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Recovery of short-chain organic acids (SCOAs) obtained from anaerobic fermentation process

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ABSTRACT

Short-chain organic acids (SCOAs) are the intermediates in the anaerobic fermentation process, and can be used in food, textile, and pharmaceutical industries to produce different end use products. SCOAs can be separated, purified, and concentrated by different processes, such as distillation, extraction or membrane-based systems. SCOAs production adds more profitable possibilities to an acidic fermentation process by integration these marketable acids as highly concentrated mixtures with other refinery processes. The present study investigated two approaches for recovering of SCOAs: i) the production of clarified SCOAs liquid by microfiltration (MF) and then performing their concentration by reverse osmosis (RO) and ii) the recovery and concentration by the so-called integrated neutralization and acidified reaction method. The results of MF showed that some SCOAs were retained in the retentate together with the solids. However, in the following RO treatment, SCOAs could be successfully concentrated with a yield retention of over 90 % from the SCOAs liquid. In the latter method, a color-free SCOAs liquid was obtained with an increase in the total SCOAs concentration from 23 g/L to 146 g/L.

1. Introduction

In recent years, the formation of various food wastes has been extensively studied. FAO (FAO, 2019) reported that from the annual food production approximately 14 %, corresponding to 400 billion dollars, is wasted between the harvesting and the point before the retail. Another 17 % of food is wasted at the retail and the consumer level (Nairobi, 2021). Although the major task would be to prevent the generation of the food waste from sustainability point of view, once generated it is important to explore it as the raw material for new products, to which they are feasible, due to their high content of carbohydrates, lipids, and proteins. One of promising technologies is to convert them to short-chain organic acids (SCOAs) (also known as volatile fatty acids, VFAs) via anaerobic acidic fermentation. SCOAs are formed during anaerobic digestion (AD) as intermediates and by changing the process conditions, they can be recovered as by-products (cf., (Bartek et al., 2021; Rasi et al., 2022)). These renewable intermediates are needed to replace the fossil resources in extensive industrial production of chemicals and fuels (like alcohols, aldehydes, ketones, esters, olefins, polyhydroxyalkonoates (PHAs), and biodiesel). Compared to the methane formed during AD, SCOAs have higher added value and more versatile utilization possibilities. For example, one ton of food waste treated with AD (for energy) is worth of 76 €, while its value as unrefined caproic acid is 1000 € (refined value 2000–3000 € per ton of food waste) (De Groof et al., 2019). The different application possibilities for SCOAs complicate the evaluation need for their purification and/or concentration methods. For example, using SCOAs as a raw material for other biological processes, the intense purification processes might not be needed. In contrast, using SCOAs for recycling of waste neodymium-iron-boron (NdFeB) magnets (Niskanen et al., 2022), the purification step might play a crucial role. In this study, SCOAs refer to acetic, propionic, butyric, isobutyric, valeric, isovaleric, and caproid acids.

The SCOAs produced via AD contain organic impurities, are diluted, and they usually require further treatment before using for the manufacturing of new products. However, due to their high solubility, challenges have been emerged in the recovery of these acids. Membrane technologies show advantages over the traditional purification and concentration technologies that make them more attractive, efficient, and sustainable (Zhou et al., 2013a; Zhou et al., 2013b; Pervez et al., 2022). Besides the easiness to modify the process variables, control the deposition of particles on the membrane surface by the modification of hydrodynamic conditions, and scaling-up the processes are relatively simple and linear. Microfiltration (MF) can be effectively introduced in

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the production line, since it offers a possibility to produce solid-free acid fraction (Pervez et al., 2022). On the other hand, reverse osmosis (RO) is a feasible technology to produce an acid concentrate, since it is expected that the acids are mostly not passing through the membrane like the clean water phase. Nevertheless, a rotary evaporator (a rotavap) is the device used in chemical laboratories for the efficient and gentle removal of solvents from samples by vacuum evaporation. Due to its optimal extraction and distillation performance, the rotary evaporation process is one of the most widely used methods of solvent evaporation (Miller and Liu, 2017). Additionally, it should be pointed out that a conventional and azeotropic distillation (Pal and Nayak, 2017; Chien et al., 2004) cannot remove effectively water in the process recovering SCOAs from a mixed aqueous solution, which contains approximately 95 % or less of water. Considering a substantially anhydrous mixture of the acids with low concentration may not be also economically separated into its components by simple fractional distillation (Atasoy et al., 2018). For example, the recovery of acetic acid from an acidic fermentation liquor, which contains very low levels of this acid, is economically not very efficient, due to the high non-ideal vapor/liquid equilibrium properties of the acetic acid/water system (Román-Ramírez, 2015). As a result, manufacturers are typically facing low acetic acid yields and extensive treatment costs.

