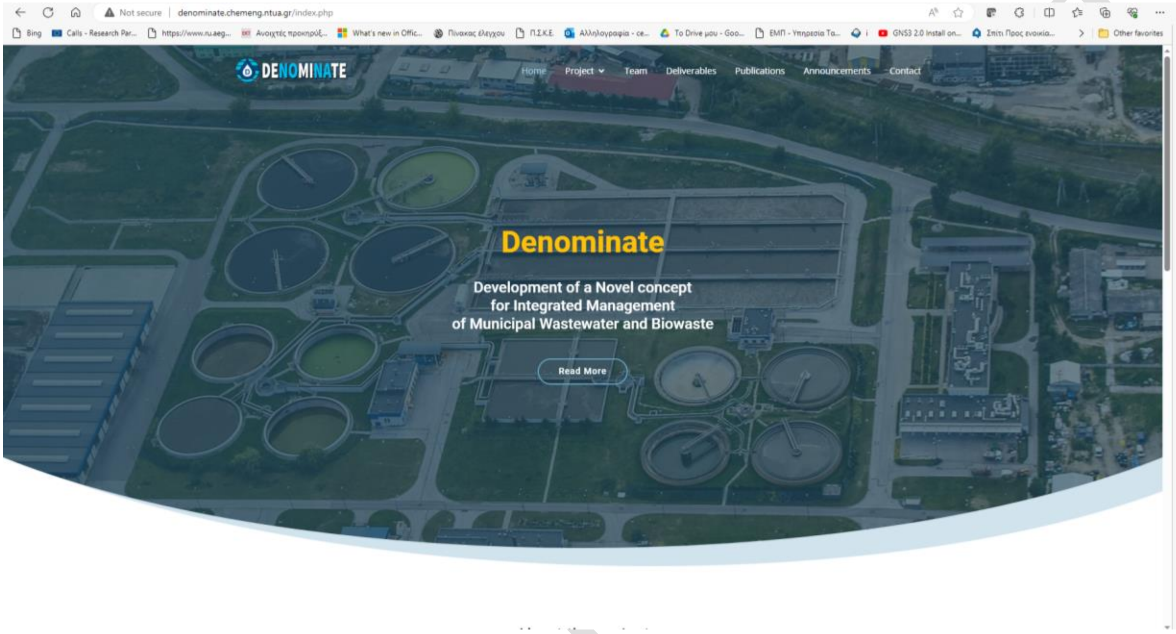
WP9 Επικοινωνία και διάδοση

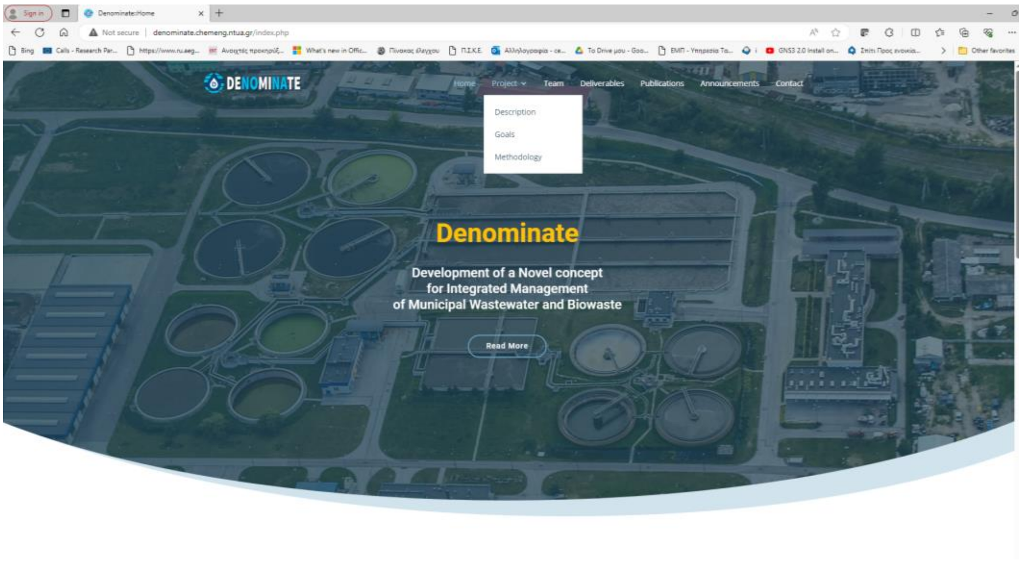
D.9.1 Ιστοσελίδα του έργου.

