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Kinetic study of two-step mesophilic anaerobic-aerobic waste sludge digestion: Focus on biopolymer fate

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ABSTRACT

Kinetics of the sequential anaerobic–aerobic digestion operated under mesophilic conditions on waste activated sludge of a full-scale wastewater treatment plant was investigated. Special focus was given to the fate of proteins and carbohydrates, given the influence of biopolymers on dewatering properties of the sludge. Kinetic tests were performed to characterize the suspended solid degradation and the trend of biopolymers in both digestion steps. Volatile solid degradation rates were 0.93 and 0.52 kg_{VS} m^{-3} d^{-1} in anaerobic and aerobic conditions, respectively. Different models (1st order, Michaelis-Menten, Valentini and Contois) have been compared for VS degradation: Contois equation provided the best data fitting (correlation coefficients $\geq$0.99). Evolution of biopolymers during two-step process exhibited a similar pattern: during the anaerobic phase, an increase of about one order of magnitude was observed for carbohydrates and of 100% for proteins, while in the aerobic bioreactor both decreased of 29 and 73%, respectively. Data from kinetic tests were employed to model the biopolymer patterns taking into account their production from the hydrolysis of particulate organic substrate and their biodegradation in the different anaerobic and aerobic reaction environments. Michaelis-Menten equation gave satisfactory predictions of the biopolymer fate with correlation coefficients ranging from 0.92 to 0.97, for both carbohydrates and proteins.

1. Introduction

Sludge digestion, both anaerobic and aerobic, are complex microbiological processes involving mixed cultures biodegrading organic matter, mainly in particulate form, thus both chemical and biological aspects have to be taken into account in predicting their evolution. During anaerobic digestion, different groups of microorganisms cooperate to convert organic material into energy in the form of methane via chain reactions involving hydrolysis, acidogenesis, acetogenesis and methanogenesis (Batstone et al., 2002a). These steps are interdependent and the performance of each step affects the next one (Shana et al., 2013). However, the hydrolytic process of particulate organic matter is widely considered as the rate-limiting step of the overall process, therefore the hydrolysis still remains the best investigated and characterized process of the chain (Vavilin et al., 2008). In the specific case of waste sludge, mainly constituted by cellular material, the first digestion step involves the cell membrane rupture (cellular lysis) with the consequent release of intracellular material in colloidal form constituted by biopolymers, i.e. lipids, proteins, carbohydrates and nucleic acids. The major organic constituents of sewage sludge are carbohydrates and proteins, which according to Jimenez et al. (2013), account on approximately 70% of VS. Biopolymers are hydrolysed by extracellular enzymes, and then converted, via volatile acids, to biogas, but depending on the operating conditions of the digester, the conversion can be incomplete with consequent residual presence of biopolymers in the digestate (Shana et al., 2013). In addition, the liquid phase of digestate is also rich of ammonia nitrogen produced by the hydrolysis process and not completely utilized for the anabolic phase of the biomass growth in anaerobic conditions (Zupancic and Ros, 2008).

Biopolymers (in particular proteins and carbohydrates) strongly affect the feasibility and costs of sludge treatment and disposal, and their key role has been extensively investigated and demonstrated (Novak et al., 2003; Wang et al., 2006). In fact, residual biopolymers in the digested sludge have a strong negative effect on the dewaterability properties, so determining an increase of the polymer conditioning demand. This was well highlighted in a study of Novak and Park (2004) observing a direct correlation between the concentration of biopolymers in solution and the polymer-conditioning dose both for anaerobic and aerobic digestion.

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Several studies have suggested the sequential anaerobic-aerobic digestion process as an effective alternative for enhancing performance of the conventional single-stage digestion of sewage sludge (Novak et al., 2011; Tomei et al., 2011a). Kumar et al. (2006) illustrated the main benefit of the sequential approach: anaerobic or aerobic reaction environments are able to provide optimal biodegradability conditions for different volatile solid (VS) sludge fractions and different micropollutants, resulting in a complementary beneficial effect of the sequential digestion. This feature allows achieving a consistent reduction of the solid fraction and, at the same time, improving the "quality" of the produced sludge. In the sequential digestion, the post-aerobic stage following the anaerobic one provides, besides the additional removal of VS, a beneficial effect on the digested sludge dewaterability given the more effective removal of biopolymers as reported in several previous studies (Tomei et al., 2011a; Tomei and Carozza, 2015). An alternative configuration of the sequential digestion is the operation of the aerobic digester under alternate aeration conditions, thus achieving not only the nitrification, but also the complete nitrogen removal through a simultaneous nitrification-denitrification process (Parravicini et al., 2008; Tomei et al., 2016a). Moreover, Tomei et al. (2016b) reported that the increase of the aerobic temperature from 20° to 37 °C enhanced the removal of the volatile solid and the nitrification and denitrification kinetics, and, at the same time, improved the dewaterability properties and reduced the content of microbial indicators in the digestate.

Previous studies on modelling of the sequential digestion process were focused on VS degradation (Tomei et al., 2011b) and on the nitrogen fate (Morras et al., 2014; Tomei et al., 2016a), when intermittent aeration was applied to the post-aerobic treatment unit. Concerning the biopolymer fate, to the best of our knowledge, a kinetic model of carbohydrate and protein evolution has been proposed only for the anaerobic digestion of sewage sludge (Christ et al., 2000).