According to challenges on various methods for the recovery of SCOAs (Atasoy et al., 2018), this study aimed at the separation of SCOAs from the anaerobic acid fermentation process feed via using two methods: i) pressure driven membrane techniques and ii) integration of neutralization and acidification reactions-based methods with a rotary evaporator. Firstly, the production of SCOAs was carried out without pH adjustment in the acid fermentation process. In the membrane-based processing, MF was studied for the clarification of the SCOAs liquid, and then RO was used to concentrate the clarified SCOAs liquid. Secondly, in the modified integrated neutralization and acidification method (mainly based on (Edmonds and Krchma, 1931)), SCOAs from mixed aqueous solutions were first converted into their salts, which can be dehydrated without decomposition, and then liberated these salts to free acids together their recovery. Additionally, this study attempted to find out the potential of these methods for the concentration of the organic acids and thereafter to evaluate the processing options to utilize the different SCOAs' concentrate for the various end use possibilities from the market point of view.

2. Materials and methods

2.1. Anaerobic fermentation

An 1 m^3 leach-bed biogas reactor under mesophilic conditions (37 °C) (Pyykkönen et al., 2023) was used for acid fermentation to produce the SCOAs-containing liquid. Municipal biowaste (from Forssa, Finland) was used as raw material. In total, 350 kg of biowaste (33.3 % total solids (TS) and 29.3 % volatile solids (VS)) was used with 18 kg cutter dust. In total, 230 L of percolation liquid was used, of which 90 L was from operational biogas plant, Laukaa, Finland. Rest of the percolation liquid was from the previous pilot scale biogas experiment (Pyykkönen et al., 2023). The circulation of percolation liquid through the biomass was started at the second day of the experiment. Every 6 h 10 L of liquid was spread over the biomass and collected back to the percolation tank from below the biomass. The circulation frequency was increased after 11 days to 10 L in every 4 h and day 15 to 10 L in every 2 h. From day 19 the circulation was 25 L in every 2 h until the end of the experiment (day 28). The high circulation frequency was used to overload the process in a way that the pH decreased unfavorable for methanogens in percolation liquid. After the experiment, the percolation liquid was used as a sample for further processing.

2.2. Pre-treatment of the liquid phase from the acid fermentation

A decanter centrifuge (Laboratory decanter, model MD 60, Lemitech, Germany) was used to pre-treat the original SCOAs liquid containing solids that was obtained from acid fermentation phase. The decanter centrifugation was carried out using a speed of 10,000 rpm, differential speed of 200 rpm, and weir (inner diameter) of 44 mm. The decanted samples were manually filtered through the 125 μm mesh filter to further ensure the reduction of the solids that would foul the membranes. Samples from acid fermentation as well as after pre-treatment, were stored at −20 °C prior to further processing.

2.3. Membrane experiments

MF and RO were carried out using a Labstack M20 plate-and-frame unit (Alfalaval, Denmark). The membrane characteristics are described in Table 1. The unit consists of a feed tank, pump, pressure gauges, membrane module with a hydraulic pump, and a pressure control valve. The MF membrane was MFP2 (Alfalaval, Denmark) with a pore size of 0.2 μm and made of with fluoro polymer a polypropylene support material. This membrane was chosen to further improve the microbiological status of the SCOAs liquid by removing the bacteria present in the feed together with the removal of the solid debris. The RO membrane was RO98pHt (Alfalaval, Denmark), which is a thin film composite polyamide membrane with a polypropylene support material. This RO membrane resisted higher pH and temperature and could be easily cleaned using harsh cleaning conditions when necessary. The active membrane area used for the filtrations was 0.036 m^2.

2.4. MF and RO experiments

As shown in Scheme 1, the digestate liquid from the acid fermentation process was used for clarification in the MF experiments. Before MF, the liquid was decanted and pre-filtered through a 125 μm sieve. The MF experiments were carried out in a batch concentration mode (permeate removed continuously and retentate returned to the tank). The sample was recirculated for 3 min before the permeate flux measurements were started. The permeate fluxes were calculated after every 250 mL of permeate collected. Prior and after each experiment the membranes were washed with alkaline cleaning agent (P3-Ultrasil 110, in a 10 mL/10 L concentration for 30 min) at a pressure of 2 bar and approximately at 30 °C, rinsed, and pure water flux measurements were performed. The cleaning was sufficient if at least 75 % of the original flux value was restored.

