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$SIMS_{WASTE\text{-}AD}$ - A modelling framework for the environmental assessment of agricultural waste management strategies: Anaerobic digestion

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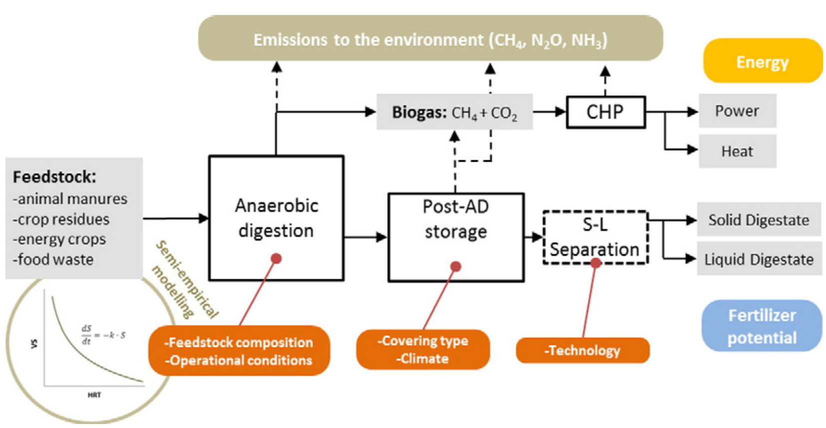
HIGHLIGHTS

- A new modeling approach to calculate GHG and NH_3 emissions from anaerobic digestion processes is proposed.
- The new model is used to simulate C and N flows and GHG emissions for a set of scenarios exploring different conditions.
- Post-digestion emissions and its relationship with the anaerobic digestion performance are the main factors affecting net GHG emissions.
- Gas tight digestate storage is recommended as well as operational conditions enhancing the process efficiency.
- Potential for GHG mitigation through manure anaerobic digestion is higher in warmer regions, where it should be promoted.
- The model can be integrated in holistic approaches to develop adequate mitigation strategies in the agricultural sector.

GRAPHICAL ABSTRACT



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ABSTRACT

On-farm anaerobic digestion (AD) has been promoted due to its improved environmental performance, which is based on a number of life cycle assessments (LCA). However, the influence of site-specific conditions and practices on AD performance is rarely captured in LCA studies and the effects on C and N cycles are often overlooked. In this paper, a new model for AD ($SIMS_{WASTE\text{-}AD}$) is described in full and tested against a selection of available measured data. Good agreement between modelled and measured values was obtained, reflecting the model capability to predict biogas production ($r^2 = 0.84$) and N mineralization ($r^2 = 0.85$) under a range of substrate mixtures and operational conditions. $SIMS_{WASTE\text{-}AD}$ was also used to simulate C and N flows and GHG emissions for a set of scenarios exploring different AD technology levels, feedstock mixtures and climate conditions. The importance of post-digestion emissions and its relationship with the AD performance have been stressed as crucial factors to reduce the net GHG emissions (−75%) but also to enhance digestate fertilizer potential (15%). Gas tight digestate storage with residual biogas collection is highly recommended (especially in temperate to warm climates), as well as those operational conditions that can improve the process efficiency on degrading VS (e.g. thermophilic range, longer hydraulic retention time). Beyond the effects on the manure management stage,

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LCA
Mitigation

$SIMS_{WASTE\text{-}AD}$ also aims to help account for potential effects of AD on other stages by providing the C and nutrient flows. While primarily designed to be applied within the $SIMS_{DAIRY}$ modelling framework, it can also interact with other models implemented in integrated approaches. Such system scope assessments are essential for stakeholders and policy makers in order to develop effective strategies for reducing GHG emissions and environmental issues in the agriculture sector.

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1. Introduction

Inadequate management of animal manure and other agricultural wastes has been identified as a major cause of environmental issues at global (climate change, ozone depletion) and regional scale (soil acidification, aquatic eutrophication, particle matter formation). Agricultural waste management is the largest source of the atmospheric ammonia (NH_3) emissions from terrestrial sources (Bouwman et al., 1997), and it is also estimated to contribute substantially to methane (CH_4) and nitrous oxide (N_2O) emissions from agriculture, accounting for about 12–40% and 30–50%, respectively (Oenema et al., 2005).

In the EU-28, livestock manure is the largest agricultural waste stream, with over 1100 Mton per year, mainly associated with dairy and pig farming. While historically manure has been a valuable source of nutrients for crop cultivation, intensification of modern livestock production has caused excessive manure surpluses in hot spot areas of high livestock density, which poses large risks of nutrient losses in different pathways, such as leaching of nitrogen (N) and phosphorus (P) diffuse pollution to waters, or emissions to the atmosphere in the form of polluting gases (e.g. N_2O, NH_3) and N_2 (Oenema et al., 2007).

