Journal of Environmental Management 375 (2025) 124193



Contents lists available at ScienceDirect

Journal of Environmental Management

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



Research article



Characterisation and anaerobic digestion of fat, oil and grease (FOG) waste from wastewater treatment plants

Luca Alibardi [a,*], Alice Strazzabosco [b], Raffaello Cossu [c]

[a] Cranfield Water Science Institute, Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK
[b] Queensland Government, Brisbane, 4000, QLD, Australia
[c] Department of Civil, Environmental and Architectural Engineering, University of Padova, Via Marzolo 9, 35131, Padova, Italy

ARTICLE INFO

Keywords:
Fat
Oil
Grease
FOG
Anaerobic digestion
Dark fermentation

ABSTRACT

The materials removed in the oil separation units of wastewater treatment plants can be referred to as fat, oil and grease (FOG) waste. FOG waste accumulation in treatment plants can cause clogging of pipes, production of excessive scums and foams, and negatively affect air/liquid oxygen transfer.

While conventional disposal routes of this material can be limited by its water and organic content, FOG can represent a source of bio-energy other than bio-diesel production. This research determined the chemical and physical characteristics of FOG waste collected at four different wastewater treatment plants and defined the potential for energy recovery via dark fermentation and anaerobic digestion as treatment options for final disposal. The FOG samples featured markedly distinct physical aspects in connection with the oil separation technologies: solid agglomerate with a high content of lipids from vortex-type separation and semi-solid agglomerate with a low content of oils and fats from horizontal-flow chambers. All FOG waste presented high potential for methane production with values ranging from 460 to 865 Nm^3CH_4/tVS but low yields of biological hydrogen via dark fermentation. This study addresses a knowledge gap in the scientific literature on the characteristics of FOG waste from treatment plants and defines possible routes for sustainable management via bio-energy recovery.

1. Introduction

Vegetable, animal and mineral lipids are present in municipal or industrial wastewater both in liquid (oil) and semi-solid (grease) forms. Uncontrolled discharge of fat, oil and grease (FOG) in sewer networks is responsible for the accumulation of congealed agglomerates (i.e., fatbergs) leading to blockages and sewer overflows that are disruptive for society and costly to repair for the water service companies (Yusuf et al., 2024; Sultana et al., 2022; He et al., 2017). If discharged in surface water bodies, FOG waste reduces oxygen transfer affecting aerobic life and animals, creates anoxic zones leading to odour emissions or generating unesthetic foamy areas and compromises the use of surface water for recreational purposes (Wallace et al., 2017). Similarly, FOG causes operational problems at wastewater treatment plants such as pipe clogging, impacts on oxygen transfer efficiencies or the presence of excessive foaming in settling and oxidation tanks (Pintor et al., 2016).

The problem of accumulation of FOG in sewer networks is extensively discussed in the scientific literature with studies aiming to define the formation mechanisms of FOG build-ups (Yusuf et al., 2023; Iasmin et al., 2016), FOG characteristics (Mohana et al., 2023) and remediation strategies for sewer network applications (Baena et al., 2022; Gurd et al., 2020). On the contrary, there is a lack of knowledge on the characteristics of FOG removed at wastewater treatment plants and on the possibilities for its management and disposal.

In wastewater treatment plants, FOG waste is typically removed at the head of the works, up front of the primary sedimentation tanks. Removal processes are based on either gravity separation or air flotation with oil separation units having different types of reactor configuration (Pintor et al., 2016). In gravity separation units, FOG floats to the water surface due to the lower specific weight and is generally removed by surface scraping blades. In air flotation devices, the injection of small air bubbles traps oils and fat particles and moves them upwards towards calm flotation zones, from where they are removed (Romero-Güiza et al., 2022).

Only a few papers have been published so far with information on the management of FOG waste specifically recovered from wastewater

* Corresponding author. Cranfield Water Science Institute, Cranfield University, Cranfield, MK43 0AL, UK.
E-mail address: l.alibardi@cranfield.ac.uk (L. Alibardi).

https://doi.org/10.1016/j.jenvman.2025.124193
Received 31 July 2024; Received in revised form 31 December 2024; Accepted 17 January 2025
Available online 24 January 2025
0301-4797/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

treatment plants. These research papers focused on estimating FOG production (Collin et al., 2020), establishing FOG fate (Simion Beldean-Galea et al., 2013) or assessing the effects of anaerobic digestion of FOG waste collected at wastewater treatment works but in co-digestion with sludge or organic waste (Alqaralleh et al., 2019; Martín-González et al., 2011). To the best of the authors' knowledge, no papers focused on the detailed characteristics of the FOG waste from oil separation systems at wastewater treatment works and how these technologies affect the FOG waste composition.

FOG waste from wastewater treatment plants can be used for biodiesel production, disposed to landfills, treated by thermal processes (e.g., incineration, gasification or pyrolysis) or by biological processes (e.g., composting or anaerobic digestion), but the actual routes of disposal will depend on the FOG waste characteristics. The conversion of FOG into biodiesel can advantage of the low cost of the substrate, its potential wide availability and the absence of competition with edible oils but the established production processes are not suitable for treating these types of feedstocks due to the high free fatty acid and moisture contents (Ahmed and Huddersman, 2022; Abomohra et al., 2020). The disposal of FOG waste in landfills can be limited by regulations due to the content of biodegradable organic substances (Cossu et al., 2017) while energy recovery by thermal treatments can be negatively affected by the moisture content of this type of waste (Xiao et al., 2022; Bratina et al., 2017). Conversely, the high content of biodegradable organic substances in FOG waste makes this type of waste a good candidate for biological treatments to either recover energy by anaerobic digestion or to exploit its carbon and nutrient content via composting (Ansari et al., 2024; Czekała et al., 2023).

FOG waste has been considered as a feedstock with the potential to enhance biogas production in co-digestion with sewage sludge or organic waste (Salama et al., 2019). Despite this potential, the addition of lipid-rich substrates to anaerobic digestion can lead to the accumulation of long-chain fatty acids and this can cause inhibition of acidogenic and methanogenic activity (Szabo-Corbacho et al., 2024; Kurade et al., 2020). Due to these risks, anaerobic digestion of FOG waste is only considered for co-digestion, where legislations allow this practice, with limited full-scale applications therefore co-digestion is an underutilised disposal route (Nghiem et al., 2017).

The anaerobic co-digestion of FOG materials is investigated in scientific literature by using pure fatty acids (Peces et al., 2020; Cavaleiro et al., 2008) or FOG waste obtained from grease traps or fat condenser tanks of food service establishments or meat treatment centres (Berninghaus and Radniecki, 2022; Wang et al., 2020) or extracted lipid from food waste leachate (Kang et al., 2021; Saha et al., 2018). These later studies used FOG materials that are not fully representative of the waste collected from oil-separation units at wastewater treatment works, therefore this lack of knowledge hinders the definition of sustainable solutions for the management of this type of waste.

This work aimed to determine the characteristics of FOG waste collected at wastewater treatment plants and how these are affected by the type of oil separation unit and to identify the potential for energy recovery via biological anaerobic processes. The specific objectives were to perform a detailed physical and chemical characterisation of FOG samples from four different oil separation processes at full scale and to establish the potential productions of biohydrogen and biomethane via dark fermentation and anaerobic digestion batch tests, respectively. The novelty of the research is its specific focus on FOG waste collected at wastewater treatment plants with a detailed characterisation that addresses the lack of knowledge on this type of FOG material.

