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Research paper

Meta-analysis of methane yields from anaerobic digestion of dairy cattle manure

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ABSTRACT

This work presents a novel meta-analysis for methane yields from anaerobically digesting dairy cattle manure. A database is compiled from 115 articles (2181 cases) by systematically assessing the academic literature. Y_{CH_4} and secondary variables collected in the database describe performance, operation conditions of digester and manure composition. Inputs to the database are normalised to enable inter-study uni- and multi-variate analysis, according to different types of digesters.

Most cases (N = 1299) are reported for batch digesters and meta-analysis results in a mean Y_{CH_4} of 0.230±0.016 m^3kg^{-1}. CSTR (N = 241), results in mean of 0.190±0.016 m^3kg^{-1} (random-effect model). Other continuous digesters, such as fixed-film, plug-flow and UASB require further cases for the application of meta-analysis. For non-specified semi-continuous digesters (N = 347), the mean calculated by the random-effect model is 0.204±0.032 m^3kg^{-1} (N = 27).

With respect to multi-variate analysis of operation conditions, batch digesters form four clusters, while two clusters are identified for CSTR and three for semi-continuous digesters. For variables describing manure composition, batch digesters present eight clusters, while CSTR and semi-continuous digesters have insufficient cases. The strongest correlations found for these secondary variables (Spearman's rho: −0.685 and −0.696) result for pH and Y_{CH_4} in batch and CSTR, respectively.

Maximum Y_{CH_4} estimated by meta-analysis are proposed to replace the default IPCC values because they are based on a larger sample size and integrate updated literature. In particular, markedly higher Y_{CH_4} are obtained for Asia, Middle East and Indian Subcontinent than those in the IPCC guidelines.

1. Introduction

This meta-analysis examines the methane yields (Y_{CH_4}) found in the literature for anaerobic digestion (AD) of dairy cattle manure. The dairy sector is responsible for 4% of global anthropogenic greenhouse gas (GHG) emissions [1]. To reduce the carbon footprint of milk-producing farms, AD has been proposed as a mitigating technology. AD converts the volatile solids (VS) in cattle manure to biogas (CH_4 and CO_2 mixture) and digestate [2]. Consequently, GHG emissions are decreased by: i) avoiding high global warming CH_4 from manure management systems; ii) generating renewable energy that substitutes fossil fuels and; iii) producing digestate that replaces mineral fertilisers. In order to quantitatively predict these benefits, assumptions on the performance of AD processes are critical [3].

In this respect, Y_{CH_4} is a metric widely utilised in mass and energy balances to calculate the CH_4 production. The Y_{CH_4} corresponds to the CH_4 formed by unit of VS and is defined as follows:

$$Y_{CH_4}\left[m^3kg^{-1}\right] = \frac{CH_{4,output}}{VS_{input}} \quad (1)$$

Theoretical, modelled and experimental values of Y_{CH_4} are available in the literature. Theoretical estimates commonly use the Buswell equation [4,5] which is based on the chemical composition and stoichiometry of degradation reactions. However, actual Y_{CH_4} are less than theoretical values because not all organic material converts to biogas (e.g. non-degradable solids, inhibition of reaction and/or generation of new bacteria). Thus, utilising theoretical

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Y_{CH_4} can over-estimate CH_4 production for AD scenarios. For models of Y_{CH_4} (e.g. ADM1 [6] and Linke et al. [7]), validations are based on experimental work with limited AD operation conditions. Therefore, increasing the sample size of experimental results can provide a more robust source of validation. Although, empirical values of Y_{CH_4} are available in multiple (and increasing) publications, it is challenging to integrate results differing in operation conditions, slurry compositions and units of measurements. This work addresses this by applying meta-analysis techniques to systematically review and numerically combine the research on Y_{CH_4} in the dairy sector.

Meta-analysis has traditionally developed in the medical sciences but in recent years has been applied in the bio-energy sector [8,9]. For biogas generation from dairy farms, qualitative reviews are dominant [10–12]. Only two meta-analysis [13,14] exist for AD of dairy manure, however, they are focused on different aspects of the process (i.e. microbial communities [13] and the effects over farm emissions [14]). Additionally, to the authors' knowledge, this is the first work to integrate such numerous cases from the academic literature in the field.