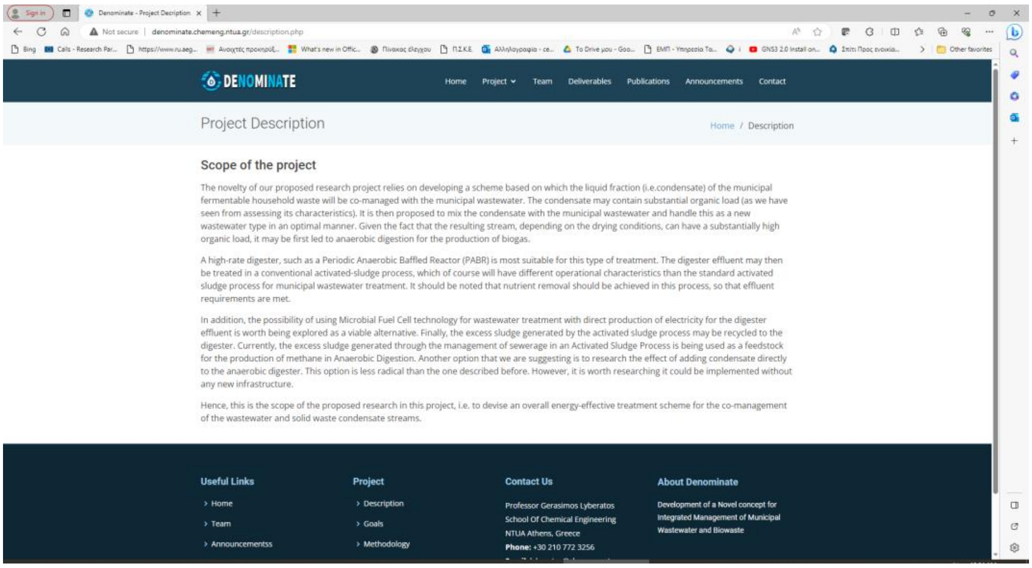
Δημιουργήθηκε η ιστοσελίδα του έργου DENOMINATE [M18]



Όπου καταχωρήθηκαν όλες οι σημαντικές πληροφορίες του έργου όπως:

- η περιγραφή του έργου
- οι στόχοι καθώς και
- η μεθοδολογία που ακολουθήθηκε





Project Description

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Scope of the project

The novelty of our proposed research project relies on developing a scheme based on which the liquid fraction (i.e.condensate) of the municipal fermentable household waste will be co-managed with the municipal wastewater. The condensate may contain substantial organic load (as we have seen from assessing its characteristics). It is then proposed to mix the condensate with the municipal wastewater and handle this as a new wastewater type in an optimal manner. Given the fact that the resulting stream, depending on the drying conditions, can have a substantially high organic load, it may be first led to anaerobic digestion for the production of biogas.

A high-rate digester, such as a Periodic Anaerobic Baffled Reactor (PABR) is most suitable for this type of treatment. The digester effluent may then be treated in a conventional activated-sludge process, which of course will have different operational characteristics than the standard activated sludge process for municipal wastewater treatment. It should be noted that nutrient removal should be achieved in this process, so that effluent requirements are met.

In addition, the possibility of using Microbial Fuel Cell technology for wastewater treatment with direct production of electricity for the digester effluent is worth being explored as a viable alternative. Finally, the excess sludge generated by the activated sludge process may be recycled to the digester. Currently, the excess sludge generated through the management of sewerage in an Activated Sludge Process is being used as a feedstock for the production of methane in Anaerobic Digestion. Another option that we are suggesting is to research the effect of adding condensate directly to the anaerobic digester. This option is less radical than the one described before. However, it is worth researching it could be implemented without any new infrastructure.

Hence, this is the scope of the proposed research in this project, i.e. to devise an overall energy-effective treatment scheme for the co-management of the wastewater and solid waste condensate streams.

