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# Environmental assessment of nutrient recycling from biological pig slurry treatment – Impact of fertilizer substitution and field emissions

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## HIGHLIGHTS

- Direct field emissions from organic fertilizer dominated environmental impacts.
- The amount of avoided mineral fertilizers largely influenced environmental impacts.
- Modified plant available nitrogen calculation considers total nitrogen emissions.
- Calculation method for amount of avoided mineral fertilizers.

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ABSTRACT

Pig slurry treatment is an important means in reducing nitrogen loads applied to farmland. Solid phase separation prior to biological treatment further allows for recovering phosphorus with the solid phase. The organic residues from the pig slurry treatment can be applied as organic fertilizers to farmland replacing mineral fertilizers. The environmental impacts of nutrient recycling from aerobic, biological pig slurry treatment were evaluated applying the life cycle assessment (LCA) methodology. LCA results revealed that direct field emissions from organic fertilizer application and the amount of avoided mineral fertilizers dominated the environmental impacts. A modified plant available nitrogen calculation (PAN) was introduced taking into account calculated nitrogen emissions from organic fertilizer application. Additionally, an equation for calculating the quantity of avoided mineral fertilizers based on the modified PAN calculation was proposed, which accounted for nitrogen emissions from mineral fertilizer application.



## 1. Introduction

Pig slurry treatment has considerably gained in importance in France, especially in the region of Brittany, where 57% of the French pork is produced (Duflot and Roguet, 2012). As the whole region is classified as nitrate vulnerable zone based on the EU Nitrates Directive from 1991 (European Commission, 1991), the maximal annual nitrogen load from animal waste spread on farmland is limited to 170 kg N $ha^{-1}$ $year^{-1}$. In 2005, over 300 pig slurry treatment systems processed 2.1 million $m^3$ pig slurry, of which about 85% were treated biologically by nitrification/denitrification (Levasseur and Lemaire, 2006). About 35% of the treatment plants separated the solid phase of the raw pig slurry by centrifugation to obtain a phosphorus-rich residue (75–80% phosphorus extraction), which is composted and then mainly exported to regions outside of Brittany to reduce phosphorus and nitrogen application in Brittany. It can, however, be expected that the application of solid phase separation by centrifugation increases in the future. The prefect of Brittany limited the maximal annual phosphorus load applied to farmland to 95 kg P $ha^{-1}$ $year^{-1}$ to reduce phosphorus emissions from agriculture in order to comply with the EU Water Framework Directive from 2000 (European Commission, 2000).

Due to their nutrient contents, effluents and residues from animal farming and slurry treatment can be applied to farmland as organic fertilizers, replacing the application of mineral fertilizers. The fertilizing value of organic fertilizers, however, is lower than for mineral fertilizers, because organic fertilizers contain both mineral forms of nitrogen and organic nitrogen. The organic nitrogen needs to be mineralized by soil microorganisms before it is available to plants. In order to replace mineral fertilizers by organic fertilizers at equivalent nutrient and fertilizing values, the nutrient

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contents and the mineral fertilizer equivalent (MFE) of the organic fertilizers need to be known. Typically, MFE values reported in literature have been used in life cycle assessment (LCA) studies of manure processing techniques (Bayo et al., 2012; De Vries et al., 2012a; Prapaspongsa et al., 2010) or sewage sludge management (Johansson et al., 2008; Linderholm et al., 2012). Methods for calculating the MFE of an organic fertilizer based on its characteristics have been reported (Delin et al., 2012; Water Environment Federation, 2005), but have not yet been used for LCA studies.

Emissions to air, water and soil associated to the application of mineral and organic fertilizers to farmland contribute to acidification and particulate matter formation ($NH_3$ and $NO_x$), climate change ($N_2O$), eutrophication (mainly through leaching of $NO_3^-$ and $PO_4^{3-}$), and human toxicity and ecotoxicity (heavy metals). Many LCA studies take only nitrogen emissions into account (De Vries et al., 2012a; Hansen et al., 2006; Johansson et al., 2008; Prapaspongsa et al., 2010; Rehl and Müller, 2011). A few studies also included phosphorus emissions (De Vries et al., 2012b; Hamelin et al., 2011; Jury et al., 2010; Langevin et al., 2010), while additional consideration of heavy metal emissions is rare (Bayo et al., 2012). The calculation of field emissions is typically based on emission factors reported in literature. The use of model equations for calculating field emissions has been reported only for some studies (Jury et al., 2010; Langevin et al., 2010; Rehl and Müller, 2011). Hansen et al. (2006) used a complex agro-ecosystem model describing the water, heat, carbon, and nitrogen dynamics in the soil–plant–atmosphere system to determine emission coefficients for nitrogen emissions from organic fertilizer application.

In this study, environmental impacts were evaluated for nutrient recycling from a pig slurry treatment system most commonly used in France. Special attention was paid to determination of field emissions from fertilizer application and substitution of mineral fertilizers.