Thus, different environmental policies (e.g. Gothenburg Protocol, EU Nitrate Directive) have been enforced to make the agricultural sector reduce their emissions. Moreover, scientific-based evidence has put at the top of the Intergovernmental Panel on Climate Change (IPCC) agenda the role of agriculture, both at the production and demand sides, on mitigating climate change (Smith et al., 2014).

At the production side, technologies for the treatment of agro-industrial residues, such as composting or anaerobic digestion (AD), have been pointed out for their potential to reduce the environmental burdens associated with the food production system, and in particular to livestock husbandry (Gregg and Smith, 2010; Haberl et al., 2010; Steiner et al., 2010). Simultaneously they can help to improve on-farm management efficiency and to convert by-products into valuable resources, thereby enhancing the development of a circular economy and reducing the depletion of finite resources. However, they also affect agricultural systems beyond the farm boundaries, through changes in carbon (C) and nutrient cycles that may shift different interactions between the organic amendment applied (i.e. compost, digestate), the environmental losses, and the land functions linked to soil quality and fertility (e.g. soil structure) (Möller and Müller, 2012).

Anaerobic digestion has been promoted with policies and strategic decisions due to its improved environmental performance, which is based on a number of life cycle assessments (LCA) (Huttunen et al., 2014). However, most of LCA-based studies on AD rely on unit process data from commercial databases or IPCC default emission factors (EF) (IPCC, 2006) and neglect specific C and N cycling effects of AD process (Cederberg et al., 2013; Meier et al., 2015; Styles et al., 2015). Furthermore, a number of studies have shown the influence of site-specific conditions and management practices on AD performance (Boulamanti et al., 2013; Liebetrau et al., 2013) which may not be fully captured in over-simplified LCA approaches.

Although complex mechanistic models like ADM1 (Batstone et al., 2002) have proved to be well suited for the modelling of biogas production from several organic wastes, their applicability is generally limited due to the large number of stoichiometric and kinetic equations involved, for which detailed parametrization is required. For strategic studies, where specialised data are not available and absolute precision can be compromised (e.g. LCA studies), simpler models demanding few input parameters are more suitable than complex ones to explore the potential differences on biogas production and nutrient transformation of AD systems under a range of site and management situations. Therefore, there is a need for more flexible tools that can balance simplicity and attempt to represent C and N flows in AD processes while being sensitive to most of the factors that are well known to influence GHG emissions and environmental losses.

The overall objective of this work is to provide a description of the $SIMS_{WASTE\text{-}AD}$ model, their main features and applicability, so it can be integrated as a decision support system in future assessments of mitigation strategies for agricultural production chains.

Individual sub-objectives are: (i) to describe the development of a new AD model ($SIMS_{WASTE\text{-}AD}$), including their main principles and characteristics, (ii) to test the model outputs against a selection of available measured data and (iii) to evaluate the model response (GHG emissions, N losses) to changes in management and climate conditions. Conceptually designed as part of a comprehensive modelling framework, $SIMS_{WASTE\text{-}AD}$ is intended to be a useful mathematical model to analyse the environmental implications of AD within agricultural systems, taking into account site-specific conditions, such as substrate composition and technology applied, but also potential trade-offs in emissions (pollution swapping) relative to farm and land management.

2. Materials and methods

2.1. Overarching modelling framework

The $SIMS_{WASTE\text{-}AD}$ has been developed as part of an integrated approach comprising animal farm (e.g. $SIMS_{DAIRY}$: Del Prado et al., 2011), crop cultivation ($SIMS_{NIC}$: (Gallejones et al., in press) and LCA (Del Prado et al., 2013). A modular modelling framework has been developed, where different sub-models that simulate the different compartments of a whole-farm system are linked following a mass balance principle of the considered substances (C, N, P, K) (Fig. 1). The model intends to capture internal feed-backs and loops between the farm components and simulates flows and transformations of nutrients. In order to reflect the interactions between the components of the system under study, together with the associated externalities involved, life cycle approach is applied at every stage, accounting for impacts related to fuel and energy production as well as potential benefits, such as biogas production and compost or digestate application.

As indicated in Fig. 1, the present study is focused on the description of the approach developed for modelling the waste management stage in the specific case AD is applied. Among the technologies available, anaerobic digestion (AD) and composting (CO) were selected as the most widespread treatment options for agricultural waste in liquid and solid form respectively, whereas storage of untreated manure was considered as the conventional management scenario. The scope of the model involves the waste treatment stage after animal housing and previously to application on the field.

2.2. General description of the AD conceptual model

The main objective of the $SIMS_{WASTE\text{-}AD}$ model is to simulate the main C and nutrient (N, P, K) flows and transformations during the

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