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Project
- Description
- Goals
- Methodology

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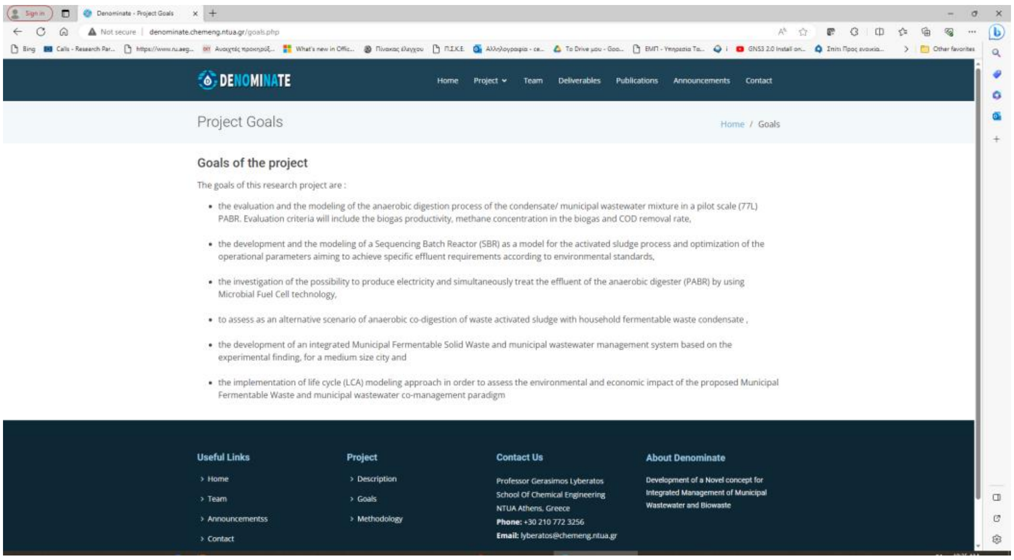
About Denominate
Development of a Novel concept for Integrated Management of Municipal Wastewater and Biowaste



Project Goals

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Goals of the project

The goals of this research project are :

- the evaluation and the modeling of the anaerobic digestion process of the condensate/ municipal wastewater mixture in a pilot scale (77L) PABR. Evaluation criteria will include the biogas productivity, methane concentration in the biogas and COD removal rate,
- the development and the modeling of a Sequencing Batch Reactor (SBR) as a model for the activated sludge process and optimization of the operational parameters aiming to achieve specific effluent requirements according to environmental standards,
- the investigation of the possibility to produce electricity and simultaneously treat the effluent of the anaerobic digester (PABR) by using Microbial Fuel Cell technology,
- to assess as an alternative scenario of anaerobic co-digestion of waste activated sludge with household fermentable waste condensate ,
- the development of an integrated Municipal Fermentable Solid Waste and municipal wastewater management system based on the experimental finding, for a medium size city and
- the implementation of life cycle (LCA) modeling approach in order to assess the environmental and economic impact of the proposed Municipal Fermentable Waste and municipal wastewater co-management paradigm

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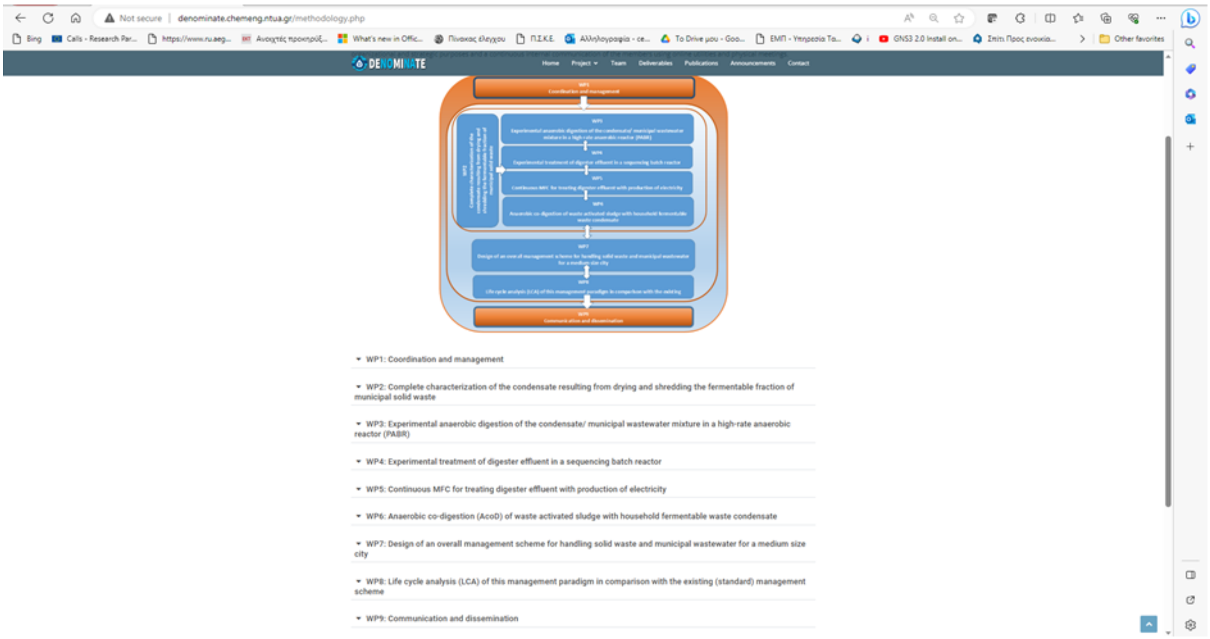
About Denominate
Development of a Novel concept for Integrated Management of Municipal Wastewater and Biowaste