## 2. Methods

### 2.1. LCA approach and goal and scope

LCA is a standardized methodology (ISO 14040) for evaluating the environmental impacts associated with the entire life cycle of a product, process or service. In this study, environmental impacts related to nutrient recycling from biological pig slurry treatment were evaluated using the LCA methodology. Nutrients were recycled by applying all effluents and residues of the treatment system – compost, biological sludge, and supernatant – as organic fertilizers to farmland. The fertilizing value of the organic residues was determined using different calculation methods reported in literature (Delin et al., 2012; Water Environment Federation, 2005). Nitrogen, phosphorus, and heavy metal (Cu, Zn, Cd, Cr, Ni, Hg, Pb, As) emissions directly related to field application of mineral and organic fertilizers were calculated with emission models reported in literature (Nemecek and Schnetzer, 2012; Smaling, 1993). Environmental impacts related to emissions of pathogens and medicines (e.g. antibiotics and hormones) from fertilizer application were excluded from the study. An operational method for taking into account environmental impacts related to pathogens is not available and information on the fate of medicines during pig slurry treatment is missing. The main function of the studied system remains the treatment of pig slurry so that the functional unit is the treatment of 1 $m^3$ pig slurry.

### 2.2. System description and system boundaries

The LCA study comprised all steps of pig slurry treatment, transportation and application of produced organic fertilizers, as well as avoided production, transportation and application of replaced mineral fertilizers including emissions from treatment and fertilizer application (Fig. 1). The system studied included environmental impacts related to infrastructure and equipment needed for pig slurry treatment, and energy consumption. The animal production itself was excluded from the study.

The biological pig slurry treatment system studied is located in a French nitrate vulnerable zone, such as Brittany, and was designed for a treatment of 15 $m^3$ $day^{-1}$ raw pig slurry. The raw slurry is homogenized and stored in an open storage tank. The solid phase of the pig slurry (10% of the weight of raw slurry) is then separated by centrifugation. The solid phase is naturally composted in a covered shed using a forced aeration system and regular turning. The liquid phase undergoes biological treatment by nitrification/denitrification with intermittent aeration in an open tank. The biological sludge produced during aerobic treatment is separated from the liquid phase by sedimentation in a settling tank. The settling tank also serves as storage tank for the settled sludge (no sludge recirculation; up to 9 months storage). The supernatant withdrawn from the top of the settling tank is stored in an open lagoon before it is distributed through a piping system for irrigation on near cropland. The biological sludge is spread on farmland near the farm (3 km), while the compost is transported for long distances (450 km). Considered compositions of raw pig slurry and produced organic fertilizers are given in Table 1.

### 2.3. Field emissions from fertilizer application

Field application of both mineral and organic fertilizers results in direct emissions to air, soil and water. In this study, different emission models were used to calculate direct field emissions from fertilizer application. The emission models take into account different types of fertilizers, application methods, soil conditions, and climate conditions, among others. Emissions were calculated for mean French climate and soil conditions, whose determination is described in the Supplemental materials.

#### 2.3.1. Ammonia emissions

Ammonia emissions from mineral fertilizer application were calculated using the emission model presented in the EMEP/EEA Air Pollutant Emission Inventory Guidebook 2009 (European Environment Agency, 2009) (Eq. (1)).

$$E_{fert,\mathrm{NH_3}} = \sum_{i=1}^{I}\sum_{j=1}^{J}(N_{fert,i,j} \cdot EF_{i,j} \cdot (1 - p_{alk,j} \cdot (1 - c_{\mathrm{pH},i}))) \quad (1)$$

with $E_{fert,\mathrm{NH_3}}$ being the ammonia emission flux [kg $NH_3$], $N_{fert,i,j}$ being the mass of N applied by fertilizer type $i$ in region $j$ [kg N], $EF_{i,j}$ being the emission factor for fertilizer type $i$ in region $j$ [kg $NH_3$ $(kg\ N)^{-1}$], $p_{alk,j}$ being the proportion of region $j$ with soil pH > 7.0, and $c_{pH,i}$ being the soil pH multiplier for fertilizer type $i$. The emission factor $EF_{i,j}$ is a function of the mean spring temperature in region $j$. Equations for calculating $EF_{i,j}$ for different types of mineral fertilizers, and soil pH multipliers are given in Table A1 in the Supplemental materials. Calculated emission factors for a mean French spring temperature of 13.7 °C and 47.3% of French arable land with soil pH > 7.0 are summarized in Table 2.

Ammonia emissions from organic fertilizer application were calculated with the AGRAMMON model presented by the Agrammon Group and used by Nemecek and Schnetzer (2012).

$$\mathrm{NH_3\text{-}N} = \mathrm{TAN} \cdot (EF + c_{app}) \cdot c_x \quad (2)$$

where $NH_3$-N is the emission of ammonia [kg $NH_3$-N], TAN is the total ammonium nitrogen of the organic fertilizer [kg N], $EF$ is the emission factor for the organic fertilizer [%TAN/100], $c_{app}$ is a correction factor influencing the emission factor (applies only for liquid