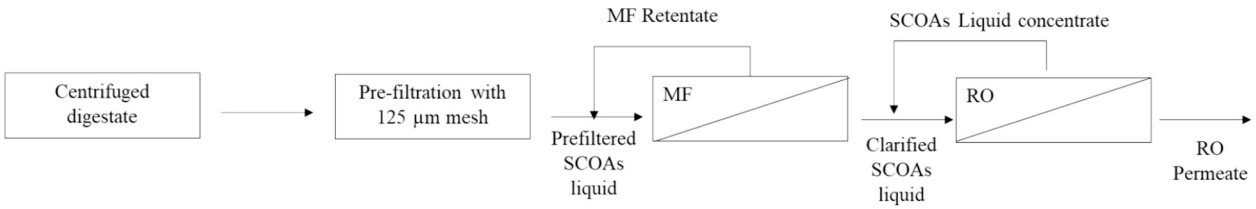
The permeate from MF was collected from two test runs to produce 5 L of clarified acid fraction and was subjected to concentration by the RO process at a pressure of 40 bar in a batch concentration mode. Cleaning and pure water flux measurements were carried out as in the case of MF with the slightly different amount of the cleaning agent and length of the cleaning cycle (50 mL/10 L 1 h, except one run where two washing cycles were needed to recover the pure water fluxes).

Beside the permeate flux, the retention of the individual SCOAs both in MF and RO was evaluated.

Table 1
Characteristics of the membranes used in SCOAs concentration.

Membrane	MFP2	RO98pHt
Manufacturer	AlfaLaval	AlfaLaval
Type	fluoro polymer	thin film composite
Support material	polypropylene	polypropylene
pH range	1–11	2–11
Typical operating pressure (bar)	1–3	15–42
Salt rejection (2000 ppm NaCl, 16 bar, 25 °C)	N.A.*	≥ 98 %
Pore size	0.2 μm	N.A.

N.A. not applicable



Scheme 1. The scheme of the complex membrane techniques with pre-treatments in the concentration of SCOAs liquid.

Retention of the membranes for the different single compounds was calculated using Eq. (1).

$$R = \frac{c_{feed} - c_{permeate}}{c_{feed}} x100\ (\%), \quad (1)$$

where c is the concentration.

The permeate flux was calculated using Eq. (2).

$$J = \frac{\Delta V}{A^{*}\Delta t}, \quad (2)$$

where V is the volume (L), A is the effective membrane area (m^2), and t is the time of filtration (h).

Mass balances were calculated for the different compounds in the MF and RO processes using the corresponding permeate and retentate data.

2.5. Integrated neutralization and acidification reactions method

In accordance with the present process in Scheme 2, a centrifuged digestate (100 *g*) with a pH value of 5.6 was neutralized to pH 6.7 with an alkaline material, such as sodium bicarbonate (Merck, ACS, Reag. Ph Eur). The neutralization reaction is shown in Eq. (3). The resulting solution from the neutralization was evaporated to almost dryness using a rotary vacuum evaporator system (BUCHI Rotavapor R-134). The bath temperature was 70 °C and vacuum 120 mb. The volumes of evaporating and receiving flask were 500 mL and 1 L, respectively. In this stage, the process was stopped, and 95 g of water recovered. The residue, which essentially contained sodium salts of organic acids was treated with concentrated sulfuric acid (95 % *v*/v) in quantities sufficient to obtain a pH value about 3 (according to Eq. (4)). The organic acid mixture was distilled under vacuum for collecting anhydrous SCOAs liquid in the receiving flask. Three replicated measurements were made to check the ability of the method to generate similar results for multiple preparations of the same sample.

