM, TOC)
ORWARE[c]	USS – COW	ph ox, eut, acid, cc	Yes (N, P)	ND	No	Yes (N_2O, NH_3, NO_3^-, NO_x, P, HM)	No
EASYWASTE[d]	COW	EDIP	Yes (N, P, K,)	ND	Yes	Yes (N, P, ETM, TOC)	No
(Jury et al. 2010)	DCE	ECOINDICATOR 99, cc, eb	No (allocation)	Yes (N: 0.54 – 0.83 / P: ND / K: ND)	No	Yes (N_2O, NH_3, NO_x, NO_3^-, PO_4^{3-}-)	NA
(De Vries et al. 2012)	DPS	RECIPE (m)	Yes (N, P, K)	N: 0.65 / P: 1 / K: 1	Yes	Yes (CH_4, NH_3, NO, N_2O, NO_3^-, PO_4^{3-})	No
(Poeschl et al. 2012b; Poeschl et al. 2012a)	DC	RECIPE (m, e)	Yes (N, P, K)	N: DFB 0.45; DC 0.65 / P: 1 / K: 1	No	Yes (CH_4, NH_3, NO, N_2O, NO_3^-, PO_4^{3-})	No
(Hamelin et al. 2011)	DPS - DCS	EDIP	Yes (N, P, K)	N: PS 0.7; CS 0.75; CM 0.85/ P: 0.81 / K: 0.97	Yes	Yes (CH_4, NH_3, NO, N_2O, NO_3^-, PO_4^{3-})	No

Yes: included; No: not included or not presented; NA: non applicable; ND: not documented; HM: heavy metals; TOC: trace organics compounds

[a] CM: cattle manure; CS: cattle slurry; PS: pig slurry; USS: urban sewage sludge; CUSS: compost of urban sewage sludge; ISS: industrial sewage sludge; COW: compost of organic waste; DEC: digestate of energetic crop production; DC: digestate from codigestion (animal manures, agricultural residues, dedicated crop productions…); DPS: digestate of pig slurry; DCM: digestate from cattle manure; LF: leachate (liquid fraction) separated from digestate.

[b] Impact assessment method: CML, ECOINDICATOR 99, EDIP, RECIPE (*m* midpoint ; *e* endpoint), USETOX (ILCD handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability 2010) lists and describes the impact assessment method, see this document for details) / impacts of a method: *cc* climate change ; *oz dep*: ozone depletion; *eb* energetic balance : *acid* acidification ; *eut* eutrophication ; *ph ox* photochemical oxidation; *tox* human toxicity; *ecotox* ecotoxicity ; *lu* land uses / *inventory*: references without impact assessment.

[c] ORWARE model references: USS: (Kärrman and Jönsson 2001; Lundin et al. 2004; Tidåker et al. 2006) – COW: (Dalemo et al. 1997; Sonesson et al. 1997; Dalemo et al. 1998; Thomsson 1999; Sonesson et al. 2000; Eriksson et al. 2002; Mendes et al. 2003; Eriksson et al. 2005)

[d] EASEWASTE model references: (Kirkeby et al. 2006a; Kirkeby et al. 2006b; Christensen et al. 2007; Bhander et al. 2008; Boldrin and Thomas-Hojlund 2008; Bhander et al. 2010; Boldrin et al. 2010; Bernstad and la Cour Jansen 2011; Manfredi et al. 2011; Andersen et al. 2012)

Some works do not deal with nitrogen and phosphorus emissions to the environment due to FR spreading (Beavis and Lundie 2003; Hospido et al. 2005; Houillon and Jolliet 2005; Tarantini et al. 2007; Murray et al. 2008; Hong et al. 2009; Peters and Rowley 2009; Liu et al. 2013; McDevitt et al. 2013) and deal only with the benefit of avoided fertilizer. Other works present agricultural field emissions without description (Pasqualino et al. 2009), according to the ORWARE model (Kärrman and Jönsson 2001; Lundin et al. 2004; Tidåker et al. 2006), partially without nitrate leaching (Lundin et al. 2000), according to experimental data (Johansson et al. 2008) or determined according to models (Nemececk and Schnetzer 2012) proposed by Ecoinvent guidelines (Foley et al. 2010; Hospido et al. 2010). To finish, few works (Sablayrolles et al. 2010) consider both FR emissions and avoided emissions due to avoided mineral fertilizer use. Recently, Yoshida et al. (2013) reviewed 35 LCA studies dedicated to sewage sludge treatment (28 with agricultural use). This work shows the variability of the perimeters: 11 references with emissions to air during biosolids spreading, 11 with heavy metals emissions to soil, and 2 with carbon storage. A substitution of mineral fertilizer is done in 25 of them.