2. Materials and methods

2.1. Wastewater treatment plants and oil separation processes

FOG waste samples removed by oil separation units were collected from four municipal wastewater treatment plants located in the Veneto Region, Italy. The technical characteristics of treatment facilities are presented in Table 1. The flowsheets of all treatment facilities comprise coarse and fine screening, oil separators and grit removal units, primary sedimentation, biological treatment with activated sludge process for organics and nitrogen removal using the modified Ludzack-Ettinger predenitrification configuration (Henze et al., 2011) and secondary sedimentation. Plants A and C have tertiary treatments for chemical phosphorus (P) removal and final effluent disinfection. Plant D has a final polishing stage by constructed wetlands while Plant B has no P removal or tertiary treatments. Plants A and B have onsite anaerobic digestion for the treatment of sewage sludge.

FOG waste from Plant A is sent off-site for final disposal via incineration while FOG waste from plants C and D is sent to composting facilities. Only in Plant B the FOG waste is co-digested with sewage sludge in the on-site anaerobic digestion unit.

2.2. FOG waste characterisation

The samples collected from the four sites were characterised by the following physical-chemical parameter: total solids (TS), volatile solids (VS), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), free and saline ammonia (NH_4^+), nitrate (NO_3^-), sulphates (SO_4^{2-}), total phosphorus (P_{tot}), oils and fats content, protein content, concentrations of Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn and respirometry index at 4 days (RI_4).

TOC was obtained as the difference between the total carbon (TC) and inorganic carbon (IC) of the samples. TC and IC were measured using a TOC analyser (TOC-V CSN, Shimadzu). Organic nitrogen (N_{org}) was obtained by the difference between the TKN and NH_4^+. Oil and fat content was measured by gravimetric determination of the products from Soxhlet extraction using Hexane as solvent (AOAC, 2003). Protein content was obtained by acid digestion followed by distillation and titration with HCl. A factor of 6.25 was used to convert Nitrogen to proteins (AOAC, 2003). Concentrations of Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn were measured through acid digestion of samples and analysis using an Inductively Coupled Plasma (ICP) analyser (OES Optima 4200, PerkinElmer). The respirometry index (RI_4, mgO_2/gTS) was measured as the cumulative oxygen consumption after 4 days by using a Sapromat apparatus (Sapromat E, Voith-Sulzer Papertechnology). All other parameters were measured according to standard methods (APHA, 1999).

Settling tests were carried out to evaluate whether settleable solids were removed with FOG waste, considering that the oil separation process takes place before primary sedimentation. Settling tests were carried out in Imhoff cones, the samples were homogenised to a solid concentration of 10 g TS/l and the sedimentation period was 2 h (APHA, 1999).

2.3. Biochemical methane potential tests

These tests aimed to evaluate the methane (CH_4) production potential of the FOG waste samples. Tests were carried out in 1 L Pyrex batch reactors, hermetically closed by means of silicon plugs to sample both

Table 1
Characteristics of the wastewater treatment plants from which the FOG waste samples were collected and the type of oil separation unit installed.

Wastewater treatment plant	Plant size (Population equivalent)	Wastewater sources	Oil separation unit	FOG waste disposal
A	100,000	Residential	Circular – vortex	Incineration
B	127,500	Residential/ industrial	Aerated longitudinal	Co-digestion
C	40,500	Residential	Aerated circular	Composting
D	50,000	Residential	Aerated longitudinal	Composting

gas and liquid during the anaerobic treatment. The total volume of substrate, inoculum and tap water, was 500 ml in each reactor. All tests were performed at a controlled temperature of 35 °C ± 1 °C.

Tests were performed at a substrate concentration of 10 g VS/l. The ratio between the volatile solids of the substrate and the volatile solids of the inoculum (Food/Microorganisms - F/M) was 0.5 gVS/gVS. Tests lasted 70 days. Granular sludge from a full-scale up-flow anaerobic sludge blanket reactor of a brewery factory located in the Veneto Region, Italy, was used as inoculum. Inoculum had a TS content of 16% and a VS content of 76%, referred to TS. These experimental conditions were selected from published protocols (Holliger, 2016; Alibardi and Cossu, 2015; Angelidaki et al., 2009). Similarly, the activity and the extracellular hydrolytic profile of the inoculum were tested as per established protocols (Holliger, 2016; Angelidaki et al., 2009). The pH of the digestion liquid and the quantity and quality of biogas were monitored constantly. The biogas volume was measured by adopting the dislocation method. The pressure produced in the reactor by the biogas production process moved an equal quantity of liquid to a second bottle filled with an acidified (pH < 3) and saline (NaCl 25%) solution to avoid the dissolution of methane and carbon dioxide into the liquid. The volume of the liquid moved, and, accordingly, the volume of biogas produced, was measured with a graduated cylinder. The quality of the biogas produced in terms of CH_4 and carbon dioxide (CO_2) percentages in the reactors' headspace was measured using a portable gas analyser (LFG 20, Eco-Control) (Alibardi and Cossu, 2015).

Blank tests were also prepared as above but without substrate to measure the quantity of methane produced only by the biomass and this value was subtracted from test results to report net values.

All tests were carried out in triplicate.

2.4. Biochemical hydrogen potential tests

These tests aimed to evaluate hydrogen (H_2) production potential by dark fermentation of the FOG waste. Tests were carried out similarly to biochemical methane potential tests but with the following differences. The inoculum was subjected to a thermal shock at 100 °C for 4 h to inhibit the activity of methane-producing bacteria (Alibardi et al., 2012). The substrate concentration analysed was 10 g VS/l with a F/M ratio of 0.5 gVS/gVS. These conditions were selected from published protocols (Alibardi and Cossu, 2015; Giordano et al., 2011). H_2 concentration in reactors' headspace was monitored using a gas chromatograph (HP 5890) using a 30 m HP-MOLSIV capillary column and nitrogen as carrier gas. CH_4 and CO_2 concentrations were measured using a portable gas analyser (LFG 20, Eco-Control) (Alibardi and Cossu, 2015).

2.5. Calculation of cumulative gas volumes and mathematical models

The volumes of CH_4 and H_2 produced between each measurement were calculated using the following equation (Van Ginkel et al., 2005):

$$V_{C,t} = C_{C,t} \bullet V_{G,t} + V_H \bullet \left(C_{C,t} - C_{C,t-1}\right) \quad (1)$$

Where:

$V_{C,t}$ is the volume of hydrogen or methane produced in the interval between t and t-1.

$C_{C,t}$, $C_{C,t-1}$ are hydrogen or methane concentrations measured at times t and t-1.

$V_{G,t}$ is the volume of biogas produced between time t and t-1.

V_H is the volume of the headspace of reactors.

The total gas produced was therefore determined by adding the totals of the single productions, calculated from the beginning of the test until the end of the experiment. All CH_4 and H_2 volumes are reported at a temperature of 0 °C and a pressure of 1 atm.

To compare the results obtained in the different tests, data were interpolated using a Gompertz equation when dealing with a latency phase or a first-order kinetic equation in a situation of exponential production.

The Gompertz equation (2) used is as follows:

$$P(t) = P_{tot} \bullet exp\left\{ - exp\left[R \bullet e\frac{(\lambda - t)}{P_{tot}}\right]\right\} \quad (2)$$

where:

$P(t)$ is the total volume of CH_4 or H_2 produced at moment t;

P_{tot} is the maximum CH_4 or H_2 yield.