D9.2 Δραστηριότητες και διάδοση των αποτελεσμάτων

Η ομάδα του DENOMINATE απαρτίζεται από τα ακόλουθα ερευνητικά μέλη όπου βοήθησαν για την ολοκλήρωση αυτού του έργου:

Καθ. Γεράσιμος Λυμπεράτος (επιστημονικός υπεύθυνος)

Δρ. Κωνσταντίνα Παπαδοπούλου (ΕΔΙΠ)

Δρ. Ασημίνα Τρεμούλη (μεταδιδάκτωρ)

Δρ. Γεώργιος Μάριος Λύτρας (μεταδιδάκτωρ)

Δρ. Θεόφιλος Καμπερίδης (μεταδιδάκτωρ)

Αχιλλέας Ζαρκαλίου (υποψήφιος διδάκτωρ)

Γεράσιμος Κανέλλος (υποψήφιος διδάκτωρ)

Στα πλαίσια του έργου DENOMINATE ολοκληρώθηκαν 8 διπλωματικές (παρακάτω πίνακας), ενώ είναι υπο ολοκλήρωση τα διδακτορικά των Α. Ζαρκαλίου και Γ. Κανέλλος, στην Σχολή Χημικών Μηχανικών ΕΜΠ στο εργαστήριο Οργανικής Χημικής Τεχνολογίας.

Όνομα	Επώνυμο	Τίτλος
ΑΝΤΙΓΟΝΗ	ΣΤΑΜΕΛΟΥ	Αξιοποίηση υγρού κλάσματος αποβλήτων τροφίμων για παραγωγή αέριων βιοκαυσίμων σε αντιδραστήρα CSTR
ΕΥΑΓΓΕΛΙΑ	ΠΡΙΦΤΗ	Συν-επεξεργασία αστικών υγρών αποβλήτων σε αντιδραστήρα SBR (Sequencing Batch Reactor – αντιδραστήρας διαλείπουσας λειτουργίας)
ΑΝΝΑ	ΜΩΚΟΥ	Επεξεργασία αστικών υγρών αποβλήτων σε ταχύρρυθμο βιοαντιδραστήρα (PABR), με λειτουργία (ABR)
ΙΩΑΝΝΑ – ΕΛΕΝΗ	ΚΙΟΥΚΗ	Επεξεργασία υγρών αποβλήτων σε αντιδραστήρα SBR (Sequencing Batch Reactor - αντιδραστήρας διαλείπουσας λειτουργίας)
ΔΗΜΗΤΡΙΟΣ	ΜΙΧΟΠΟΥΛΟΣ	Σταθεροποίηση αποβλήτων από φωτοβολταϊκά πάνελ
ΑΝΤΩΝΙΟΣ	ΚΟΝΔΥΛΗΣ	Συνεπεξεργασία υγρού κλάσματος τροφικών αποβλήτων με λυματολάσπη για παραγωγή αέριων βιοκαυσίμων σε αντιδραστήρα CSTR
Ευφροσύνη	Κουτρουμάνου	Μελέτη ενεργειακής αξιοποίησης του συμπυκνώματος της ξήρανσης ζυμώσιμων αστικών αποβλήτων
Ευάγγελος Μάριος	Καστρίνης	Μελέτη Διαφορετικών Υλικών Κατασκευής σε Μικροβιακή Κυψελίδα Καυσίμου