Therefore, the main objective of this study was to investigate the fate of carbohydrates and proteins in the sequential anaerobic-aerobic digestion of waste sludge and to characterize the kinetics of their biodegradation in both anaerobic and aerobic environments. In addition, a model of biopolymer release and consumption in combination with VS degradation has been formulated as a tool to evaluate the applicability of the sequential anaerobic-aerobic sludge digestion. Experimental data of kinetic tests on real waste sludge performed at the previously defined (Tomei et al., 2016b) optimal operating conditions (i.e. intermittent aeration and aerobic mesophilic temperature) were employed for the calibration and validation of the proposed kinetic models.

2. Materials and methods

2.1. Experimental apparatus and kinetic tests

Kinetic tests were carried out in two lab-scale anaerobic and aerobic bioreactors (volume 7.4L) operated as sequencing batch reactors (SBRs): reaction time lasted 24 h for both anaerobic and aerobic units, while feeding and discharging operations, performed manually, were practically instantaneous. Anaerobic digestate was taken at the end of the anaerobic reaction phase under mixed conditions, and fed to the aerobic digester. Applied organic load rates (OLRs) were in the ranges of 1.5–1.9 $kg_{VS}\ m^{-3}\ day^{-1}$. Sludge Retention Time (SRT) was controlled at 15 and 12 d for anaerobic and aerobic reactor, respectively. Being the bioreactors operated without settling, the SRT is equivalent to Hydraulic Retention Time (HRT).

The anaerobic bioreactor (work volume 7 L) was fed once per day (flow rate 0.47 Ld^{-1}, exchange ratio ($V_{fed}/V_{reactor}$) 0.07) with secondary sludge collected from the oxidation tank of the Rome North (Italy) wastewater treatment plant (WWTP). Before feeding the anaerobic reactor, the sludge was thickened for 18–24 h to reach the established VS loads. An equivalent volume of digested sludge was extracted daily from the bioreactor and fed to the aerobic reactor (work volume 4.5 L, flow rate 0.37 $L\ d^{-1}$, exchange ratio 0.08).

The aerobic bioreactor was operated under intermittent aeration cycles (40 min on and 20 min off) by supplying air with a compressor and controlling dissolved oxygen at a set point value $\geq 3\ mg\ L^{-1}$.

The two reactors were equipped with mechanical stirrers fitted with helicoidal blades; their temperature was controlled at 37 ± 0.5 °C by a thermostatic bath. pH was regularly monitored to verify that values around neutrality (i.e. 7.2–7.8 for both reactors) were maintained and when necessary, pH has been corrected by addition of an alkaline solution of NaOH (5 M).

Anaerobic reactor was inoculated with a biomass originated from the full-scale anaerobic sludge digester of the Treviso WWTP (Italy) while the aerobic inoculum was taken from the aerobic tank of the Rome North WWTP (Italy). Additional information on the WWTP and experimental apparatus are given elsewhere (Tomei et al., 2016b).

Samples of the influent and the effluent of the two digesters were analysed daily for TS and VS, while soluble COD (COD_{sol}) and biopolymers (carbohydrates and proteins) measurements were performed twice a week. These data were part of an experimental campaign aimed to investigate the sequential anaerobic-aerobic digestion of sewage sludge under different operating conditions, e.g. temperature and SRT, whose results are extensively reported in Tomei et al. (2016b).

When stable performance was reached for both reactors, batch kinetic tests were performed. According to Kim and Novak (2011) it has been assumed that stable performance was associated to stable VS removal efficiency (characterized by standard deviation (SD) < 10% vs. time). As additional criterion to ensure the presence of stable conditions, bioreactors were operated for at least 3 times the SRT before conducting the kinetic tests. For each bioreactor, after the feeding phase, periodic samples were collected during the reaction phase (at time 2, 10 and 24 h from the beginning of the test) and analysed for TS and VS concentrations. Moreover, a more frequent sampling for soluble carbohydrates and proteins determination, was carried out at time intervals of around 1 h during the first 10 h of the test and then at the end of the working cycle (i.e. after 24 h). Capillary suction time (CST) was measured in the feed and in the digestates at the end of each test. Biogas production was monitored during the kinetic tests, and methane fraction of biogas was also measured at least once for each test. Table 1 shows the operating conditions of the kinetic tests and specifies their utilization in the calibration and validation phases.

2.2. Analysis

VS, TS, $N—NH_3$, $N—NO_2$ and $N—NO_3$ concentrations were determined according to Standard Methods (APHA, 2012); COD_{sol} was measured on samples centrifuged (10 min at 4000 rpm) and filtered at 0.45 μm, by using Cell Tests (MERCK-referring to EPA 410.4 method), based on potassium dichromate oxidation and spectrophotometric determination (Spectroquant Nova30).

Soluble proteins were measured on centrifuged and filtered samples according to the Bradford assay (Bradford, 1976), by using standard solutions of bovine serum albumin (whitin the range of 10–125 $mg\ L^{-1}$). Concentration was determined through absorbance readings (Spectrophotometer Perkin Elmer UV/VIS Lambda 25) at a wavelength of 595 nm.