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Towards a comprehensive greenhouse gas emissions inventory for biosolids

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ABSTRACT

Effective handling and treatment of the solids fraction from advanced wastewater treatment operations carries a substantial burden for water utilities relative to the total economic and environmental impacts from modern day wastewater treatment. While good process-level data for a range of wastewater treatment operations are becoming more readily available, there remains a dearth of high quality operational data for solids line processes in particular. This study seeks to address this data gap by presenting a suite of high quality, process-level life cycle inventory data covering a range of solids line wastewater treatment processes, extending from primary treatment through to biosolids reuse in agriculture. Within the study, the impacts of secondary treatment technology and key parameters such as sludge retention time, activated sludge age and primary-to-waste activated sludge ratio (PS:WAS) on the life cycle inventory data of solids processing trains for five model wastewater treatment plant configurations are presented. BioWin® models are calibrated with real operational plant data and estimated electricity consumption values were reconciled against overall plant energy consumption. The concept of “representative crop” is also introduced in order to reduce the uncertainty associated with nitrous oxide emissions and soil carbon sequestration offsets under biosolids land application scenarios. Results indicate that both the treatment plant biogas electricity offset and the soil carbon sequestration offset from land-applied biosolids, represent the main greenhouse gas mitigation opportunities. In contrast, fertiliser offsets are of relatively minor importance in terms of the overall life cycle emissions impacts. Results also show that fugitive methane emissions at the plant, as well as nitrous oxide emissions both at the plant and following agricultural application of biosolids, are significant contributors to the overall greenhouse gas balance and combined are higher than emissions associated with transportation. Sensitivity analyses for key parameters including digester PS:WAS and sludge retention time, and assumed biosolids nitrogen content and agricultural availability also provide additional robustness and comprehensiveness to our inventory data and will facilitate more customised user analyses.

1. Introduction

The role of sludge treatment in wastewater treatment plants (WWTPs) has changed considerably over the last 50 years. Historically, unit operations associated with the solids stream, including thickening, anaerobic digestion and dewatering have received much less attention than the water line counterparts, probably owing to the much higher wastewater volumetric throughputs and the need for enhanced biological nutrient removal to meet increasingly stringent effluent quality requirements (Oleszkiewicz and Barnard, 2006). However, the relevance of solids line processes in the last two decades has grown significantly, due to the recognised potential for nutrients and resource recovery, as well as the generation of electricity and heat from biogas (Peccia and Westerhoff, 2015).

While the need to satisfy effluent discharge standards imposed by local regulators ensures operational continuity of WWTPs, a balance should be struck between the quality of these waste stream outputs and the environmental impacts associated with energy and chemical use during such advanced wastewater treatment (Foley

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et al., 2010; Lundie et al., 2004). In urban water resources management, the term 'fit for purpose' typifies this balancing act and recognises the need to better match water treatment intensity with the water quality needs of specific end uses (Nair et al., 2014; Short et al., 2015). The quantification of these trade-offs is best done by environmental life cycle assessments (LCAs) of wastewater treatment systems (Corominas et al., 2013).

For the solids line, numerous LCAs have been undertaken to assess the environmental benefits and drawbacks of various treatment process configurations (Yoshida et al., 2013). WWTP processes covered by such LCAs include aerobic and anaerobic digestion, drying, liming and incineration, with solids stream end use options such as landfill, cement manufacturing and agriculture also assessed (Brown et al., 2010; Murray et al., 2008; Peters and Rowley, 2009; Yang et al., 2015). Differences in the outcomes of these studies are associated with local site-specific factors, but more importantly relate to technical assumptions made during the LCA process itself (Yoshida et al., 2013).

Life cycle inventory (LCI) data associated with the treatment of sludge is usually dispersed and reflects country-specific practices and the associated regulatory requirements. In fact, most commercial LCI databases respond to a European context where incineration is generally preferred over land application as an end use. However, in countries such as the United States, Canada, the United Kingdom and Australia land application of biosolids is the most common beneficial reuse pathway (Spinosa, 2011). For example, the preferred sludge stabilisation process in Australia is anaerobic digestion (46%) followed by centrifuge dewatering (48%) or lagoon drying, with the most common biosolids end use being agricultural land application (59%) (ANZBP, 2013). At the WWTP, the impacts from potentially important process parameters (e.g., sludge age during secondary treatment, or the effects of digester solids retention time (SRT) and feed ratio of primary to waste activated sludge (WAS) on biogas production) are usually not taken into account during LCI data compilation (Doka, 2009). In addition, the most important source of uncertainty in biosolids LCAs results when biosolids is applied to land relates to assumptions made regarding nitrous oxide (N_2O) emissions and carbon sequestration credits (Brown et al., 2010; Peters and Rowley, 2009). However, Yoshida et al. (2013) found that only 10 out of 35 studies included nitrous oxide emissions and only 3 out 35 studies included carbon sequestration in previous LCAs dealing with biosolids land application.