$$RCOOH + NaHCO_3 \rightarrow RCOONa + CO_2 + H_2O \quad (3)$$

$$2RCOONa + H_2SO_4 \rightarrow 2RCOOH + Na_2SO_4 \quad (4)$$

2.6. Analytical determinations

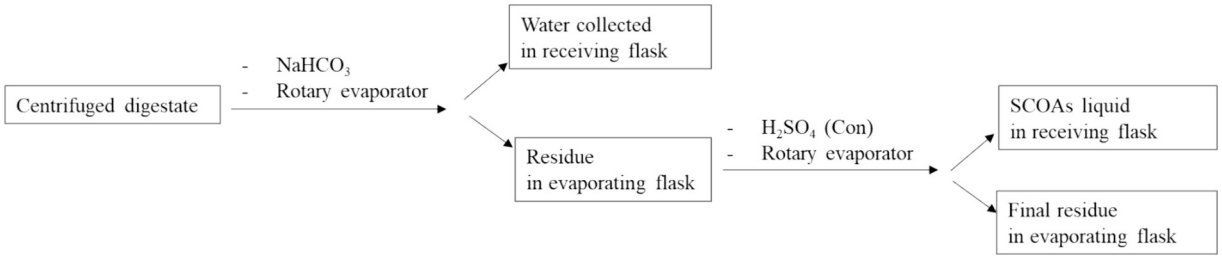
TS and VS were determined according to SFS 3008 (Finnish Standard Association, 1990). Samples for SCOAs analyses were centrifuged (1831 ×*g*, 10 min) and filtered with Chromafil GF/PET-20/25 filters. Concentrations of acetic, propionic, isobutyric, *n*-butyric, isovaleric, valeric, and caproic acids were determined using an HP 6890 gas chromatograph (GC) with an HP 7683 autosampler (Hewlett-Packard, Little Falls, USA) and GC ChemStation Rev. B.03.02 software. The GC was fitted with a 10 m × 0.53 mm i.d. x 1 µm film HP-FFAP capillary column (Agilent Technologies, USA) and a flame ionization detector with helium as a carrier gas (9 mL/min). Oven temperatures were 60–78 °C (25 °C/min), isothermal 1 min, 150 °C (7.5 °C/min), and 25 °C/min to 180 °C with a final time of 3 min. The injector and detector temperatures were 220 °C and 280 °C, respectively.

3. Results and discussion

3.1. Clarification process by MF

For the effective membrane process, there was a need for clarification process that removes the impurities, such as proteins, fibers, and sugars from the SCOAs liquid, because these impurities would cause the membrane to foul (Aktij et al., 2020).The effectiveness of the clarification process was evaluated through the change in the permeate flux. This flux was decreasing over the time, due to the deposits of compounds on the membrane surface or in the membrane pores (Fig. 1). The lowest starting fluxes were 64.43 Lm^{-2} h^{-1} and the highest ones 93.28 Lm^{-2} h^{-1}, but these values dropped until the end of filtration by 28.0 % and 36.5 %, respectively, to the corresponding final values of 46.39 Lm^{-2} h^{-1} and 59.23 Lm^{-2} h^{-1} (Fig. 1). The pH of the solution was not adjusted, and the filtration was done with the native pH of the SCOAs liquid around pH 6. Kim et al. (Kim et al., 2005) reported that permeate flux was high at a pH range of 5.5–7.5, while under strong acidic or base conditions the particles precipitate rapidly on the membrane surface.

Clarification as well as the decrease of the microbiological load of the SCOAs liquid were also studied by Zacharof and Lovitt (Zacharof and Lovitt, 2014), who successfully produced sterile and particle-free acetic and butyric acid solutions using a 0.2 µm membrane. Kim et al. (Kim et al., 2005) used ceramic MF membranes for the filtration of the SCOAs liquid. They concluded that it was a proper method to reduce the microorganism load of the solution, and approximately 80 % of the VFAs were recovered in the permeate. Tao et al. (Tao et al., 2016) evaluated the recovery efficiency of the acids using a modified polyethersulfone MF membrane and could increase the recovery percentage to 90 %, like our results. On the other hand, Jänisch et al. (Jänisch et al., 2019) concluded that ultrafiltration supports the clarification process better than MF, since with MF membranes still some solids remain in the



Scheme 2. Integrated neutralization and acidification reactions method for SCOAs recovery.

