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Anaerobic degradation of 2-propanol: Laboratory and pilot-scale studies

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HIGHLIGHTS

- The anaerobic degradation of 2-propanol was successfully scaled-up to a pilot-EGSB.
- 2-propanol up to 25 g COD L^{-1} did not inhibit ethanol degradation.
- After a short lag, brewery sludge degraded 2-propanol at 0.29 kg COD kg-VS^{-1} d^{-1}.
- Sudden rise in 2-propanol load delayed solvent consumption over methane production.
- 20 °C is recommended as the minimum temperature for 2-propanol anaerobic degraders.

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ABSTRACT

The anaerobic degradation of 2-propanol, an important industrial solvent, was scaled-up from batch assays to a pilot expanded granular sludge bed (EGSB) reactor at 25 °C. Batch studies indicated that 2-propanol followed Haldane kinetics, with a maximum rate at 10 g COD L^{-1}. Concentrations as high as 25 g COD L^{-1} did not inhibit the degradation of ethanol, a common co-solvent. Similar specific methanogenic activities (SMA) were obtained for water-solvent and water-brewery sludges (88 and 77 ml CH_4 g-VS^{-1} d^{-1} at 5 g COD L^{-1}). Continuous degradation showed a lag-phase of three weeks with water-brewery sludge. Increases in 2-propanol load from 0.05 to 0.18 kg COD kg-VS^{-1} d^{-1} caused a shift from the consumption of soluble matter to methane production, indicating polyhydroxybutyrates (PHB) accumulation. Conversely, smooth increases of up to 0.29 kg COD kg-VS^{-1} d^{-1} allowed 2-propanol degradation without PHB accumulation. The slowdown rate of 2-propanol-oxidizer and acetate-utilizing methanogen bacteria below 20 °C adversely impacted both removal and CH_4 yield.

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1. Introduction

2-propanol is widely used as a solvent in many different chemical industries, such as rubber, cosmetics, textiles, surface coatings, inks and pesticide formulations, with worldwide manufacturing exceeding 1x10^6 tons per year. As with other organic solvents, the main environmental concern is related to the release into the atmosphere of volatile organic compounds (VOCs) during its industrial use. More investigation of technologies for VOC control is required since the abatement of VOCs is a key factor in the protection of the environment and of public health (European Union, 2010). Biological abatement of 2-propanol in industrial emissions has already been demonstrated as a successful method, using aerobic conditions for the treatment, such as a biotrickling filter (San-Valero et al., 2014; Pérez et al., 2013). Recently, anaerobic bioscrubbering was shown to be a promising alternative for the treatment of air emissions containing VOCs of high solubility in water, such as for example in food packaging printing, which is a growing sector of economic importance in the EU. In this process, VOCs in the air are first scrubbed with water and then degraded anaerobically in an EGSB reactor, thus recycling dilute organic waste gases into bioenergy (Waalkens et al., 2015). The anaerobic bioscrubber successfully treated air emissions from the evaporation of ink in the printing press of a flexographic facility. An industrial prototype was used for the removal of emissions containing ethanol (60–65%), ethyl acetate (20–25%) and 1-ethoxy-2-propanol (10–15%) as the main VOCs, reporting removal efficiencies (REs) of 93 ± 5% in the EGSB, obtained at 25.1 ± 3.2 °C and with a methane yield of 0.32 Nm^3 CH_4 kg COD removed^{-1} (Bravo et al., 2017). In order to expand the applicability of this VOC abatement technology,

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Nomenclature

AMPTS	Automatic Methane Potential Test System
BMP	Biochemical Methane Potential
COD	chemical oxygen demand
CSTR	continuous stirred tank reactor
EGSB	expanded granular sludge bed
HRT	hydraulic retention time
IC	internal circulation
OLR	organic loading rate
PHB	polyhydroxybutyrates
RE	removal efficiency
S-B1	sludge from an IC reactor treating brewery wastewater (The Netherlands)
S-B2	sludge from an IC reactor treating brewery wastewater (Spain)
S-FP	sludge from a pilot-scale EGSB reactor treating package printing effluents
SLR	sludge loading rate
SMA	specific methanogenic activity
TS	total solids
VFA	volatile fatty acid
VOC	volatile organic compound
VS	volatile solids

since 2-propanol is also used as the main bulk solvent of ink formulations in flexography instead of ethanol, its anaerobic degradation must be investigated.

