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Increased carboxylate production in high-rate activated A-sludge by forward osmosis thickening

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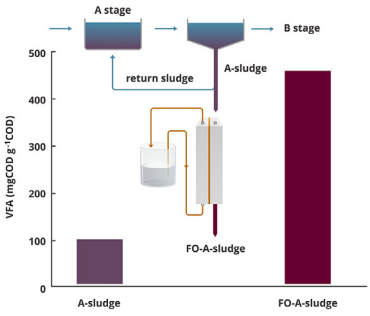
HIGHLIGHTS

- Forward osmosis thickening increases VFA production from sludge fermentation.
- Concentration through FO favorites production of longer chain fatty acids.
- Forward osmosis combined physical and chemical pretreatment increasing the soluble/total COD ratio.

GRAPHICAL ABSTRACT



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ABSTRACT

Domestic wastewater represents a considerable feedstock for organics but the high dilution makes their recovery typically unsuccessful. Here we investigated three routes to 10-fold concentrate the organics using forward osmosis (FO) (Draw solution (DS) 2.2 M $MgCl_2$): directly on domestic wastewater, A-sludge, or secondary sludge, with the end goal of increasing volatile fatty acid (VFA) yield from subsequent 9-day fermentation tests. Forward osmosis concentrated the total COD by a factor of 8.2 ± 1.2, 10.1 ± 2.4 and 4.8 ± 0.2 with respect to the raw streams of wastewater, secondary sludge and A-sludge. The soluble fraction of the COD was concentrated up to 3.5 times in the A-sludge and 2.1 times in the secondary sludge; the result of a combined effect of the chemical action of Mg^{2+} (diffused from the DS) on sludge disaggregation and cell lysis, and the physical action of recirculation and air-scouring of the A-sludge in the FO-unit.

The FO-concentrated A-sludge produced 445 ± 22 mg COD-VFA g^{-1} COD_{fed}, which was 4.4 times higher than for the untreated A-sludge. No VFA were produced from untreated secondary sludge, but after FO-concentration 71 ± 5 mg COD-VFA g^{-1} COD_{fed} could be reached. Due to the low organics in wastewater even after FO-concentration (1.08 ± 0.08 g COD L^{-1}), no notable VFA production occurred. The combination of A-stage technology and membrane technology for dewatering and COD concentration could be a key advancement to increase VFA production from domestic wastewater, whereby at least 45% of the COD can be recovered as valuable VFA.

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1. Introduction

The global domestic wastewater production is estimated at 330 billion m^3 annually [1]. Significant research efforts are focused on the recovery of water and nutrients [2] from this waste stream and particularly in the conversion of the organic fraction into energy as biogas. Recently, an alternative route was developed whereby these organics are converted into volatile fatty acids (VFAs), which are building blocks for a multitude of valuable products such as biopolymers [3], medium or long chain fatty acids [4] and biofuels [5]. However, the generally low organic content of domestic wastewater (<600 mg L^{-1}) hampers efficient recovery, and is one of the main limitations in developing feasible bioproduction platforms [6].

An evident means to concentrate organics is to work via sludge, generated from the wastewater as substrate and separated via settling. The conventional activated sludge (CAS) process is typically performed with high aeration energy, and at solid retention time (SRT) of 8–20 days, resulting in a very efficient organic carbon removal, but yielding a sludge with poor digestion efficiency due to the high sludge age and high sludge oxidation [7,8].

An attractive alternative approach is the "Adsorption-Bioxidation" (AB) process [9]. The AB system is a two-stage treatment system where the first stage (A-stage) is typically operated at low hydraulic retention time (HRT 15–30 min) and low SRT (between 3 hours and 1 day). The soluble and colloidal organic matter is removed in the A-stage through bioflocculation into microbial A-sludge. The A-sludge is also separated in a clarifier, while the effluent is then taken to the subsequent B-stage to ensure polishing of the wastewater [2,9]. A-sludge is usually digested to biogas with high digestion efficiency (higher than that of CAS) due to the remarkably low sludge age and high biodegradability [9,10].

However, due to the poor settling performance of the A-sludge, the COD content is still too diluted to ensure high VFA production [6,11]. A-stage is operated at 2–10 kg BOD kg^{-1} VSS d^{-1} [9] while optimum settling is obtained between 0.3 and 0.6 kg BOD kg^{-1} VSS d^{-1} [12]. CAS systems are typically operated at 0.25 kg BOD kg^{-1} VSS d^{-1} [13], achieving good sludge settling but with a relatively high water content. Thus, a further concentration of both A-sludge and secondary sludge is needed to ensure sufficiently high VFA production for extraction (>5 g L^{-1}) and further valorization into high value products [14,15].