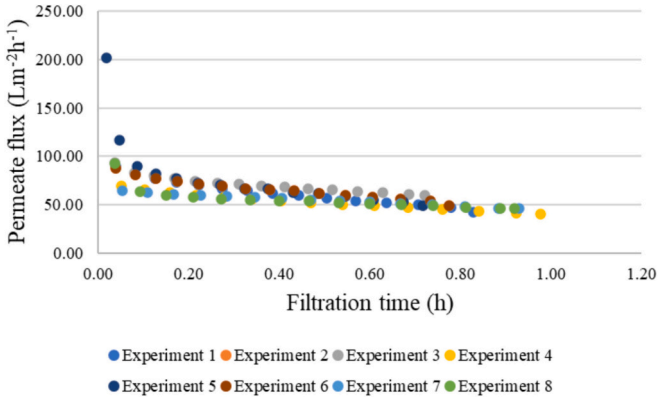


Fig. 1. Permeate fluxes of SCOAs liquid in MF. Different experiments are repeated under the same process conditions. Kim et al. (Kim et al., 2005) modelled the recovery of SCOAs from liquid organic sludge, and reported the flux decline to be attributed mostly to the concentration polarization, i.e., the deposition of the solids on the membrane surface in the MF process. In our research, the cleaning efficiency of the membranes was good; 85.71–100 % of the original water flux was recovered after the washing cycle. Hence, it was expected that the membranes were not irreversibly fouled, but rather concentration polarization played a significant role in the flux decline over the time of the filtration. However, MF resulted in a clarified permeate as it is illustrated in Fig. 2.

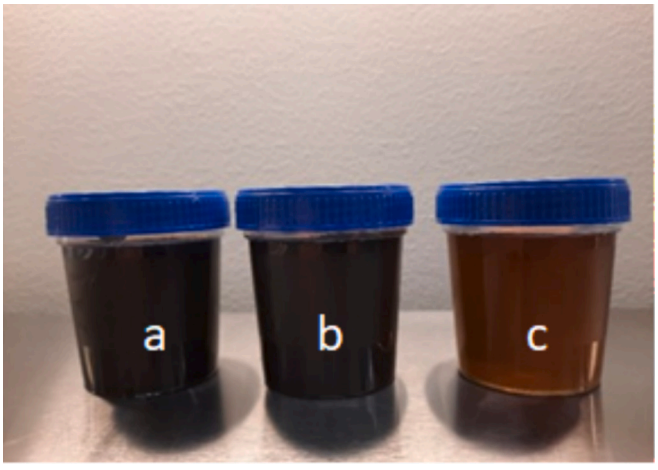


Fig. 2. The visual comparison of MF feed (a), MF retentate (b), and MF permeate (c).

permeate and may cause, due to the possibility of fouling of the membrane, the next step of the production economically unfeasible. In our study, similar turbidity in the MF permeate was not observed as indicated by Jänisch et al. (Jänisch et al., 2019), and hence, it was selected as the first filtration step.

The distribution of the SCOAs was determined from the MF feed, permeate, and retentate. Overall, in the MF experiments, in the feed, the dominant SCOA was caproic acid (8.55 g/L in the feed and 7.75 g/L in the permeate). The second significant acid was acetic acid with a concentration of 6.50 g/L in the feed and 6.05 g/L in the permeate as indicated by the experiment 1. In contrast, the results from the experiment 3 showed that the major acid was caproic acid 7.25 g/L in the feed and 6.65 g/L in the permeate, while the second significant acid was butyric acid (instead of acetic acid) with a concentration of 6.00 g/L and 5.55 g/L in the feed and permeate, respectively.

The retention of the compounds by the membrane showed versatile results in the MF process. The highest retention showed in one MF run was by isovaleric acid, followed by propionic, caproic, acetic, butyric, valeric, and isobutyric acids with values of 25.00 %, 14.28 %, 9.35 %, 6.92 % and 6.89 % and 5.88 % and 0 %, respectively. Hence, these results indicated that not all the organic acids were gone through the MF membrane in use, just as in the case of the results by Tao et al. (Tao et al., 2016).

The example of the mass balance obtained in one MF run is illustrated in Table 2.

The calculations illustrated that the highest loss was observed in the case of caproic acid, followed by acetic acid in the MF process, while isobutyric acid was fully permeated through the MF membrane and recovered in the permeate.

3.2. Concentration process by RO

RO can be used to effectively concentrate SCOAs liquid. In our work, the results were made without the modification of the pH at a pressure of 40 bar, and the samples were recycled for 3 min before the permeate flux was measured.

The results indicated that the flux decline in RO was sharp in the function of the filtration time (Fig. 3). The filtration was continued until approximately 2.5-fold concentration was achieved similarly as that reported by Zhou et al. (Zhou et al., 2013a) when separating acetic acid from monosaccharides.