Η διάδοση των αποτελεσμάτων του έργου DENOMINATE πραγματοποιήθηκε με 2 δημοσιεύσεις σε διεθνή περιοδικά με κριτές και 9 ανακοινώσεις σε διεθνή και εθνικά συνέδρια, όπως παρουσιάζονται παρακάτω:

Δημοσιεύσεις σε διεθνή περιοδικά με κριτές

1. *G.M. Lytras, E. Koutroumanou, and G., Lyberatos, Anaerobic co-digestion of condensate produced from drying of Household Food Waste and Waste Activated Sludge, Journal of Environmental Chemical Engineering, Volume 8, Issue 4, 2020, DOI: 10.1016/j.jece.2020.103947.*
2. Zarkaliou A., Kougias C., Mokou A., Papadopoulou K*. Lyberatos G. Anaerobic Digestion of Synthetic Municipal Wastewater (MWW) in a Periodic Anaerobic Baffled Reactor (PABR): Assessment of COD

Removal and Biogas Production, *Applied Sciences* (2022), 12 (24), https://doi.org/10.3390/app122413037.

Ανακοινώσεις σε διεθνή συνέδρια

3. *G. Kanellos, A. Tremouli, G. Lytras, A. Kondylis, G. Lyberatos, Co-digestion of the liquid fraction of food waste with waste activated sludge, 8th International conference of engineering for waste and biomass valorization, WasteEng2020.*
4. Lyberatos G., keynote speaker, Integrated management of municipal wastewater with source collected biowaste"International Conference "Protection & Restoration of the Environment - PREXVI", Kalamata, July 5-8 2022, Elite Resort Hotel
5. *A. Zarkaliou, C. Kougias, K. Papadopoulou, G. Lyberatos, Anaerobic Digestion of Municipal Wastewater (MWW) in a Periodic Anaerobic Baffled Reactor (PABR), 17th International Conference on Environmental Science and Technology Athens, Greece, 1 to 4, CEST2021.*
6. *T. Kamperidis, P. Pandis, E. Vlachaki, A. Tremouli, G. Lyberatos, Condensate originating from household fermentable waste as a substrate for microbial fuel cells, 17th International Conference on Environmental Science and Technology Athens, Greece, 1 to 4 September 2021, CEST2021.*
7. Zarkaliou A., Papadopoulou K.*, Mokou A., Kiouki E., Lyberatos G., Development of a novel concept for interrated management of municipal wastewater and biowaste. 9th International Conference on Engineering for Waste and Biomass Valorisation WasteEng2022, Copenhagen (Denmark), June 27-30, 2022
8. Zarkaliou A. Prifti E., Kokkas T., Papadopoulou K.*, Lyberatos G., Development of an innovative scheme for the simultaneous treatment of municipal wastewater and the condensate from drying food waste, 18th International Conference on Environmental Science and Technology. CEST2023, 30 August to 2 September 2023, Athens, Greece.
9. Lyberatos G., keynote presentation Combined management of food waste and municipal wastewater, 18th International Conference on Environmental Science and Technology. CEST2023, 30 August to 2 September 2023, Athens, Greece.

Ανακοινώσεις σε εθνικά συνέδρια

10. Ζαρκαλίου Α, Παπαδοπούλου Κ*, Λυμπεράτος Γ, Ανάπτυξη Καινοτόμου Προσέγγισης για την Ολοκληρωμένη Διαχείριση των Αστικών Υγρών Αποβλήτων και Βιοαποβλήτων, 13ο Πανελλήνιο Επιστημονικό Συνέδριο Χημικής Μηχανικής Πάτρα, 2-4 Ιουνίου 2022