Forward osmosis (FO) is a potentially energy-efficient and low-cost technique for concentration of challenging feed streams such as waste activated sludge (WAS) [16,17] and domestic wastewater [18]. FO is based on the spontaneous process of osmosis, in which water is transported through a semi-permeable membrane from a feed solution (FS) of relatively low solute concentration (low osmotic pressure) to a draw solution (DS) of relatively high solute concentration (high osmotic pressure). The membrane allows for water transport but displays a high rejection of solutes [19]. Draw solutes, such as $MgCl_2$, need to have a low molecular weight, a high diffusivity, produce high osmotic pressures, are well-retained by the FO membrane, are non-toxic and cheap [20]. Concentrating any stream using FO causes an increase in its dissolved solutes content, due to a build-up of rejected solutes from the feed itself as well as the diffusion of solutes from the draw solution into the feed. The latter is referred to as reverse salt diffusion (RSD).

Here, we applied FO to concentrate the organics of domestic wastewater, high-rate activated A-sludge and secondary sludge to undergo a subsequent fermentation for VFA production purposes. FO dewatering fluxes of the different streams were compared. $MgCl_2$ was chosen as draw solute because of the high osmotic pressure generated by these solutions combined with the lower RSD compared to monovalent salts such as NaCl [19]. VFA yields and composition of the concentrated streams were measured and compared to the non-concentrated streams to assess the effect of concentration by FO. The effect of salt leakage during FO was investigated by carrying out fermentation experiments with and without addition of $MgCl_2$.

2. Materials and methods

2.1. Substrate collection

A-sludge was collected from the return flux to the A-tank in Nieuwveer WWTP (Breda, The Netherlands). Domestic secondary sludge and domestic wastewater were collected from Destelbergen WWTP (Destelbergen, Belgium). Characteristics of the substrates are summarized in Table 1. Mixed liquors as collected were used as FO feed. Part of a second batch of A-sludge (7.76 ± 0.16 g COD L^{-1}, 4.41 ± 0.14 g VSS L^{-1}) was stored at 4 °C and gravity-concentrated (removing the liquid volume above the settled sludge – resulting in a concentration of 3.8 times) to carry out fermentation tests to study the effects of RSD.

Table 1
Characteristics of the streams. Analysis were carried out in triplicate.

	Domestic wastewater	Secondary sludge	A-sludge
pH	7.42	7.26	7.15
Conductivity (mS cm^{-1})	1.4	1.3	1.8
Total solids, TS (g L^{-1})	0. 26 ± 0.04	4.89 ± 0.83	6.73 ± 0.59
Volatile solids, VS (g L^{-1})	0.10 ± 0.03	2.83 ± 0.48	5.06 ± 0.62
Volatile solids, VS/TS (%)	38	58	78
Total suspended solids, TSS (g L^{-1})	<0.01	4.01 ± 0.04	5.43 ± 0.52
Volatile suspended solids, VSS (g L^{-1})	<0.01	2.51 ± 0.05	4.22 ± 0.48
Volatile suspended solids, VSS/TSS (%)	-	63	78
Kjeldahl nitrogen, TKN (mg N L^{-1})	9 ± 0	974 ± 15	476 ± 40
Total ammonia nitrogen, TAN (mg N L^{-1})	7 ± 5	56 ± 7	577 ± 20
Total chemical oxygen demand, tCOD (g L^{-1})	0.132 ± 0.016	4.482 ± 0.979	8.398 ± 0.362
Soluble chemical oxygen demand, sCOD (g L^{-1})	0.033 ± 0.003	0.215 ± 0.007	1.252 ± 0.023
Soluble chemical oxygen demand, sCOD/tCOD (%)	25	5	15
Fe (mg L^{-1})	6 ± 0	141 ± 1	271 ± 7
P (mg L^{-1})	463 ± 38	223 ± 1	200 ± 4
S (mg L^{-1})	3111 ± 189	85 ± 9	56 ± 5
K (mg L^{-1})	437 ± 29	47 ± 0	40 ± 2
Na (mg L^{-1})	45 ± 2	85 ± 3	54 ± 2
Ca (mg L^{-1})	387 ± 3	201 ± 7	233 ± 4
Mg (mg L^{-1})	1658 ± 242	37 ± 0	41 ± 1