R is the gas production rate.

λ is the latency phase.

e is Euler's number.

The quantities P, R, and λ were obtained by minimizing the square of the difference between observed and calculated values, using Microsoft Excel's Solver function.

When no latency phase was detected, the first-order kinetic equation (3) used was as follows:

$$P(t) = P_{tot} \bullet \left(1 - e^{-k \bullet t}\right) \quad (3)$$

where:

$P(t)$ is the volume of CH_4 or H_2 produced at time t.

P_{tot} is the maximum CH_4 or H_2 yield.

k is the kinetic constant.

The parameters $Ptot$ and k were estimated minimizing the square of the difference between observed and calculated values using Microsoft Excel's Solver function.

3. Results and discussion

3.1. Characteristics of the materials collected

Samples were collected from four plants where FOG waste removal was performed using different oil-separation systems to establish if the removal process had an impact on FOG waste characteristics. Plant A had a circular grit and grease removal unit equipped with a central propeller to generate a vortex movement of the water. On the contrary, the other plants used either circular or longitudinal tanks with air injection from the bottom to make lipid-rich materials (oils and fats) float by the uprising movement of the air bubble created (Table 1). These technologies are the most common types of oil-separation systems applied at wastewater treatment plants, and they often also remove heavy suspended solids like sand and grit. This combined removal is possible thanks to the different densities of FOG waste and sand/grit, allowing their collections from separate parts of the reactors (typically the top for FOG and bottom for sand/grit) and generating separate streams for potential recovery (Czop et al., 2025).

The materials collected from the four sites were different in shape and composition (Fig. 1). The sample collected from plant A was only made of ball-shaped solid agglomerates of sizes varying from 1 to 5 cm (Fig. 1A). The sample from plant B also contained ball-shaped agglomerates but of smaller sizes and more irregular shapes, and mixed with fruit and vegetable peels, seeds, hair, paper and plastic materials (Fig. 1B). On the contrary, samples C and D were both semi-solid materials similar to a thick sludge, brown or black, made of less identifiable materials with no presence of ball-shaped agglomerates as for samples A and B (Fig. 1C and D).

The shapes of sample A are similar to FOG balls collected at pumping stations within sewer networks (Rizkianto et al., 2024; Collin et al., 2020; Williams et al., 2012). Whilst produced in functionally different process units (oil separation versus pumping station), the ball shape can be induced by the vortex and centrifugal forces caused by propellers or pumps. Ball-shaped FOG agglomerates were also reported in wastewater treatment plants (Collin et al., 2020; Williams et al., 2012) but the exact location of their collection was not specified and therefore it is not possible to associate their production with oil separation units or other

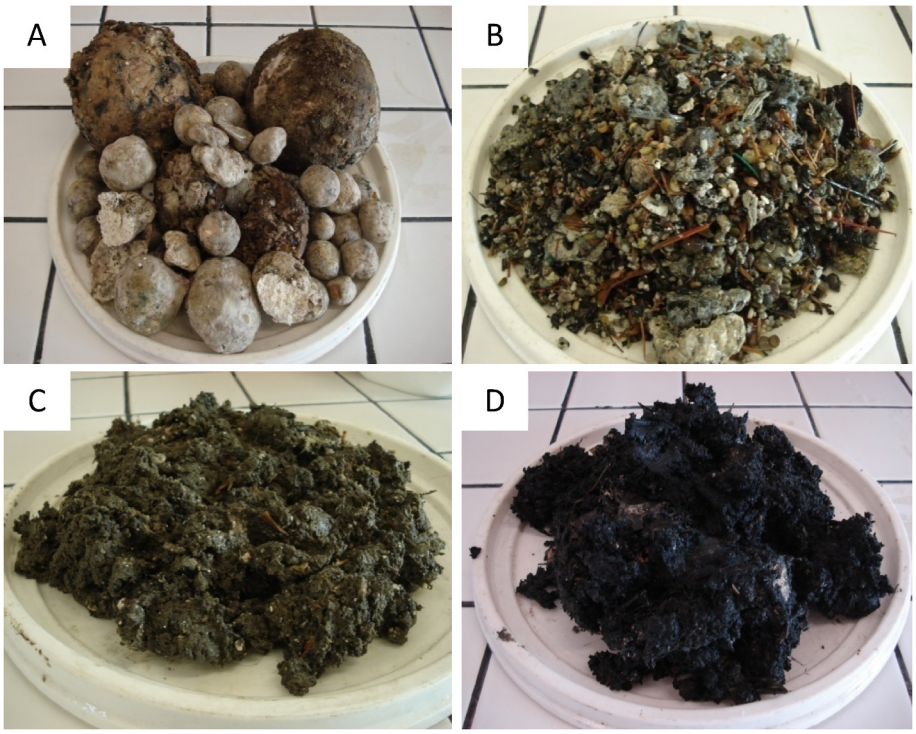


Fig. 1. Samples collected from the four wastewater treatment plants.

processes in the treatment works.

Sample A was characterised by the highest content of both TS and lipids of the four samples with up to 70% of TS made of lipids either as oils or fats. (Table 2). TOC content was also the highest among the four samples while nitrogen and phosphorus contents were the lowest. This indicates that the FOG balls are characterised by a high C/N ratio and the high TOC content can be explained by the large presence of lipids, organics that are characterised by a high content of C, and the small presence of N and P is due to a limited content of proteins. Sample B had a lipid content of 35%, which is lower than sample A, despite the presence of FOG balls. The TKN and P contents were comparable for samples A and B (Table 2). The TOC concentration for sample B was 63% and the C/N ratio was 154 because of a low nitrogen content. Both samples A and B had a respirometry index of 13 gO_2/kgTS. The slow biodegradability of these two samples can be attributed to the high content of lipids, which are generally characterised by slow hydrolysis rates (Holohan et al., 2022), and the high C/N ratios that can limit microbial growth and degradation thus leading to low oxygen demands (Puyuelo et al., 2011).

On the contrary, samples C and D were characterised by a much lower lipid content, if compared to A and B, in both cases around 10%. TOC content was instead comparable with values between 53 and 57%. Both samples C and D had higher TKN, N-NH_4^+ and protein contents thus lower C/N ratios of 13% and 31%, respectively. Biodegradability of samples C and D was higher than samples A and B as the RI_4 values were 151 and 92 mgO_2/gTS, respectively.

The characteristics of sample A are similar to data reported for FOG agglomerates from sewer networks (Hao et al., 2020) or FOG balls from pumping stations or wastewater treatment works (Rizkianto et al., 2024; Collin et al., 2020). These types of FOG waste are generally characterised by low moisture and lipids contents between 50 and 90% of TS, as for sample A.

Sample B has some characteristics similar to FOG materials such as the high C/N ratios and the low content of P, but the lower content of lipids, if compared to sample A, suggests that the oil-separation at plant B removes also other materials reducing both the lipid content and the

Table 2
Chemical-physical characterization of materials collected from the oil separation units.