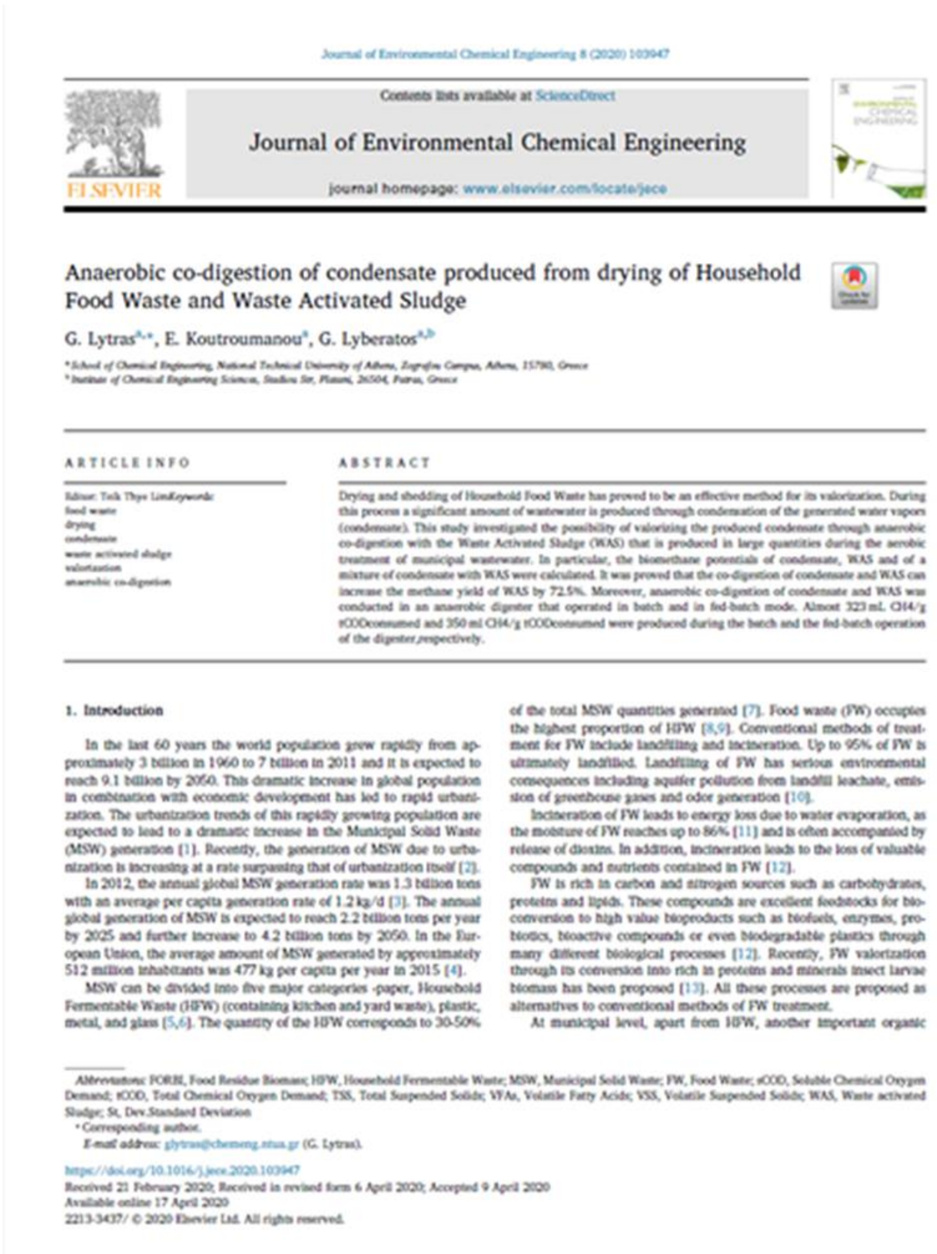
11. Α. Ζαρκαλίου, Κ. Παπαδοπούλου*, Γ. Λυμπεράτος Ολοκληρωμένη διαχείριση των βιοαποβλήτων και αστικών υγρών αποβλήτων για παραγωγή βιοαερίου, ΕΛΛΗΝΙΚΗ ΕΤΑΙΡΕΙΑ ΔΙΑΧΕΙΡΙΣΗΣ ΣΤΕΡΕΩΝ ΑΠΟΒΛΗΤΩΝ σε συνεργασία με την International Solid Waste Association (ISWA), «Επιτάχυνση της Μετάβασης στην Κυκλική Οικονομία - Ευκαιρίες & Κίνδυνοι», 28—29 Σεπτεμβρίου 2022 (Πολυτεχνείο, Πατησίων)

D.9.3 Έκθεση σχεδίου διάδοσης στο τέλος του έργου

Παρακάτω παρουσιάζεται ολοκληρωμένα η διάδοση των αποτελεσμάτων του έργου DENOMINATE

Publication

1. G.M. Lytras, E. Koutroumanou, and G., Lyberatos, Anaerobic co-digestion of condensate produced from drying of Household Food Waste and Waste Activated Sludge, Journal of Environmental Chemical Engineering, Volume 8, Issue 4, 2020, DOI: 10.1016/j.jece.2020.103947.