The anaerobic degradation of 2-propanol has rarely been studied in the past. Moreover, the literature shows variations in the reported inhibition/biodegradable levels. This can mostly be explained by the complexity of the anaerobic digestion process, with phenomena such as acclimation that significantly impacts on the inhibition of organic compounds (Chen et al., 2008). The data in the literature mainly refers to batch assays. For example, Chou et al. (1978a) found that the addition of 2-propanol up to 4 g COD L^{-1} did not inhibit methane production by using acetate as the reference substrate and an enriched culture of methane bacteria not previously acclimated at 35 °C. In contrast, another author found that 2-propanol is inhibitory for methanogenic bacteria with a reported tolerance of 0.2 M at 36 °C (Widdel, 1986). A recent study by Ince et al. (2011) shows also an inhibitory effect on the acetoclastic methane production pathway by using acetate as substrate working at 37 °C. Degradation of acetate was inhibited with an initial exposure to 0.1 M of 2-propanol. Repeated exposures resulted in higher inhibitions. Regarding the continuous anaerobic degradation of 2-propanol, only one study treating a mixture of organic solvents was found. Henry et al. (1996) operated a 20 L anaerobic hybrid reactor with a non-enriched culture treating a mixture of methanol, ethanol, propionate, butyrate, ethyl acetate and 2-propanol. The process was able to successfully remove a total organic loading rate (OLR) of up to 4 g COD L^{-1} d^{-1} at 35 °C, with a 2-propanol concentration fed to the reactor of 0.5 g L^{-1}. A more systematic study of the anaerobic biodegradability of 2-propanol is required, especially under sub-optimal mesophilic and psychrophilic conditions.

The main objective of this study was to investigate the degradation of 2-propanol with granular sludge systems at ambient temperature, in order to expand the applicability of the anaerobic bioscrubber technology to industries which use 2-propanol as the main solvent. Therefore, the biodegradability of 2-propanol was first evaluated in batch assays, including the influence of the granular sludge (water-brewery and water-solvent cultures). Additionally, the potential inhibition of 2-propanol on the degradation of ethanol was assessed, since it is usual to find the common use of both solvents in the chemical industry. Based on the batch results, the continuous degradation of 2-propanol was assessed at laboratory scale using a culture coming from an anaerobic reactor treating brewery wastewaters (water-brewery culture), in order to determine the OLR that can be efficiently treated and to evaluate the acclimation time. Finally, the influence of these two key parameters (OLR and acclimation time) in the performance of the process was evaluated using an industrial prototype of EGSB seeded with a water-brewery culture. To the best of our knowledge, there are no previous reported data for an anaerobic pilot-scale bioreactor using 2-propanol as the main carbon source. Thus, this study is expected to provide guidelines for the start-up and operation of anaerobic reactors treating industrial wastewater containing 2-propanol.

2. Materials and methods

2.1. Sources of granular sludge

Anaerobic granular sludges from different pilot- or full-scale anaerobic bioreactors working at sub-optimal mesophilic temperatures were used in this study. The characteristics of the sludge are shown in Table 1. S-FP sludge was obtained from a pilot-scale EGSB treating package printing effluents (Altacel B.V., Weesp, the Netherlands), with a yearly average water temperature of 22 °C. This reactor had been treating wastewaters containing solvents from the scrubbing of the VOC air emissions of the facility for more than a year. The main substances in the wastewater were 1-ethoxy-2-propanol (62 ± 12%), ethanol (26 ± 14%), 2-propanol (8 ± 4%) and 1-methoxy-2-propanol (6 ± 2%). S-B1 sludge was obtained from a full-scale internal circulation (IC) reactor treating brewery wastewater (Heineken, Zoeterwoude, the Netherlands), working at 26 °C. S-B2 sludge was obtained from a full-scale IC reactor also treating brewery wastewater (Font Salem, El Puig, Spain), operating between 22 °C and 32 °C. The sludges from the breweries (S-B1 and S-B2) were not exposed to 2-propanol prior to their use in this work. The three types of sludge had similar total solids (TS) and volatile solids (VS) content; however, S-B1 had a larger granule size and higher sulfur content than the other two.

2.2. Batch bioassays

Biochemical Methane Potential (BMP) assays were developed for determining the anaerobic degradability of compounds, allowing the testing of the substrate in controlled and optimal conditions in a laboratory environment. Therefore, BMP assays were used to determine the ultimate methane production, specific methanogenic activity (SMA) and lag phase for the degradation of 2-propanol under specifically chosen conditions. For this purpose, 4.23 g VS L^{-1} of granular sludge were added to serum bottles (500 mL) containing a basal medium and supplemented with ethanol (95%–96% v v^{-1}, VWR) at 0.8 or 1.6 g chemical oxygen demand (COD) L^{-1}, used as a control, and with 2-propanol (99.5% v v^{-1}, Sigma Aldrich) at several concentrations. N, P, K and S were added to give a ratio of 200 g COD/g N, 600 g COD/g P, 313 g COD/g K and

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