Journal of Cleaner Production xxx (2016) 1–8

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Minimization of municipal sewage sludge by means of a thermophilic membrane bioreactor with intermittent aeration

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ARTICLE INFO

Article history:
Received 29 September 2016
Received in revised form
19 December 2016
Accepted 19 December 2016
Available online xxx

Keywords:
Intermittent aeration
Membrane biological reactor
Sludge minimization
Thermophilic biological treatment
Ultrafiltration

ABSTRACT

The increase of sewage sludge production together with the high treatment and disposal costs in the last years has pushed to study different solutions aimed at sludge minimization. In this paper, the thermophilic membrane technology was evaluated as an alternative for municipal sewage sludge reduction. The experimentation (carried out by means of a pilot scale plant, 1 m^3 volume) was divided into two steps: the first one was aimed at confirming the results obtained in a previous research focused on industrial sludge treatment; the second step was devoted to define the best process conditions (in particular the optimization of the aeration phases) and to the chemical permeate characterization. The results of the experiments highlight that the hydraulic retention time (HRT) and aeration conditions play a crucial role on the overall process performance. The volatile suspended solids removal efficiency was greater than 80% under the following conditions: HRT even lower than 15 d; 2 h of aeration - 6 h of non aeration cycles; and organic loading rate of 2.0 kgCOD m^{-3} d^{-1}. The permeate showed a good biodegradability under mesophilic conditions thus being treatable by means of conventional biological processes. Moreover, ammonia (the permeate presenting high concentrations) could be recovered as a fertilizer (stripping and subsequent washing of the exhausted gas is an established technique). Finally, the ammonia-free permeate can be valorised as a carbon source in denitrification processes.

1. Introduction

The sewage sludge produced by conventional activated sludge (CAS) wastewater treatment plants (WWTPs) is characterized by a high organic content and the presence of heavy metals, organic contaminants and/or pathogens, depending on the nature of the treated wastewater and on the process conditions.

In Europe, the yearly production of sewage sludge is estimated at 10.13 million tons of dry matter (Collivignarelli et al., 2015a) and it is expected to reach the amount of 13 million tons (Kelessidis and Stasinakis, 2012) by 2020. Moreover, the sludge treatment and disposal costs can be equal to 50–60% of the total operating costs of a WWTP (Campos et al., 2009).

Nowadays, several sewage sludge reuse options (e.g. for agricultural application, as substrate in constructed wetlands, in cement production, for ceramic making, ….) have been identified and investigated in the scientific literature (Ahmad et al., 2016). However, the chemical-physical-microbiological properties of the sludge can restrict its chances of reuse. Thus, minimization is anyway an interesting solution.

Many WWTPs are equipped with a specific biological treatment stage aimed at stabilizing the sludge and reducing its production. Among these treatments, anaerobic digestion is widely used (Pérez-Elvira et al., 2006; Tyagi and Lo, 2013), with the valuable opportunity to recover energy from biogas and, possibly, nutrients (especially phosphate) from the supernatant by means of chemical precipitation (Huang et al., 2015). However, during the years, many alternative solutions for sludge minimization have been studied. Interesting technologies placed in the water line seem to be: chemical oxidation, especially with ozone (Zhang et al., 2009), for the promotion of lysis-cryptic growth of biomass; oxic-settling-anaerobic process (OSA) (Demir and Filibeli, 2016); membrane bioreactor (MBR), especially in thermophilic conditions (Collivignarelli et al., 2014; 2015b). Moreover, the most important technologies applied in the sludge line are physical and chemical

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http://dx.doi.org/10.1016/j.jclepro.2016.12.101
0959-6526/

Please cite this article in press as: Collivignarelli, M.C., et al., Minimization of municipal sewage sludge by means of a thermophilic membrane bioreactor with intermittent aeration, Journal of Cleaner Production (2016), http://dx.doi.org/10.1016/j.jclepro.2016.12.101

pre-treatments for improving sludge hydrolysis (Carrère et al., 2010) and thus anaerobic degradability. Among sludge final treatment alternatives, the following can be mentioned: wet oxidation (Menoni and Bertanza, 2016), and sludge-to-energy technologies, such as incineration (Panepinto et al., 2016) with the possibility of phosphorus recovery from ashes (Li et al., 2017), gasification and pyrolysis (Samolada and Zabaniotou, 2014); furthermore, a promising technology seems to be sewage sludge drying (in a specific solar greenhouse) with the use of heat from OFMSW (organic fraction from municipal solid waste) composting (Rada et al., 2014).

In a previous experimentation (Collivignarelli et al., 2015c), the authors evaluated the treatability of thickened sewage sludge (coming from an industrial WWTP) by means of a thermophilic membrane bioreactor process, operating with intermittent aeration cycles. In this process, the reduction of volatile solids (VS) in the sludge is obtained through cellular lysis, promoted by the thermophilic condition and enhanced by the intermittent aeration; the alternation of aerobic and anaerobic conditions involves the activation of an uncoupled metabolism (Wei et al., 2003). The hydrolization of the fed sludge, leading to an increase of soluble COD, produces fresh organic substrate available for the thermophilic biomass. Moreover, the exothermic oxidation of this substrate releases an amount of heat which ensures autothermal conditions. In short, the results obtained by Collivignarelli et al. (2015c) demonstrate the possibility to obtain a strong sludge stabilization (the VS/TS ratio was reduced from 70% down to 45%), the reduction of VS and COD being 64% and 57%, respectively, with hydraulic retention time (HRT) of 20 d.