The aim of this meta-analysis is to quantitatively combine Y_{CH_4} measurements to enable a comprehensive understanding of this metric with respect to operational and composition variables. For this purpose, two main steps are carried out: creating a specific database and statistically analysing the collected information. A database is compiled because no specific dataset is available for the entire literature reporting Y_{CH_4} of AD in dairy farms. Research articles are found by using particular keywords and applying defined criteria (Section 2.1). The Y_{CH_4} are extracted from the selected work and entered to the database together with secondary variables (i.e. specifying operation and/or manure composition). In order to enable numerical combination, units of measurements for all variables are standardised (Section 2.2). To analyse the variables compiled in the database, uni- and multi-variate tests are introduced in Sections 2.3–2.4.

In the Results and Discussion section, key aspects of the database are first described (Section 3.1). Thereafter, Y_{CH_4} are discussed in terms of digester type (i.e. batch, continuous or semi-continuous). Multi-variate structure between key variables related to the performance of different AD systems is examined. Correlations and clustering of principal components are discussed in terms of sources of similarities and variations. The discussion finally compares results of meta-analysis models applied over maximum Y_{CH_4} to the default values of the National Guidelines for GHG emissions of the Intergovernmental Panel of Climate Change (IPCC [15], i.e. widely used to predict CH_4 emission from manure management systems).

2. Methods

This section first presents the methodology to develop the novel database of Y_{CH_4} for AD of dairy cattle manure. Second, the mathematical background for the statistical analysis of the variables in the database is introduced. All statistical calculations are performed in R v.3.0.2.

2.1. Article selection

A systematic search of articles in the academic literature is carried out to compile the database of Y_{CH_4} of dairy cattle manure and secondary variables. The selection of articles is based on the following four criteria:

i) scientific publications in the academic literature that have been peer-reviewed and are in the field of AD;
ii) primary sources;
iii) available work in journals in English to which the authors have access and;
iv) inclusion of experimental data of Y_{CH_4} for AD of dairy cattle manure.

The first criterion is defined to ensure quality results in articles that potentially report Y_{CH_4} values. The ISI Web of Knowledge platform [16] is used because it contains mainly peer-reviewed journals. The publication language is set as "English" and the publication year is not constrained. It should be noted that, although China has played an important role in the development of AD plants (e.g. by 2007 it had 26.5 million biogas plants installed [17]), articles written in Chinese are discarded by this criterion. Similarly occurs for publications from India [18]. This is significant constraint of the language criterion. However, as results will show, the selection of English articles in this work markedly contributes in bringing together a large sample size.

Keywords, logical connectors and combinations shown in Fig. 1 are used for the search of articles. The keywords aim to identify technology presence, agricultural sector and the metric of interest for this meta-analysis.

From the search results, titles and abstracts are used for a first filtering step. They are assessed to determine if studies report mono-digestion of dairy cattle manure and are primary sources (i.e. the latter corresponds to the fulfilment of the second criteria). Secondary sources are excluded to avoid duplicated values in the database. Therefore, review articles are rejected in this step. In addition, articles from a same author are verified to not repeat cases in the database.

From the titles and abstracts, articles available to the authors are collected (i.e. third criteria). The final filter step consists of selecting papers that include quantitative and empirical results (in text, tables or figures) of Y_{CH_4} for dairy cattle manure, thus, complying with the fourth criteria.

2.2. Database input

Y_{CH_4} are extracted from the selected articles to compile the database. Values of Y_{CH_4} are adapted so that all cases correspond to cumulative CH_4 production per kilogram of VS. Y_{CH_4} values are standardised to normal conditions (20 °C, 101.3 kPa) and given in "$m^3\ kg^{-1}$" (i.e. volume of methane produced per mass of VS fed to digester.

When articles report various Y_{CH_4} (e.g. profiles across time or measurements at different temperatures), multiple cases are logged into the database. To record differences between cases, secondary variables are also entered to the database (when available). Qualitative secondary variables are: author name, journal name, year of publication and location of study (country and/or continent). If the latter is not available, the location of the first author is used. For quantitative secondary variables, the first column of Table 1 shows those that are found most frequently in the literature for AD of dairy cattle manure, thus, used in this work. These variables specify AD operation conditions and chemical compositions of the undigested slurries (i.e. before entering the digester). The units of measurements for secondary quantitative variables are also presented in Table 1. If a variable is reported in different dimensions, underlying data from the original article is utilised to reconcile the units. If insufficient information is available when dimension conversion is required, the original units of measurements are recorded into the database, but the variable is excluded for numerical analysis.

To ensure that comparable experiments are combined, the results are presented separately according to type of digester (batch,