4.3. Organic fraction of municipal wastes

The use of LCA to assess waste treatment scenarios leads to dedicated simulation models. About 10 models can be found (Gentil et al. 2010), but only two have been used and take into account FR use.

ORWARE (ORganic WAste REsearch) (Dalemo et al. 1997; Eriksson et al. 2002) is a Swedish model, which has been used for real cases of waste management (Sonesson et al. 1997; Sonesson et al. 2000; Mendes et al. 2003; Eriksson et al. 2005). The model focuses mainly on climate change, acidification and eutrophication; toxicity is not addressed. FR spreading is represented with a substitution and field emissions: a simplified model of the nitrogen cycle allows determining nitrogen emissions (N_2O, NH_3, NO_3^-) and the nitrogen content replacing mineral nitrogen in the first year and the long-term. Ammonia losses are determined by Swedish experimental values, nitrate leaching by a simulation model with soil features, and nitrous oxide emissions according to IPPC recommendations. Phosphorus dynamics are assumed analogous for FR and mineral fertilizer. Dalemo et al. (1998) discuss the importance of nitrogen emissions due to FR use for the assessment of waste management scenarios. Thomsson (1999) uses ORWARE and mentions heavy metals, but without assessment because of complexity of the soil-plant mass balance.

EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies) (Kirkeby et al. 2006a; Bhander et al. 2008; Bhander et al. 2010) is a Danish model and is probably the most used LCA waste treatment tool. Assessment is carried out with the EDIP method (Wenzel et al. 1997). The model includes mineral fertilizer substitution and nitrogen, phosphorus, heavy metals and trace organic compounds emissions. Carbon storage is also modeled. However, the FR use module of the EASEWASTE model is only described in a Danish document (Hansen 2004). Effects of FR use on soil quality are not represented because of the complexity of the relation. This model shows the consequences of heavy metal emissions from agricultural residues (Kirkeby et al. 2006b) and underlines the major role of final waste destination to waste treatment assessment (Christensen et al. 2007).

EASEWASTE has been used to compare incineration, landfilling and composting of individual waste fractions (Manfredi et al. 2011). The authors observe a benefit for the composting scenario on ecotoxicity because of avoided emissions of mineral fertilizer production (chromium and mercury). EASEWASTE has been used to assess commercial compost from food waste and garden waste, which is used as growth media preparation instead of peat (Boldrin and Thomas-Hojlund 2008; Boldrin et al. 2010). The benefit of this compost on climate change (because of biogenic carbon) and eutrophication (avoided nitrogen emissions of mineral fertilizer production) is shown, but it is tempered by heavy metals emissions to soil.

Some authors (Bernstad and la Cour Jansen 2011; Andersen et al. 2012) represent the organic matter supply effect of the use of compost from household food waste by a peat substitution (substitution according to volume, 1 m^3 of peat for 1 m^3 of compost). They consider that the environmental burden is mainly determined by greenhouse gases emissions from the composting process and the benefit from the substitution (climate change, eutrophication, toxicity and ecotoxicity). Andersen et al. (2010) investigated substitution practices for compost use in gardening in two Danish towns (Aarhus and Copenhagen). This work shows a substitution only for 22 and 24% of the situations for peat, 12 and 24% for fertilizer, and 7 and 15% for manure.

Bernstad and la Cour Jansen (2012) reviewed LCAs for food waste management, mainly with respect to climate change. They reveal a large variability of the results and that the use of compost and digestate is profitable from an environmental point of view in some works, but negligible in other ones. The variability of the results is explained by the MFE value, the environmental impact of substituted fertilizer and carbon storage. The authors advise to consider nitrogen emissions from fertilizers in accordance with international recommendations (as ILCD) for impact assessment. But variability and lack of knowledge are again underlined. Only one reference with FR and avoided emissions is cited (Møller et al. 2009).

While most publications deal with waste treatment scenarios, Martinez Blanco et al. (2009) compare mineral fertilization to the use of compost from municipal organic waste for tomato crops. In this case, the use of compost avoids landfilling and landfill impacts are subtracted to the system: this substitution drives the environmental impacts and sets compost as best solution. A similar work, yielding in the same conclusions has been done for compost from wine shoot and sewage sludge (Ruggieri et al. 2009).

4.4. Animal manures

About twenty articles dedicated to cattle and pig productions have been found. Manure and slurry spreading is commonly represented. FR use impacts are usually negligible in comparison to emissions from livestock building and animal manure storage (Beauchemin et al. 2010; O'Brien et al. 2011) (and also for poultry production (Leinonen et al. 2012)). Animal manure storage and spreading are also often merged in a single step (Sonesson 2005; Thomassen et al. 2009).