In the present paper, a municipal sewage sludge, instead of an industrial one, was submitted to the same treatment, in order to confirm the results obtained in the previous research. Moreover, experimental tests were finalized at the optimization of process conditions (in particular efforts were focused on the optimization of the aeration phases). Finally, the characteristics and possible recovery/disposal options of the liquid residue were investigated. The experimentation was divided into two periods. During the first one (duration 125 d) the same aeration pattern adopted in Collivignarelli et al. (2015c) was followed. In the second period (duration 300 d) the optimization of process conditions and the characterization of the permeate, in view of its final destination, were investigated.

2. Materials and methods

2.1. Pilot plant description

The experimentation was carried out in a thermophilic MBR pilot plant (volume = 1 m^3) that works with alternate aeration (with pure oxygen)/non aeration cycles. The plant configuration and the geometrical characteristics of the pilot plant are the same as those described in Collivignarelli et al. (2015c): in particular, the ultrafiltration section consists of a vessel with 7 ceramic membranes (23 channels each, cut-off 300 kDa and pore size 10 nm). During the experimentation (between Period 1 and Period 2), the pilot plant was modified. In effect, the oxygen supply system (4 porous plate placed on the floor of the tank) was replaced with a Venturi-type device for the direct injection of pure oxygen in the recirculation line of the mixed liquor. This modification was set up in order to reduce the oxygen consumption (the mass transfer efficiency was improved by adopting this system, which is also installed in the real plant described by Collivignarelli et al., 2015d). Finally, in order to limit the foam accumulation on the water surface, a mechanical device was installed: the factors affecting foam formation have been investigated by Collivignarelli et al. (2016). Fig. 1 shows the pilot plant scheme before and after adopting these modifications, respectively.

2.2. Experimental plan and management strategies of the pilot plant

The pilot plant was fed with a thickened sludge taken from a municipal WWTP (10,000 people equivalent – PE – pre-denitrification configuration, no separate sludge stabilization). The average characteristics of the thickened sludge are summarized in Table 1.

The experimentation was divided into two periods. During the first one (Period 1) the pilot plant was conducted adopting the same aeration strategy described in Collivignarelli et al. (2015c): the aeration/non aeration phases were alternated every 4 h. This period was subdivided into three sub-periods (A, B and C) during which the feeding flow rate (Q_{in}) was varied in order to investigate the influence of the HRT. The extraction of excess sludge (Q_{purge}) was regulated with a flow rate equal to 0.1 Q_{in}. The feeding was provided at the beginning of the first non aeration phase of the morning, while the permeate was extracted the subsequent day, just before the feeding.

Between Periods 1 and 2, the pilot plant was modified as shown in Fig. 1. During Period 2, the aeration/non aeration cycles were varied so as to assess the effect on process performance. In particular, we focused on the following aspects: VS and COD removal yields, biodegradability and distribution of nitrogen forms in the effluent (permeate). Period 2 was divided into four sub-periods (D, E, F and G), each one characterized by a specific aeration pattern: a progressive increase of the duration of the non aeration phase was adopted. Moreover, in this period, Q_{purge} was reduced with respect to Period 1. The extraction of mixed liquor occurred essentially during the cleaning of the pre-filters; losses were also due to sludge foaming. Finally, during sub-period E and subsequent periods, the feeding was provided at the beginning of each non aeration phase, the permeate being continuously extracted.

For both the experimental periods, the operative temperature (55 °C), the oxygen flow rate (0.5 m^3 h^{-1}), the inflow oxygen pressure (2 bar), and the dissolved oxygen (DO) thresholds for the automatic supply were kept constant.

The detailed operative conditions of each experimental period and sub-period are summarized in Table 2.

2.3. Monitoring plan and analytical methods

The influent sludge was sampled weekly, all along the experimentation, while the mixed liquor and the permeate (effluent) were drawn daily. On these samples, the concentrations of COD, total nitrogen (TN), total solids (TS) and VS, along with pH, were measured. In addition, the distribution of nitrogen forms (NH_4^+-N, NO_3^--N, NO_2^--N and organic nitrogen) was determined in the permeate. All analyses were performed according to the official methods (APAT and IRSA-CNR, 2003; IRSA-CNR, 1984; APHA, 2012).

Respirometric tests (Oxygen Uptake Rate – OUR and Nitrate Utilization Rate – NUR), under mesophilic conditions (temperature between 20 and 25 °C), were also carried out. The aim of these tests was to evaluate the capacity of a mesophilic biomass to degrade the carbonaceous residue of the permeate, in view of a subsequent treatment in the WWTP that originated the sludge, or in view of the possible reuse as external carbon source in a denitrification process.

OUR tests were performed according to ISO 8192 (2007) standard. These tests were carried out under both endogenous (respiration due to cell maintenance) and exogenous (respiration due to degradation of a substrate) conditions. As for exogenous tests, they were always operated at the same food to mass (F/M) ratio: the