Accordingly, and in response to the knowledge gaps identified by Corominas et al. (2013), this paper provides a much needed contribution towards the development of better LCI data for the processing and land application of biosolids. LCI data presented has been developed specifically in the Australian state of New South Wales (NSW), using calibrated BioWin® models with real operational data from WWTPs with different treatment process configurations (Aurecon, 2013). While these data have locally-specific origins, the range of process technologies included ensures broader data relevance to similarly configured systems operating elsewhere. We have also included empirical data on N_2O emissions from the cropping region where the biosolids are currently applied. Carbon sequestration data is also included, while it is acknowledged that additional work is needed in this key area to improve the LCI data available for biosolids management in Australia and where similar conditions exist elsewhere.

2. Material and methods

2.1. Sewage sludge treatment

The solids treatment process configurations chosen for this study (Table 1) were selected to reflect the various configurations most commonly used to comply with regulatory licence requirements and include some of the most popular technologies for secondary treatment such as conventional activated sludge (CAS), modified Ludzack-Ettinger (MLE) and the Biodenipho™ process. Specifying the technological configuration of each treatment process train as done here, adds an additional layer of detail for LCA purposes and provides users with additional flexibility, since the performance of processes upstream of anaerobic digestion will impact the potential for biogas generation and consequently affect the overall LCA results of biosolids processing options (Barber, 2014).

Treatment trains 1 and 2 in Table 1 are associated with the treatment of sludge from primary treated wastewater which has been identified as having a higher biogas production potential and higher dewaterability. In treatment train 1, thickening is carry out using rotary drum thickeners which are also used to thicken digested sludge in recuperative thickening mode. In treatment train 2, hoppers are part of sedimentation tank design for additional thickening purposes. A purpose-built thickening step has a positive impact on the production of biogas and energy efficiency of the whole sludge line. Sludge thickened to at least 6% total solids (TS) (depending of pumping design) maximises SRT, providing a higher biogas production and minimising the heat required to keep the digester temperature at appropriate levels (Kapp, 1984). In relation to dewatering, these two trains use high speed centrifuges due to the benefits of reduced operator input and an expected higher %TS in the dewatered cake compared with low speed centrifuges or belt filter presses.

Treatment trains 3, 4 and 5 include primary sedimentation followed by secondary treatment using MLE, CAS and Biodenipho™ configurations. Activated sludge age from secondary treatment and the PS:WAS ratio have been included for these treatment trains to account for the potential impacts on biogas production as shown in Table 2. Biogas production improves with higher SRTs (Miron et al., 2000), therefore this parameter is also included in these treatment trains. Usually, the higher the WAS content, the lower the digested sludge dewaterability which leads to a lower %TS in the dewatered cake and higher polyelectrolyte requirements during centrifugation (Skinner et al., 2015).

Treatment train 3 has a sludge age of 7.5 days in summer and 9 days in winter. Primary sludge is thickened in a gravity thickener and WAS is thickened in a DAF. Primary sludge and WAS are mixed and fed to a digester at a PS:WAS ratio of 78:22 and SRT of 13 days. Treatment train 4 is a CAS treatment plant with a sludge age of 7.5 days. WAS is thickened in a high speed centrifuge and primary sludge is thickened in primary sedimentation tank hoppers. Both are mixed and fed to a mesophilic anaerobic digester with a PS:WAS ratio of 73:27 and 20 day SRT. Treatment train 5 includes CAS treatment with a 4 day sludge age running in parallel to a Biodenipho™ process with 14 day sludge age. Primary sludge is thickened in gravity thickeners while biological WAS is thickened in centrifuges, mixed and fed to a digester with a PS:WAS ratio of 43:57 and a SRT of 19 days.

Electricity consumption for all five treatment trains was calculated using equipment nameplates, running hours and loading factors from online data control systems due to lack of submetering. Total energy consumption per plant using this approach was compared against total utility bill values to confirm the accuracy of the measurements and was validated as within ±10% of the total measured value.

As part of the study, it was required to specify which equipment is included in each unit process operation. For example, electricity required for pumping from the thickening step to digestion is included in the thickening step and those associated with the