First works on livestock LCA (Cederberg and Mattsson 2000; Cederberg and Flysjo 2004; Sonesson 2005) used a Swedish model for nitrate leaching (Aronsson and Torstensson 2003). Recent works (Fantin et al. 2012; Jan et al. 2012) follow EcoInvent guidelines (Nemecek and Kägi 2007; Nemececk and Schnetzer 2012) for all emissions. When EcoInvent is not used, emissions are usually computed by national references and models (Anton et al. 2005; Antón et al. 2005; Cooper et al. 2011; Leinonen et al. 2012; Uchida and Hayashi 2012). But nitrous oxide and methane emissions are determined in most of cases by IPCC guidelines (Cederberg and Mattsson 2000; Beauchemin et al. 2010; Hörtenhuber et al. 2010; Rotz et al. 2010; O'Brien et al. 2011; Yan et al. 2011; Fantin et al. 2012; Mc Geough et al. 2012; O'Brien et al. 2012; Bonesmo et al. 2013). The use of IPCC guidelines is also found for crop production studies (Mattsson and Wallen 2003; Cooper et al. 2011; Kimming et al. 2011; Nemecek et al. 2011a; Nemecek et al. 2011b; Hakala et al. 2012). Langevin et al. (2010) work on nitrogen emissions from slurry spreading. From a literature review, they show that pedoclimatic conditions imply a variability of LCA results that can be larger than the variability resulting from spreading technics.

Nemecek and coauthors (Nemecek et al. 2011b) underline the interest of animal manure use as fertilizer with regard to resource depletion (fossil and mineral) and soil quality. This benefit is tempered by nutrient leaching due to management complexity of the organic fertilization.

4.5. Digestates

Recently, several environmental studies of anaerobic digestion plants with agricultural use of the digestate have been published. Here, again, emissions are often computed according to EcoInvent guidelines (Jury et al. 2010; De Vries et al. 2012; Poeschl et al. 2012b; Poeschl et al. 2012a). Jury et al. (2010) used an allocation approach instead of substitution to represent digestate use. A monetary value of the avoided mineral fertilizer was used. Hamelin et al. (2011) compared slurry spreading to anaerobic digestion and digestate spreading. The MFE value followed Danish legislation. Nitrous oxide emissions were calculated according to IPCC guidelines, and other nitrogen emissions were determined with a Danish model. Carbon storage was represented according to (Petersen et al. 2002). This work incorporates crop yield variations according to fertilizer type (mineralization process of the anaerobic digestion step; the nitrogen of digestate is more available for plants than nitrogen from slurry; an increase of 9 kg of wheat per kg of nitrogen was considered). Crop yield variations are represented by avoided wheat production. However, the assessments are mainly driven by avoided fertilizer, with the yield increase effect being negligible.

4.6. Biochars

Recent works focused on agricultural use of biochar (Kameyama et al. 2010; Roberts et al. 2010; Hammond et al. 2011; Ahmed et al. 2012; Mattila et al. 2012; Cao and Pawlowski 2013; Sparrevik et al. 2013). Carbon storage is usually the driver of the study and biochar use appears as an interesting solution. Cao and Pawlowski (2013) underline also the benefit on climate change and the energetic balance because of avoided mineral fertilization (They assume that biochar soil-enrichment implies a decrease of 10% of mineral nitrogen, phosphorus and potassium fertilizer use because of better nutrient bioavailability).

5. Conclusion

Agricultural use of residues is a common way for waste valorization and the fertilizing function is often represented in LCA of waste treatment systems. The use of residues as fertilizer induces usually significant impacts on the ecosystems due to heavy metals and on climate change and atmospheric pollution because of nitrogen compounds emissions. The benefit from the avoided mineral fertilizer production can counter balance the impacts from spreading emissions, but, unfortunately, this substitution is often misdescribed or only partially documented. Because MFE is a key parameter for LCA of agricultural use of residues, it should be clearly presented in the studies.

Field emissions of FR differ from mineral fertilizer emissions because of management practices and nitrogen forms. In LCA works, the variety of the system limit (no emissions, FR emission only or FR and mineral fertilizer balance) implies a variability of the results, which should be integrated in the interpretation of the results.

An LCA study dealing with agricultural use of residues should be carried out notably with:

- the references, the rules and/or the models and their parameters used to determine field emissions,
- the value used as MFE, supplemented with references and sensitivity analysis,
- a description of the system limit, which has to include the whole substituted system (mineral fertilizer emission from the production to the field emission).

Some aspects are not represented in LCA. Pathogens and health consequences are not assessed in LCA, which has to be highlighted for human waste and animal manure uses. LCA works start to deal with this (Motoshita et al. 2010), but methods are not operational. Even if methods have been developed (Milà i Canals et al. 2007; Garrigues et al. 2012), the effects of the FR organic matter on soil quality is not taken into account. Recent publications deal with carbon storage and the consequences on climate change (this can be observed in publications dedicated to biochar, for example). This should be generalized in the next years.

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