Zhou et al. (Zhou et al., 2013b) found out that an increase in pH resulted in a dramatic increase of acetic acid retention at different increasing pressures but decreased with an increase in temperature. Also, Ozaki and Li (Ozaki and Li, 2002) came up with the same observation when investigating pH in the range of 3–9, and retention was increased from 34.3 % to 99.7 %. The phenomenon behind this effect was due to the increase in charge repulsion between the membrane and the acetic acid molecules (Atasoy et al., 2018), which became deprotonated, and the membrane surface became more negatively charged along with a pH increase. On the other hand, Zhou et al. (Zhou et al., 2013a) found that the fluxes of two different RO membranes decreased from pH 2.93 to pH 4.87, and thereafter were stable up to the pH 10.

The mass balance of the RO process (Table 3) indicated that the RO membrane was almost selective for all the compounds, and only small amounts of acetic and caproic acids were detected in the permeate after the concentration process. The total loss of acids at the end of the process was 0.01 kg acid. These results suggested that the RO membrane is a good selection for the concentration of the acids in the retentate and is a viable method to reach 2.5-fold reduction in volume.

The retentions of the SCOAs in the RO process were also calculated, and were between 91.80 and 100 % indicating that some acids (i.e., acetic, caproic, and butyric acids) were gone through the membrane.

3.3. Integrated neutralization and acidification reactions method

The earlier works clearly showed the difficulty for the recovery of SCOAs, especially acetic and butyric acids by simple distillation. This was because in aqueous solutions acetic acid forms with water a constant boiling mixture and the affinity of acetic acid for water is sufficiently great to prevent the separation of this acid from the water (Fairbairn and Harpur, 1951). Other studies (Atasoy et al., 2018; Woo and Kim, 2019) reported various methods including solvent extraction with very poor recovery yields, especially for low-carbon-number fatty acids. However, a higher recovery of acetic acid ranged from 40 % to 60 % was obtained in the study with a two-step extraction procedure, in which magnesium sulfate was added until saturation and when acidified with sulfuric acid, followed by ether extraction (Larsson et al., 1984). However, in the presented process acetic acid was concentrated by 13.2 times. Hence, in the first stage, the conversion of the acids into their sodium salts (e.g., sodium acetate and sodium butyrate) made possible to remove 95 g of water. In the second stage, process continued by adding the concentrated sulfuric acid for liberating the volatile organic acids from their fused (dehydrated) salts. Therefore, the separation of

Table 2
Example of mass balances (kg) in the MF process.

	Acetic acid	Propionic acid	Butyric acid	Isobutyric acid	Valeric acid	Isovaleric acid	Caproic acid
MF_{feed}	0.033	0.004	0.022	0.001	0.009	0.002	0.043
$MF_{permeate}$	0.022	0.002	0.015	0.001	0.006	0.001	0.028
$MF_{retentate}$	0.008	0.001	0.005	0.000	0.002	0.000	0.011
Loss	0.003	0.001	0.001	0.000	0.001	0.001	0.004

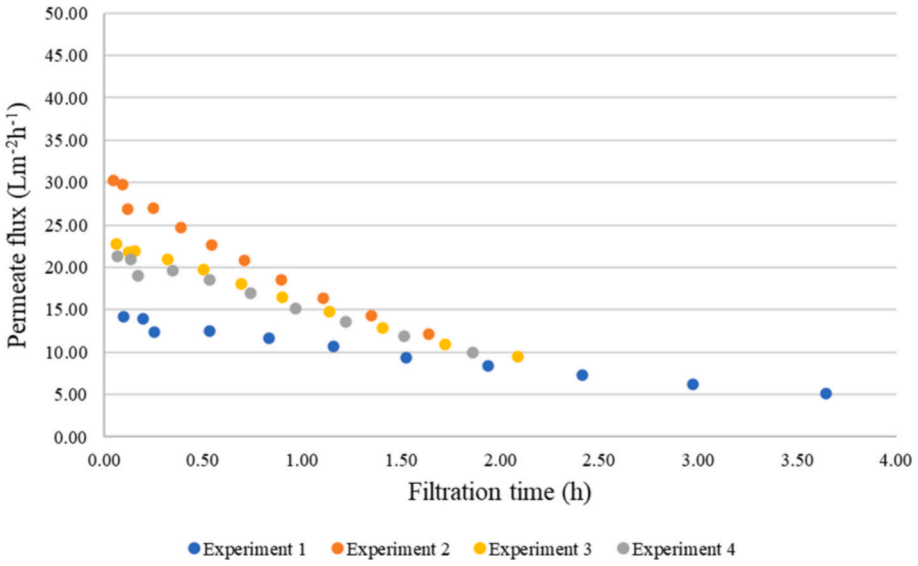


Fig. 3. Permeate fluxes in RO as the function of filtration time. Different experiments are repeated under the same process conditions. The washing procedure seemed to be effective enough and, in all cases, the pure water flux was over 70 % of the starting pure water fluxes. The least efficient results were with the trial, in which the permeate flux was the highest. The photos of the RO feed (i.e., MF permeate), retentate, and permeate are illustrated in Fig. 4. As can be seen, the permeate of the RO process seems to be clean water. The analyses of the SCOAs were also done to establish the possible permeation of these compounds into the permeate.