Parameters	Unit of measurement	Wastewater Treatment Plant			
		A	B	C	D
TS	%	71 ± 2	45 ± 4	16 ± 4	30 ± 2
VS	% TS	90 ± 2	92 ± 2	81 ± 2	86 ± 2
RI_4	g O2/kg TS	13 ± 5	13 ± 4	151 ± 15	92 ± 12
TOC	% TS	69 ± 2	63 ± 3	53 ± 4	57 ± 3
TKN	g N/kg TS	3.2 ± 0.3	4.8 ± 0.3	41.6 ± 0.8	19.2 ± 0.5
N-NH_4^+	g N/kg TS	0.3 ± 0.1	0.6 ± 0.1	9.4 ± 0.2	8.4 ± 0.2
Norg	g N/kg TS	2.6	3.5	31.7	9.7
Norg/TKN	%	90	85	77	54
N-NO_3	mg N/kg TS	8.3 ± 2.2	8.4 ± 2.1	24.0 ± 2.3	16.7 ± 1.5
C/N	g C/g N	238	154	13	31
SO_4^{2-}	g/kg TS	1.1 ± 0.4	1.3 ± 0.5	6.7 ± 1.2	1.1 ± 0.8
Ptot	g P/kg TS	1.4 ± 0.5	1.0 ± 0.3	10.5 ± 1.1	2.6 ± 0.5
Oils and Fats	% TS	70 ± 5	35 ± 3	8 ± 2	11 ± 2
Proteins	% TS	2 ± 1	3 ± 1	26 ± 2	12 ± 2
Cd	mg/kg TS	<0.01	<0.01	<0.01	<0.01
Cr	mg/kg TS	6.2 ± 2.1	23.6 ± 4.3	7.8 ± 1.8	12.7 ± 3.1
Cu	mg/kg TS	26.6 ± 3.9	27.0 ± 4.5	162.4 ± 13.5	71.4 ± 8.0
Fe	mg/kg TS	373 ± 32	934 ± 52	3123 ± 136	3340 ± 269
Mn	mg/kg TS	7.8 ± 2.4	14.9 ± 3.6	48.4 ± 5.3	37.0 ± 4.2
Ni	mg/kg TS	3.4 ± 1.2	4.7 ± 1.4	13.5 ± 2.6	9.0 ± 2.4
Pb	mg/kg TS	3.8 ± 0.8	4.2 ± 0.7	15.0 ± 1.1	9.7 ± 0.9
Zn	mg/kg TS	12.5 ± 0.8	78.4 ± 2.2	164.9 ± 6.5	37.2 ± 2.7

biodegradability of the sample.

Samples C and D are both characterised by the lowest TS and lipid contents (Table 2). Similarly, they are characterised by the lowest C/N ratios due to a TOC content below 60% and TKN values of 41.6 and 19.2 gN/kgTS for samples C and D, respectively. The IR_4 resulted in 151 and 92 gO_2/kg TS for samples C and D, respectively, indicating the readily biodegradability of these two samples. The low lipid concentrations of 8–11% together with the high moisture and nitrogen contents, if compared to typical FOG materials, make samples C and D comparable to sewage scum, primary scum or primary sludge (Rizkianto et al., 2024; di Bitonto et al., 2020). This suggests that the aeration for the two oil-separation units at plants C and D is excessive and removes large quantities of sewage sludge reducing the lipid content of the FOG waste and increasing the overall quantity of floated material.

The ash content measured in this study for all materials ranged from 8 to 19% (Table 2). These values are generally higher than those reported in the literature for FOG, ranging from 1 to 10% (Collin et al., 2020; Salama et al., 2019), suggesting that oil separation units located at the head of the works collect more inert debris than what accumulates in FOG agglomerates in the sewer networks, pumping stations or grease traps.

The analysis of the settling characteristics (Fig. 2) confirmed the observations obtained from the chemical composition of the four samples. Samples A and B featured a tendency to accumulate almost completely on the surface with a near absence of settling materials (volume index <10 mL/L after 2 h), indicating the presence of lipids and other materials with lower density than water. On the contrary, the majority of solids in samples C and D settled completely with volume indexes of 150 mL/L and 90 mL/L after 2 h, respectively. This confirms the removal of large quantities of settable solids by flotation from the oil-separation units for plants C and D, which can be caused by an excess of air addition or the use of chemical coagulants. Samples C and D are characterised by the highest concentration of Fe (>3 g/kg TS, Table 2) suggesting the use of salts of iron to induce particle aggregation and enhance the effectiveness of flotation (Pintor et al., 2016).

These results indicate that the type of oil separation units located at the head of wastewater treatment works and their operational conditions affect the characteristics of FOG waste because those units can collect materials other than lipids. The use of flotation for oil and grease separation can remove settable solids, which are then extracted together with FOG waste. This is confirmed by the low lipid concentrations and high-volume indexes of samples C and D. On the contrary, if the flotation effect due to aeration is absent, only solid agglomerates rich in FOG waste are removed as for sample A. The configuration and operation conditions of oil separation units (e.g., vortex or flotation, level of aeration, use of coagulants) can have a cascade effect on the treatment works. Higher removal of materials other than FOG waste in the preliminary treatments can reduce the solid and organic loads to the primary sedimentation or biological treatments, respectively. This can have a positive effect in reducing the energy demand for aeration for biological treatments but can also have a negative effect in reducing the availability of biodegradable carbon to sustain biological nutrient removal or the diversion of carbon to value recovery (e.g., anaerobic digestion) via primary sedimentation. Similarly, the variable characteristics of FOG waste can hinder the recoverability of lipids for other uses (e.g., biodiesel production) thus reducing the value of these materials and increasing the costs for final disposal.

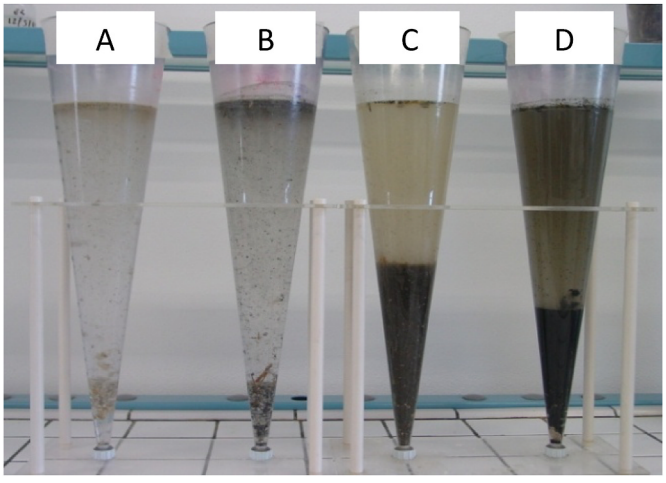


Fig. 2. Sedimentation tests of the materials collected from the four wastewater treatment plants.

3.2. Biochemical methane and hydrogen potentials

The highest potential for methane recovery via anaerobic digestion was measured for sample A (Table 3, Fig. 3). The methane yield obtained after 70 days of digestion was 865 Nm^3/tVS with a projected maximum recovery of 936 Nm^3/tVS from the interpolation of the experimental data with the Gompertz equation (2). The latter value is in the range reported for the theoretical methane potential production of lipids, up to 1000 Nm^3/t VS (Holohan et al., 2022), thus confirming that sample A is constituted mainly of oils and fats. The cumulative methane production showed a typical S-shaped curve with a value of the modelled latency phase λ of 7 days (Table 3). The high methane production potential is aligned with data for other types of FOG waste (Collin et al., 2020) and is due to the high concentration of lipids in sample A. The high C/N ratio of the sample had no effects on the microbial degradation due to the low F/M ratio of the test. The latency phase resulting from the fitting of the data with the Gomperts equation can be associated with the slow hydrolysis rate for lipids, if compared to other organics. No inhibition of the process due to the accumulation of fatty acids (Szabo-Corbacho et al., 2024) was recorded and the pH in the reactor remained stable within acceptable values for the anaerobic microorganism (6<pH < 8).