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Anaerobic co-digestion of condensate produced from drying of Household Food Waste and Waste Activated Sludge

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ABSTRACT

Drying and shedding of Household Food Waste has proved to be an effective method for its valorization. During this process a significant amount of wastewater is produced through condensation of the generated water vapors (condensate). This study investigated the possibility of valorizing the produced condensate through anaerobic co-digestion with the Waste Activated Sludge (WAS) that is produced in large quantities during the aerobic treatment of municipal wastewater. In particular, the biomethane potentials of condensate, WAS and of a mixture of condensate with WAS were calculated. It was proved that the co-digestion of condensate and WAS can increase the methane yield of WAS by 72.5%. Moreover, anaerobic co-digestion of condensate and WAS was conducted in an anaerobic digester that operated in batch and in fed-batch mode. Almost 323 mL CH4/g tCODconsumed and 350 ml CH4/g tCODconsumed were produced during the batch and the fed-batch operation of the digester,respectively.

1. Introduction

In the last 60 years the world population grew rapidly from approximately 3 billion in 1960 to 7 billion in 2011 and it is expected to reach 9.1 billion by 2050. This dramatic increase in global population in combination with economic development has led to rapid urbanization. The urbanization trends of this rapidly growing population are expected to lead to a dramatic increase in the Municipal Solid Waste (MSW) generation [1]. Recently, the generation of MSW due to urbanization is increasing at a rate surpassing that of urbanization itself [2].

In 2012, the annual global MSW generation rate was 1.3 billion tons with an average per capita generation rate of 1.2 kg/d [3]. The annual global generation of MSW is expected to reach 2.2 billion tons per year by 2025 and further increase to 4.2 billion tons by 2050. In the European Union, the average amount of MSW generated by approximately 512 million inhabitants was 477 kg per capita per year in 2015 [4].

MSW can be divided into five major categories -paper, Household Fermentable Waste (HFW) (containing kitchen and yard waste), plastic, metal, and glass [5,6]. The quantity of the HFW corresponds to 30-50% of the total MSW quantities generated [7]. Food waste (FW) occupies the highest proportion of HFW [8,9]. Conventional methods of treatment for FW include landfilling and incineration. Up to 95% of FW is ultimately landfilled. Landfilling of FW has serious environmental consequences including aquifer pollution from landfill leachate, emission of greenhouse gases and odor generation [10].

Incineration of FW leads to energy loss due to water evaporation, as the moisture of FW reaches up to 86% [11] and is often accompanied by release of dioxins. In addition, incineration leads to the loss of valuable compounds and nutrients contained in FW [12].

FW is rich in carbon and nitrogen sources such as carbohydrates, proteins and lipids. These compounds are excellent feedstocks for bioconversion to high value bioproducts such as biofuels, enzymes, probiotics, bioactive compounds or even biodegradable plastics through many different biological processes [12]. Recently, FW valorization through its conversion into rich in proteins and minerals insect larvae biomass has been proposed [13]. All these processes are proposed as alternatives to conventional methods of FW treatment.

At municipal level, apart from HFW, another important organic

Abbreviations: FORBI, Food Residue Biomass; HFW, Household Fermentable Waste; MSW, Municipal Solid Waste; FW, Food Waste; sCOD, Soluble Chemical Oxygen Demand; tCOD, Total Chemical Oxygen Demand; TSS, Total Suspended Solids; VFAs, Volatile Fatty Acids; VSS, Volatile Suspended Solids; WAS, Waste activated Sludge; St, Dev.Standard Deviation

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Available online 17 April 2020
2213-3437/

Table 1
Methane yield of co-digestion of WAS with different co-substrates. Modified from Yang et al. 2019 [34]