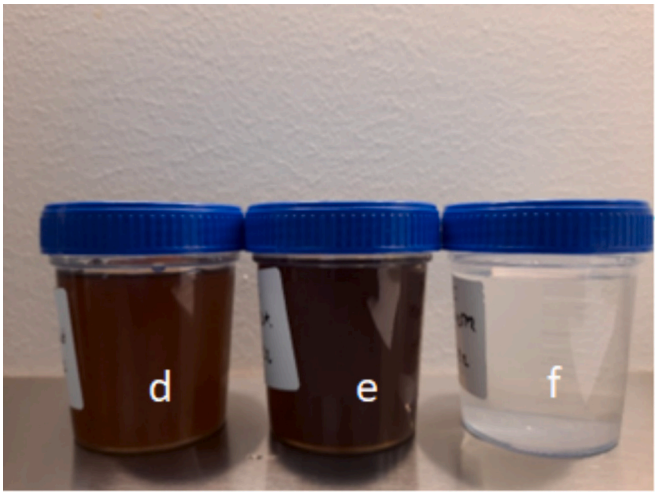


Fig. 4. The visual comparison of the RO feed (d), RO retentate (e), and RO permeate (f).

the organic acids could be accomplished as there was any affinity between them and water.In the integrated neutralization and acidification reactions method, 100 *g* of the centrifuged digestate sample was used per experiments and three replicated experiments were conducted in total to indicating repeatability of the process. The total amount of SCOAs (g/L) in the final concentrated SCOAs liquid showed an increase reaching from 23 g/L to 146 g/L (Table 4). The average concentration of acetic acid yielded from 6.7 g/L to 88.2 g/L and for butyric acid increased from 4.5 g/L to 32.9 g/L. This method proved that the recovered SCOAs liquid containing highly concentrated acetic and butyric acids could be obtained, and the total average amount of other acids in the recovered SCOAs liquid reached to 52.2 g/L, of which 34.1 g/L was caproic acid (Table 4). Additionally, a visual comparison (Fig. 5) with the initial centrifuged digested sample revealed the lack of any solid particles or other differently colored compounds, typical in digestates, in the recovered SCOAs liquid.

During the process, 1 g of the concentrated SOCAs liquid remained in the receiving flask by removing 95 g of water. Additionally, the amount of final residue (12.5 g) comprised the organic acids, sodium bicarbonate, sulfuric acid, and other substances in the centrifuged digestate. Hence, the data in Table 5 originated from Table 3 and were calculated based on the mass of the initial centrifuged digestate (100 *g*) and the

Table 3
Mass balances (kg) in the RO process.

	Acetic acid	Propionic acid	Butyric acid	Isobutyric acid	Valeric acid	Isovaleric acid	Caproic acid
RO_{feed}	0.031	0.003	0.021	0.001	0.008	0.002	0.040
$RO_{permeate}$	0.001	0.000	0.000	0.000	0.000	0.000	0.001
$RO_{retentate}$	0.027	0.003	0.018	0.001	0.007	0.002	0.036
Loss	0.003	0.000	0.003	0.000	0.001	0.000	0.003

Table 4
The mean concentrations of SCOAs (g/L) detected in the integrated neutralization and acidification reactions method.

	Acetic acid	Propionic acid	Butyric acid	Isobutyric acid	Valeric acid	Isovaleric acid	Caproic acid
Feed	6.7	0.7	4.5	0.2	1.7	0.4	8.8
Recovered SCOAs liquid	88.2	8.3	32.9	3.1	4.5	2.2	34.1

