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Technical Note

Calculating the degree of degradation of the volatile solids in continuously operated bioreactors

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ABSTRACT

Determining the degree of degradation is an important means of assessing the efficiency of biological processes. However, one should consider the fact that during degradation, the reference value, such as volume or the mass of total solids, is also subject to change. The assumption that the incoming and outgoing mass flows are identical is only possible for substrates with a high water content and hence, a low energy density. For substrates with a higher energy density, a correction by the gaseous mass flow is required, but usually its quantification is difficult, especially when examining full-scale plants or open systems. Based on the assumption that the mass of inorganic solids is constant during the process, a universally applicable equation has been developed, requiring only the input and output volatile solids concentrations for calculation.

1. Problem

Improving the efficiency of engineered biological processes is one of the main challenges of modern environmental engineering. In order to assess the efficiency of any process, measurements need to be performed. Depending on the process of interest, the applied measurement approaches differ. Typically, one can distinguish between direct measurement of the fate of individual substances (e.g. specific contaminant) or lumped fractions (e.g. chemical oxygen demand, COD) and indirect measurements of some type of product (e.g. biogas). At times both methods are used so as to validate the results with two independent measurements. For instance, measurement of both influent and effluent COD of a digester combined with recording of biogas production. The COD removal can then be inferred from the methane production. However, comparing influent and effluent concentrations is insofar problematic, as one assumes that the reference mass remains the same. This simplification is sometimes valid, however not always.

The following example of a lab-scale digester demonstrates the issue. In the first case, the digester is fed with waste sludge. The calculation of the mass flow via produced biogas is based on the following assumptions and simplifications, respectively [1]:

- COD concentration of the waste sludge is 0.05 kg kg^{-1}.
- 50% of the input COD (25 kg d^{-1}) is converted to biogas with a CH_4 volume fraction of 50% with the balance assumed to be CO_2.

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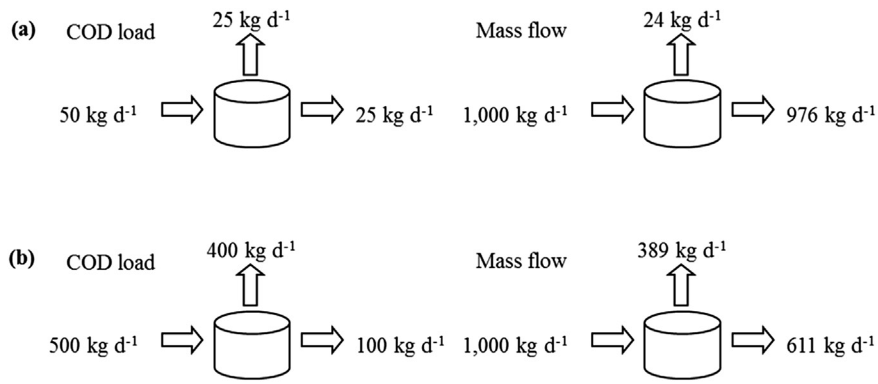

Fig. 1 – Digester's balance of COD load and mass flow including water vapor for waste sludge (a) and for grass silage (b).

- COD of CH_4 is 4 kg kg^{-1}, and the density or ρ_{CH_4} is 0.717 kg m^{-3} at STP (273 K and 101 kPa).
- COD of CO_2 is 0 kg kg^{-1} and ρ_{CO_2} is 1.977 kg m^{-3}.

The gaseous mass flow is quantified by the following equation:

$$m_{biogas} = m_{CH_4} + m_{CO_2} = \frac{\text{COD load}}{\text{COD}_{CH_4}} \cdot \left(1 + \frac{\varrho_{CO_2}}{\varrho_{CH_4}}\right) = 24 \text{ kg d}^{-1} \quad (1)$$

Additionally, the biogas is usually saturated with water vapor and under mesophilic conditions (38 °C) 0.046 kg water per m^3 of produced biogas will be lost as moisture, too. This accounts to a total moisture loss of additional 0.8 kg. However, in this case (Fig. 1a), anaerobic degradation of the sludge reduced the mass flow and hence, the reference mass value by approximately 2.4%. This difference can easily be neglected. However, if a substrate having a higher energy density and a better degradability is chosen, at the same organic loading rate, the retention time in the reactor increases due to mass lost via produced biogas.

To exemplify this second case, the assumption is now made that the digester is fed with grass silage. In addition to the information provided above, the following assumptions are made for grass silage [2]:

- COD concentration of the grass silage is 0.5 kg kg^{-1}.
- 80% of the COD (400 kg d^{-1}) is converted to biogas.

The mass flow of escaping biogas is again calculated with Eq. (1) and accounts to 376 kg d^{-1}.

From this second case (Fig. 1b) it becomes quite clear that the gaseous mass flow of approximately 38% of the total input mass can no longer be neglected. The above mentioned moisture loss rate (0.046 kg water per m^3 of biogas under mesophilic conditions of 38 °C) carries much more weight in this case (13 kg of water loss) due to the significantly higher gas production and decreases further the effluent flow. The reference value in the effluent is thereby reduced to 61% (or even more at thermophilic conditions) of its influent value. As a result, if only the influent and effluent concentrations are compared, there is a significant underestimation of the degradation rate. This difference between incoming biomass and outgoing effluent must be considered when forming mass or energy balances (e.g. for modeling purpose). The simplification that incoming and outgoing mass is approximately equal, which is assumed for instance in the original Anaerobic Digestion Model No. 1 (ADM1, [3]) for the treatment of waste sludges, is not applicable for biomasses with high energy density. A correction of the effluent flow by subtraction of the mass of formed biogas is necessary to guarantee a consistent balance.

The effect is intensified the more the reference value is subjected to change during degradation. The most prominent example is the widely-used concentration of volatile solids (VS), which is related to the mass of total solids (TS) and is expressed as kg kg^{-1} or just % TS (Fig. 2). It is obvious that due to the degradation of organic matter, the total amount of volatile solids is reduced. However, in the same time the reference value (total solids) is reduced in a similar fashion.

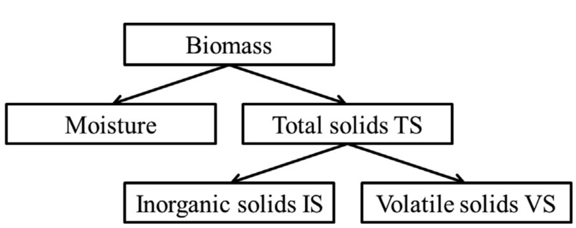

Fig. 2 – General fractionation of any biomass.

Table 1 – Applications of the presented equation for volatile solids removal in the literature so far.

Application	Reference
Mono-fermentation of grass silage	[4]
Anaerobic digestion of sewage sludge	[5]
Co-digestion of sewage sludge and food waste	[6]
Degradation of extracellular polymeric substances	[7]
Anaerobic digestion of dewatered sewage sludge	[8]
High-solid anaerobic digestion of sludge	[9]
Biodegradation of polyacrylamide	[10]
Anaerobic digestion of food waste	[11]
Anaerobic digestion of sewage sludge	[12]
Mono-fermentation of chicken manure	[13]
Mono-fermentation of maize silage	[14]