Sample B also showed an S-shaped cumulative methane production curve that was fitted with the Gompertz equation (2), but the methane potential production resulted in almost half of that of sample A. Sample B had also a longer modelled latency phase λ of almost 12 days, if compared to sample A. The lower methane potential can be attributed to the lower lipids content and the longer latency phase can be due to the presence of complex organics (e.g., fibres, peelings) that reduced the overall biodegradability of the sample.

Samples C and D had comparable behaviours during the digestion test for methane production with cumulative production following first-order kinetics for both samples (Fig. 3C and D) and a lack of any latency phase. This suggests the presence of rapidly biodegradable materials in these two samples which is typical for primary sludge collected during sedimentation (Sakaveli et al., 2021). The methane yields of samples C and D are also similar to values obtained from sewage scum, which is a waste rich in lipids and is collected from the top surface of primary

Table 3
Methane (CH_4) yield and methane content of biogas from experimental test after 70 days and maximum CH_4 yield from modelling. R and λ are the gas production rate and latency phase from the Gompertz equation (2), respectively. *k* is the kinetic constant for the first-order kinetic equation (3).

Parameter	Unit of measurement	A	B	C	D
Experimental CH_4 yield	Nm^3/t VS	865 ± 32	460 ± 16	624 ± 26	642 ± 33
CH_4 content in the biogas	% (v/v)	72	71	71	70
Modelled CH_4 yield	Nm^3/t VS	936	626	708	688
R	ml/d	19.26	8.8	–	–
λ	d	7.1	11.6	–	–
k	1/d	–	–	0.03	0.04

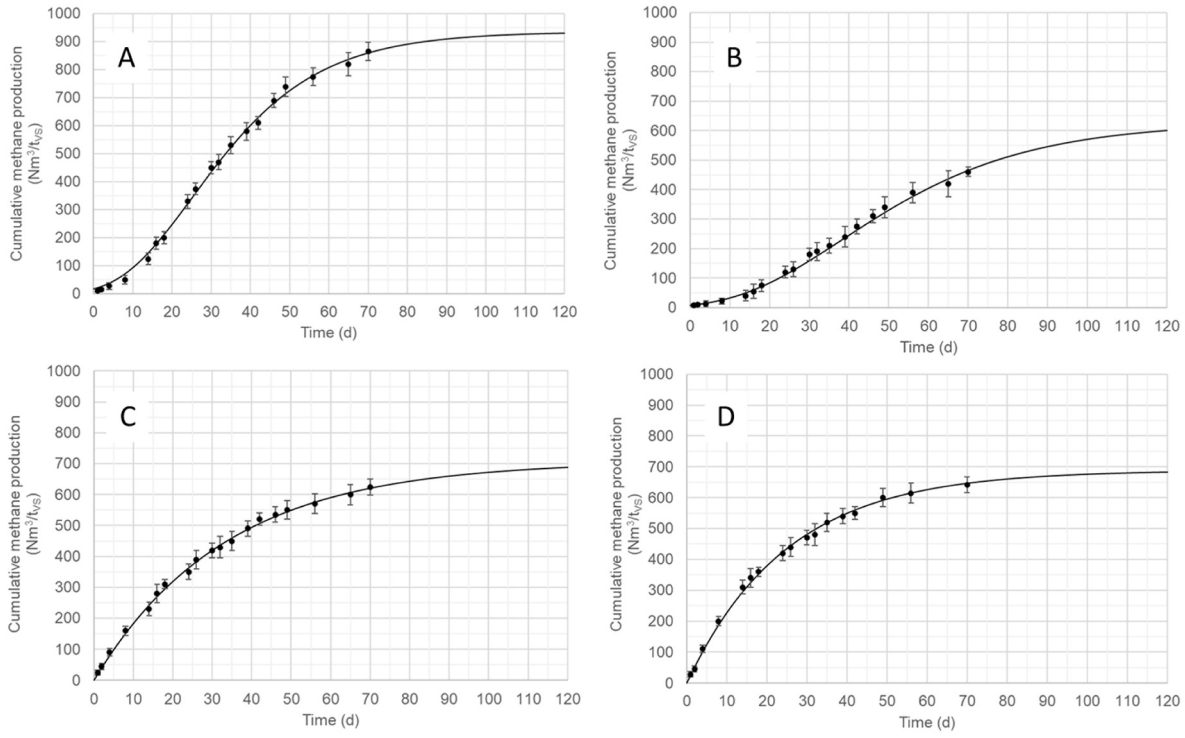


Fig. 3. Cumulative methane production from the four materials. Dots represent the experimental data with error bars representing the standard deviation. Continuous lines represent the result.

sedimentation (Aromolaran et al., 2023).

The kinetics of the methane production that were observed in this study, can be associated with the nature of the samples and their physical and chemical characteristics. Sample A is the richest in lipids content that is characterised by the highest theoretical methane potential, but hydrolysis of lipids is relatively slow if compared to carbohydrates and proteins thus leading to the presence of a latency phase. Sample B showed the longer latency phase with 11 days (Table 3) and the lowest cumulative methane production. This can still be explained by the presence of lipids in the sample that influenced the low degradability of the organics. Samples C and D had no latency phase, and this indicates a larger presence of readily biodegradable organics which is also confirmed by the high values of RI_4.

Contrary to methane potentials, biological hydrogen production yields were extremely low in all samples (Fig. 4). The highest value for specific production was obtained by the A sample (2.4 Nm^3/t VS) whilst the lowest was registered for B (1.7 Nm^3/t VS). Samples B and C obtained similar results, corresponding to 2.1 Nm^3/t VS and 2.0 Nm^3/t VS, respectively.

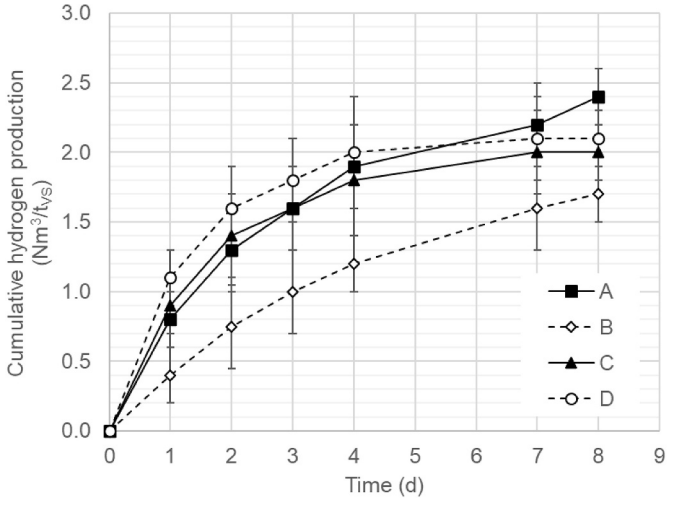


Fig. 4. Experimental specific cumulative hydrogen production from the four materials.