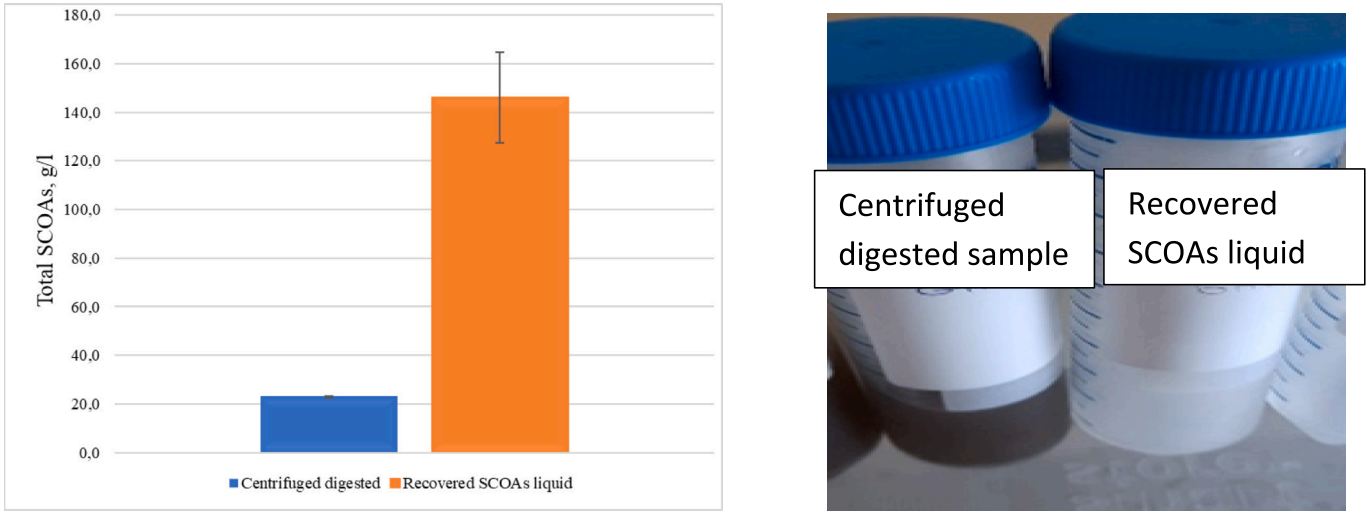


Fig. 5. Comparison of the initial centrifuged digested sample vs. SCOAs liquid on two bases. On the left: the total amount (g/L) of SCOAs in both samples. On the right: the visual comparison of two samples.

Table 5
Amount of acids (g) in the integrated neutralization and acidification reactions method.

	Acetic acid	Propionic acid	Butyric acid	Isobutyric acid	Valeric acid	Isovaleric acid	Caproic acid
Feed	0.670	0.070	0.450	0.020	0.170	0.040	0.880
Recovered SCOAs liquid	0.088	0.008	0.033	0.003	0.004	0.002	0.007
Recovered water	0.009	0.000	0.009	0.000	0.000	0.000	0.019
Residue	0.413	0.043	0.360	0.010	0.147	0.024	0.645

masses of the fractions obtained during the process (i.e., water, SOCAs liquid, and residues). The ratio of recovered SCOAs from the SCOAs liquid to the initial amount of SCOAs was 6.34 % and concentrated SOCAs weighed 0.146 g. Also, the total amount of SCOAs (0.038 g) was determined in the condensed water. The total amount of SCOAs in the residues was 1.64 g, thus, indicating that the large amount of acids was not recovered due to sticky nature of these residues.

4. Conclusions

The selection of recovery methods for SCOAs affects the suitability of these acids to different applications. However, the detailed data on the chemical composition of various SCOAs are also essential. The main aim of the present study was to develop a simple and economical concentration system for recovering SCOAs from the aqueous solutions formed during acidic anaerobic fermentation of food wastes. Two approaches were investigated. In the first case, membrane technologies (the combination use of MF and RO) were tested for the concentration of acetic, propionic, butyric, isobutyric, valeric, isovaleric, and caproic acids. The total recovery yield obtained was rather high (about 94 %), although these unit processes should be further optimized with respect to some technical questions. The second investigated technique was based on the recovery and the concentration of SCOAs by the integrated method where the acids were first neutralized for the removal of water from the acid salts formed and then these salts were liberated to obtain a final acid fraction. Also, in this case, the method successfully removed the solid particles and impurities from the initial sample and a clear SCOAs liquid was obtained. However, also in this application, some further for optimization is needed, although it seemed to offer an economical way for scaling up.

CRediT authorship contribution statement

M. Ghalibaf: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **N. Pap:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **M. Vainio:** Writing – review & editing. **N. Honkala:** Writing – review & editing. **S. Rasi:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

Hereby, I confirm that there is no conflict of interest in submitted manuscript.

Data availability

No data was used for the research described in the article.

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