The results obtained for biological hydrogen production from FOG waste from wastewater treatment plants are similar to those reported for solid organic waste fractions that are rich in lipids or proteins. Food waste fractions such as cheese, meat and fish are in fact reported to have biological hydrogen production yields between 0.8 and 5 Nm^3/t VS (Alibardi and Cossu, 2015, 2016).

The results from this study indicate that FOG waste collected from oil separation units at wastewater treatment plants are substrates that can be exploited for methane generation at anaerobic digestion plants. The mono-digestion of these types of substrates is not feasible due to the small proportion of FOG waste recovered from wastewater treatment plants, if compared to the production of primary and secondary sludge (Collin et al., 2020). The option that can be considered is anaerobic co-digestion with sludge where on-site digestion facilities are available, to avoid the need for storage and transport of FOG waste to other facilities. The methane yields that were observed in this study can boost the overall biogas production from the digestion of sewage sludge, similar to what was observed in the co-digestion of sewage sludge with lipid-rich materials from grease traps or sewer networks (Hao et al., 2020; Salama et al., 2019). This can increase the energy recovery from wastewater treatment plants thus reducing emissions and enhancing the revenue for the sale of a renewable energy source such as biomethane. The addition of this type of FOG waste to an anaerobic digester needs to consider the lipid content of the waste and maintain the ratio of lipids with other solids below 30% to avoid the risk of organic overload or the risk of generating an excessive production of long-chain fatty acids (Szabo-Corbacho et al., 2024; Long et al., 2012). Similarly, the over-addition of lipid-rich material to anaerobic digestion can generate foams on top of the liquid level in the digesters that can limit the biogas transfer from the liquid to the gaseous phase and reduce recoverability

(Diamantis et al., 2021; Salama et al., 2019).

Another aspect that needs consideration is the nature of the FOG waste. Materials rich in solid aggregates like samples A and B, necessitate pre-treatments to reduce their sizes, maximise the contact surface for bacterial degradation and avoid the occlusion of pumping systems and pipes. This can represent an additional cost to upgrade the AD facility to process this type of waste (FOG balls) that might not be returned from the increase in biogas production (Diamantis et al., 2021). On the contrary, materials similar to samples C and D that have a physical nature similar to sludge and are also characterised by a limited concentration of lipids, do not represent a risk for anaerobic digestion.

Fermentation of FOG waste from wastewater treatment plants is not a suitable solution given the limited hydrogen yields that these types of materials produce. An increase in hydrogen yields can be obtained by biomass adaptation with repeated batch cycles at increasing FOG loads (Saha et al., 2018) but the possibility of translating this procedure to continuous fermentation reactors and the effective retention of the adapted biomass in the reactors is still unclear. Despite the low hydrogen yields confirmed by this study, FOG waste can be considered as a potential feedstock if the focus of the fermentation process is the generation of short-chain fatty acids to sustain the biological nutrient removal (BNR) at wastewater treatment plants. Fermentation of FOG waste was reported to generable quantities of acetic, propionic and valeric acids in the range of 10–30% of the total acids produced, comparable to those obtained from food waste or primary sludge samples (Mahmoud et al., 2022). The practice of FOG fermentation or co-fermentation to sustain BNR can represent an alternative utilisation route for this type of waste that can avoid practical and regulatory limitations of co-digestion, but the investigations remain currently limited.

4. Conclusions

This study demonstrated the variability of the physical and chemical characteristics of the material removed from the oil separation unit of wastewater treatment plants. Such variability is affected by the type and operation of the separation unit and has consequences on the possible recovery or disposal options for these materials. FOG waste achieved high methane yields, that were directly proportional to the content of lipids, but the actual exploitation of this potential is possible in co-digestion with other substrates, where this practice is supported by legislation. The content of lipids affected hydrolysis kinetics with longer latency phases observed at higher lipids contents. FOG waste did not prove to be suitable for hydrogen production via dark fermentation, irrespective of its lipids content. The detailed characterisation of FOG waste presented in this study informs the definition of the most sustainable management and disposal routes for this type of lipid-rich material that is generally removed and collected at any wastewater treatment plant but is currently scarcely investigated in the literature.

CRediT authorship contribution statement

Luca Alibardi: Writing – review & editing, Methodology, Investigation, Formal analysis. **Alice Strazzabosco:** Writing – original draft, Investigation. **Raffaello Cossu:** Writing – review & editing, Supervision, Conceptualization.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Research data deposit: https://dspace.lib.cranfield.ac.uk/items/69aba1f2-8abe-414c-951f-92d5e5a0674e.

References

Abomohra, A.E.-F., Elsayed, M., Esakkimuthu, S., El-Sheekh, M., Hanelt, D., 2020. Potential of fat, oil and grease (FOG) for biodiesel production: a critical review on the recent progress and future perspectives. Prog. Energy Combust. Sci. 81, 100868. https://doi.org/10.1016/j.pecs.2020.100868.

Ahmed, R., Huddersman, K., 2022. Review of biodiesel production by the esterification of wastewater containing fats, oils and grease (FOGs). J. Ind. Eng. Chem. 110, 1–14. https://doi.org/10.1016/j.jiec.2022.03.031.

Alibardi, L., Cossu, R., 2015. Composition variability of the organic fraction of municipal solid waste and effects on hydrogen and methane production potentials. Waste Manag. 36, 147–155. https://doi.org/10.1016/j.wasman.2014.11.006.

Alibardi, L., Cossu, R., 2016. Effects of carbohydrate, protein and lipid content of organic waste on hydrogen production and fermentation products. Waste Manag. 47, 69–77. https://doi.org/10.1016/j.wasman.2015.07.046.

Alibardi, L., Favaro, L., Lavagnolo, M.C., Basaglia, M., Casella, S., 2012. Effects of heat treatment on microbial communities of granular sludge for biological hydrogen production. Water Sci. Technol. 66 (7), 1483–1490. https://doi.org/10.2166/wst.2012.355.

Alqaralleh, R.M., Kennedy, K., Delatolla, R., 2019. Microwave vs. alkaline-microwave pretreatment for enhancing Thickened Waste Activated Sludge and fat, oil, and grease solubilization, degradation and biogas production. J. Environ. Manag. 233, 378–392. https://doi.org/10.1016/j.jenvman.2018.11.068.

Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J.L., Guwy, A.J., Kalyuzhnyi, S., Jenicek, P., van Lier, J.B., 2009. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water Sci. Technol. 59 (5), 927–934. https://doi.org/10.2166/wst.2009.043.

Ansari, S.A., Kumar, T., Sawarkar, R., Gobade, M., Khan, D., Singh, L., 2024. Valorization of food waste: a comprehensive review of individual technologies for producing bio-based products. J. Environ. Manag. 364, 121439. https://doi.org/10.1016/j.jenvman.2023.121439.

AOAC, 2003. Official Methods of Analysis of Association of Official Analytical Chemists International, seventeenth ed. Association of Analytical Communities, Gaithersburg, MD, USA.

APHA, AWWA, WPCF, 1999. Standard Methods for the Examination of Water and Wastewater, twentieth ed. American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC.

Aromolaran, A., Sartaj, M., Abdallah, M., 2023. Supplemental sewage scum and organic municipal solid waste addition to the anaerobic digestion of thickened waste activated sludge: biomethane potential and microbiome analysis. Fermentation 9 (3), 237. https://doi.org/10.3390/fermentation9030237.

Baena, A., Orjuela, A., Rakshit, S.K., Clark, J.H., 2022. Enzymatic hydrolysis of waste fats, oils and greases (FOGs): status, prospective, and process intensification alternatives. Chem. Eng. Process. Intensif. 175, 108930. https://doi.org/10.1016/j.cep.2022.108930.

Berninghaus, A.E., Radniecki, T.S., 2022. Shock loads change the resistance, resiliency, and productivity of anaerobic co-digestion of municipal sludge and fats, oils, and greases. J. Clean. Prod. 362, 132447. https://doi.org/10.1016/j.jclepro.2022.132447.

Bratina, B., Šorgo, A., Kramberger, J., Ajdnik, U., Fras Zemljič, L., Ekart, J., Šafarič, R., 2017. From municipal/industrial wastewater sludge and FOG to fertilizer: a proposal for economic sustainable sludge management. J. Environ. Manag. 183 (3), 1009–1025. https://doi.org/10.1016/j.jenvman.2016.09.041.

Cavaleiro, A.J., Pereira, M.A., Alves, M., 2008. Enhancement of methane production from long chain fatty acid based effluents. Bioresour. Technol. 99, 4086–4095. https://doi.org/10.1016/j.biortech.2007.08.060.

Collin, T., Cunningham, R., Jefferson, B., Villa, R., 2020. Characterisation and energy assessment of fats, oils and greases (FOG) waste at catchment level. Waste Manag. 103, 399–406. https://doi.org/10.1016/j.wasman.2019.12.035.

Cossu, R., Fantinato, G., Pivato, A., Sandon, A., 2017. Further steps in the standardization of BOD5/COD ratio as a biological stability index for MSW. Waste Manag. 68, 16–23. https://doi.org/10.1016/j.wasman.2017.06.037.

Czekała, W., Nowak, M., Piechota, G., 2023. Sustainable management and recycling of anaerobic digestate solid fraction by composting: a review. Bioresour. Technol. 375, 128813. https://doi.org/10.1016/j.biortech.2023.128813.

Czop, M., Wyczarska-Kokot, J., Kalka, J., Kudlek, E., Balcerzak, L., Jamry, A., Kopiec, W., Nowak, K., Piwowarczyk, M., Zackiewicz, W., 2025. Possibilities of using waste from wastewater treatment plants to create soil-like materials. Desalination Water Treat. 321, 100907. https://doi.org/10.5004/dwt.2025.100907.

di Bitonto, L., Todisco, S., Gallo, V., Pastore, C., 2020. Urban sewage scum and primary sludge as profitable sources of biodiesel and biolubricants of new generation. Bioresour. Technol. Rep. 9, 100382. https://doi.org/10.1016/j.biteb.2020.100382.

Diamantis, V., Eftaxias, A., Stamatelatou, K., Noutsopoulos, C., Vlachokostas, C., Aivasidis, A., 2021. Bioenergy in the era of circular economy: anaerobic digestion technological solutions to produce biogas from lipid-rich wastes. Renew. Energy 168, 438–447. https://doi.org/10.1016/j.renene.2020.12.125.

Giordano, A., Cantù, C., Spagni, A., 2011. Monitoring the biochemical hydrogen and methane potential of the two-stage dark-fermentative process. Bioresour. Technol. 102 (6), 4474–4479. https://doi.org/10.1016/j.biortech.2010.12.112.

Gurd, C., Villa, R., Jefferson, B., 2020. Understanding why fat, oil and grease (FOG) bioremediation can be unsuccessful. J. Environ. Manag. 267 (1), 110647. https://doi.org/10.1016/j.jenvman.2020.110647.

Hao, J., de los Reyes III, F.L., He, X., 2020. Fat, oil, and grease (FOG) deposits yield higher methane than FOG in anaerobic co-digestion with waste activated sludge. J. Environ. Manag. 268, 110708. https://doi.org/10.1016/j.jenvman.2020.110708.

He, X., de los Reyes III, F.L., Ducoste, J.L., 2017. A critical review of fat, oil, and grease (FOG) in sewer collection systems: challenges and control. Crit. Rev. Environ. Sci. Technol. 47 (13), 1191–1217. https://doi.org/10.1080/10643389.2017.1382282.

Henze, M., van Loosdrecht, M.C.M., Ekama, G.A., Brdjanovic, D., 2011. Biological Wastewater Treatment: Principles, Modelling and Design, vol. 7. IWA Publishing. https://doi.org/10.2166/9781780401867.

Holliger, C., Alves, M., Andrade, D., Angelidaki, I., Astals, S., Baier, U., Bougrier, C., Buffiere, P., Carballa, M., de Wilde, V., Ebertseder, F., Fernandez, B., Ficara, E., Fotidis, I., Frigon, J.C., Fruteau de Laclos, H., Ghasimi, D.S.M., Hack, G., Hartel, M., Heerenklage, J., Horvath, I.S., Jenicek, P., Koch, K., Krautwald, J., Lizasoain, J., Liu, j., Mosberger, L., Nistor, M., Oechsner, H., Oliveira, J.V., Paterson, M., Pauss, A., Pommier, S., Porqueddu, I., Raposo, F., Ribeiro, T., Rusch Pfund, F., Stromberg, S., Torrijos, M., van Eekert, M., van Lier, J., Wedwitschka, H., Wierinck, I., 2016. Towards a standardization of biomethane potential tests. Water Sci. Technol. 74 (11), 2515–2522.

Holohan, B.C., Duarte, M.S., Szabo-Corbacho, M.A., Cavaleiro, A.J., Salvador, A.F., Pereira, M.A., Ziels, R.M., Frijters, C.T.M.J., Pacheco-Ruiz, S., Carballa, M., Sousa, D. Z., Stams, A.J.M., O'Flaherty, V., van Lier, J.B., Alves, M.M., 2022. Principles, advances, and perspectives of anaerobic digestion of lipids. Environ. Sci. Technol. 56 (8), 4735–4750. https://doi.org/10.1021/acs.est.1c07868.

Iasmin, M., Dean, L.O., Ducoste, J.J., 2016. Quantifying fat, oil, and grease deposit formation kinetics. Water Res. 88, 786–795. https://doi.org/10.1016/j.watres.2015.11.003.

Kang, D., Saha, S., Kurade, M.B., Basak, B., Ha, G.-S., Jeon, B.-H., Lee, S.S., Kim, J.R., 2021. Dual-stage pulse-feed operation enhanced methanation of lipidic waste during co-digestion using acclimatized consortia. Renew. Sustain. Energy Rev. 145, 111096. https://doi.org/10.1016/j.rser.2021.111096.

Kurade, M.B., Saha, S., Kim, J.R., Roh, H.-S., Jeon, B.-H., 2020. Microbial community acclimatization for enhancement in the methane productivity of anaerobic co-digestion of fats, oil, and grease. Bioresour. Technol. 296, 122294. https://doi.org/10.1016/j.biortech.2019.122294.

Long, J.H., Aziz, T.N., de los Reyes III, F.L., Ducoste, J.J., 2012. Anaerobic co-digestion of fat, oil, and grease (FOG): a review of gas production and process limitations. Process Saf. Environ. Protect. 90 (3), 231–245. https://doi.org/10.1016/j.psep.2011.10.001.

Mahmoud, A., Hamza, R.A., Elbeshbishy, E., 2022. Enhancement of denitrification efficiency using municipal and industrial waste fermentation liquids as external carbon sources. Sci. Total Environ. 816, 151578. https://doi.org/10.1016/j.scitotenv.2021.151578.

Martín-González, L., Castro, R., Pereira, M.A., Alves, M.M., Font, X., Vicent, T., 2011. Thermophilic co-digestion of organic fraction of municipal solid wastes with FOG wastes from a sewage treatment plant: reactor performance and microbial community monitoring. Bioresour. Technol. 102 (7), 4734–4741. https://doi.org/10.1016/j.biortech.2011.01.060.

Mohana, A.A., Roddick, F., Maniam, S., Gao, L., Pramanik, B.K., 2023. Component analysis of fat, oil and grease in wastewater: challenges and opportunities. Anal. Methods 15, 5112–5128. https://doi.org/10.1039/d3ay00985d.

Nghiem, L.D., Koch, K., Bolzonella, D., Drewes, J.E., 2017. Full scale co-digestion of wastewater sludge and food waste: bottlenecks and possibilities. Renew. Sustain. Energy Rev. 72, 354–362. https://doi.org/10.1016/j.rser.2017.01.062.

Peces, M., Pozo, G., Koch, K., Dosta, J., Astals, S., 2020. Exploring the potential of co-fermenting sewage sludge and lipids in a resource recovery scenario. Bioresour. Technol. 300, 122561. https://doi.org/10.1016/j.biortech.2019.122561.

Pintor, A.M.A., Vilar, V.J.P., Botelho, C.M.S., Boaventura, R.A.R., 2016. Oil and grease removal from wastewaters: sorption treatment as an alternative to state-of-the-art technologies. A critical review. Chem. Eng. J. 297, 229–255. https://doi.org/10.1016/j.cej.2016.03.121.

Puyuelo, B., Ponsá, S., Gea, T., Sánchez, A., 2011. Determining C/N ratios for typical organic wastes using biodegradable fractions. Chemosphere 85 (4), 653–659. https://doi.org/10.1016/j.chemosphere.2011.06.066.

Rizkianto, F., Oshita, K., Takaoka, M., 2024. Valorization of fat balls and primary scum from wastewater treatment: a promising renewable lipid feedstock for biodiesel production. Water Sci. Technol. 89, 2073. https://doi.org/10.2166/wst.2024.089.

Romero-Güiza, M., Asiain-Mira, R., Alves, M., Palatsi, J., 2022. Induced air flotation for fat, oil, and grease recovery in urban wastewater: a proposed methodology for system optimization and case study. J. Water Process Eng. 50, 103201. https://doi.org/10.1016/j.jwpe.2022.103201.

Saha, S., Jeon, B. -H., Kurade, M.B., Chatterjee, P.K., Chang, S.W., Markkandan, K., Salama, E.-S., Govindwar, S.P., Roh, H.-S., 2018. Microbial acclimatization to lipidic-waste facilitates the efficacy of acidogenic fermentation. Chem. Eng. J. https://doi.org/10.1016/j.cej.2018.09.220.

Sakaveli, F., Petala, M., Tsiridis, V., Darakas, E., 2021. Enhanced mesophilic anaerobic digestion of primary sewage sludge. Water 13 (3), 348. https://doi.org/10.3390/w13030348.

Salama, E.-S., Saha, S., Kurade, M.B., Dev, S., Chang, S.W., Jeon, B.-H., 2019. Recent trends in anaerobic co-digestion: fat, oil, and grease (FOG) for enhanced biomethanation. Prog. Energy Combust. Sci. 70, 22–42. https://doi.org/10.1016/j.pecs.2018.08.002.

Simion Beldean-Galea, M., Vial, J., Thiébaut, D., Comanc, V., 2013. Characterization of the fate of lipids in wastewater treatment using a comprehensive GC×GC/qMS and statistical approach. Anal. Methods 5, 2824–2831. https://doi.org/10.1039/C3AY00060E.

Sultana, N., Roddick, F., Gao, L., Guo, M., Pramanik, B.K., 2022. Understanding the properties of fat, oil, and grease and their removal using grease interceptors. Water Res. 225, 119141. https://doi.org/10.1016/j.watres.2022.119141.

Szabo-Corbacho, M.A., Sharma, P., Míguez, D., de la Sovera, V., Brdjanovic, D., Etchebehere, C., García, H.A., van Lier, J.B., 2024. Inhibitory effects of long chain fatty acids on anaerobic sludge treatment: biomass adaptation and microbial community assessment. Environ. Technol. Innov. 33, 103529. https://doi.org/10.1016/j.eti.2023.103529.

Van Ginkel, S.W., Oh, S.-E., Logan, B.E., 2005. Biohydrogen gas production from food processing and domestic wastewater. Int. J. Hydrogen Energy 30, 1535–1542. https://doi.org/10.1016/j.ijhydene.2004.09.017.

Wallace, T., Gibbons, D., O'Dwyer, M., Curran, T.P., 2017. International evolution of fat, oil and grease (FOG) waste management: a review. J. Environ. Manag. 187, 424–435. https://doi.org/10.1016/j.jenvman.2016.11.003.

Wang, L., Hossen, E.H., Aziz, T.N., Ducoste, J.J., de los Reyes III, F.L., 2020. Increased loading stress leads to convergence of microbial communities and high methane yields in adapted anaerobic co-digesters. Water Res. 169, 115155. https://doi.org/10.1016/j.watres.2019.115155.

Williams, J.B., Clarkson, C., Mant, C., Drinkwater, A., May, E., 2012. Fat, oil and grease deposits in sewers: characterisation of deposits and formation mechanisms. Water Res. 46, 6319–6328. https://doi.org/10.1016/j.watres.2012.09.002.

Xiao, H., Li, K., Zhang, D., Tang, Z., Niu, X., Yi, L., Lin, Z., Fu, M., 2022. Environmental, energy, and economic impact assessment of sludge management alternatives based on incineration. J. Environ. Manag. 321, 115848. https://doi.org/10.1016/j.jenvman.2022.115848.

Yusuf, H.H., Roddick, F., Gao, L., Pramanik, B.K., 2023. Tackling fat, oil, and grease (FOG) build-up in sewers: insights into deposit formation and sustainable in-sewer management techniques. Sci. Total Environ. 904, 166761. https://doi.org/10.1016/j.scitotenv.2023.166761.

Yusuf, H.H., Roddick, F., Jegatheesan, V., Jefferson, B., Gao, L., Pramanik, B.K., 2024. Uncovering the impact of metals on the formation and physicochemical properties of fat, oil and grease deposits in the sewer system. Chemosphere 364, 143033. https://doi.org/10.1016/j.chemosphere.2024.143033.



https://dspace.org/

Characterisation and anaerobic digestion of fat, oil and grease (FOG) waste from wastewater treatment plants

Alibardi, Luca; Strazzabosco, Alice; Cossu, Raffaello

2025-02
Elsevier
https://doi.org/10.1016/j.jenvman.2025.124193
Alibardi L, Strazzabosco A, Cossu R. (2025) Characterisation and anaerobic digestion of fat, oil and grease (FOG) waste from wastewater treatment plants. Journal of Environmental Management, Volume 375, February 2025, Article number 124193

Downloaded from a DSpace repository. https://dspace.org/