Co-substrates	Optimal mixed ratio[a]	Running condition	OLR	Biogas yield	Methane yield	Reference
Swine manure	30:70 (w/w)	Semi-continuous mesophilic	1.91 g VS/L/d	402 ml biogas/ g VS_{added}	192.5 ml CH_4/ g COD_{added}[b]	Borowski et al. 2014 [40]
Wheat straw	19:11 (VS)	Batch mesophilic	-		345.5 ml CH_4/ g VS_{added} 243.3 ml CH_4/ g COD_{added}[b]	Elsayed et al. 2016 [41]
Coffee grounds	85:15 (dry solid)	CSTR thermophilic	7.54 g COD/L/d	185 ml/g COD_{added}	107.9 ml CH_4/ g COD_{added}[b]	Qiao et al. 2013 [42]
Microalgae	25:75 (VS)	Batch mesophilic	-		442.5 ml CH_4/ g VS_{added} 311.6 ml CH_4/g COD_{added}[b]	Beltrán et al. 2016 [43]
Cheese whey	5:95 (v/v)	Batch mesophilic	-		301.2 ml CH_4/g VS_{added} 212.1 ml CH_4/g COD_{added}[b]	Fernández et al. 2014 [44]
	5:95 (v/v)	Batch thermophilic	-		250.6 ml CH_4/g VS_{added} 176.5 ml CH_4/g COD_{added}[b]	
Olive mill wastewater	5:95 (v/v)	Continuous mesophilic	0.9 g VS/L/d	304 ml biogas/g VS_{added}	157.1 ml CH_4/g COD_{added}[b]	Maragkaki et al. 2017 [45]
Brewery sludge	75:25 (w/w)	CSTR mesophilic	1.37 g VS/L/d	650 ml biogas/g VS_{added}	220 ml CH_4/g $COD_{removed}$	Pecharaply et al. 2007 [46]
Meat Processing sludge	46:54 (VS)	CSTR mesophilic	3.46 g VS/L/d		463 ml CH_4/g VS_{added} 326.1 ml CH_4/g COD_{added}[b]	Luostarinen et al. 2009 [47]
Co-substrates	Optimal mixed ratio[a]	Running condition	OLR	Biogas yield	Methane yield	Reference
Fat, oil and grease	64:36 (VS)	Semi-continuous mesophilic	2.34 g VS/L/d		598.4 ml CH_4/g VS_{added} 421.4 ml CH_4/g COD_{added}[b]	Wan et al. 2011[48]
Trapped Grease waste	23:77 (VS)	CSTR mesophilic	1.6 g VS/L/d		369 ml CH_4/g VS_{added} 259.9 ml CH_4/g COD_{added}[b]	Silvestre et al. 2011 [49]
	27:73 (VS)	CSTR thermophilic	2.1 g VS/L/d.		277 ml CH_4/g VS_{added} 195.1 ml CH_4/g COD_{added}[b]	Silvestre et al. 2014 [50]
Food wastewater	75:25 (v/v)	Semi-continuous thermophilic	6.88 g COD/L/d		316 ml CH_4/g $COD_{removed}$	Jang et al. 2015 [51]
	75:25 (v/v)	Semi-continuous mesophilic	6.88 g COD/L/d		268 ml CH_4/g $COD_{removed}$	Jang et al. 2016 [52]
Food waste	50:50 (VS)	Semi-continuous mesophilic	2.43 g VS/L/d		321 ml CH_4/g VS_{added} 226 ml CH_4/g COD_{added}[b]	Heo et al. 2004 [53]
Fruit waste	21:79 (w/w)	Semi-continuous mesophilic	3 g VS/L/d		300 ml CH_4/g VS_{added} 211 ml CH_4/g COD_{added}[b]	Fonoll et al. 2015 [54]

[a] The mixed ratio is Co-substrate:WAS

[b] Calculated based on origin data of the publication and regarding a VS:COD ratio of 1:1.42.

stream that is generated in large quantities is the Waste Activated Sludge (WAS). The WAS is produced during the treatment of municipal wastewater using the activated sludge method. Considering a total COD production of 120 g per person per day, a sludge production of 50-60 g dry matter per capita per day is expected [14,15].

Anaerobic Digestion (AD) has been proposed as an environmentally friendly and cost- effective alternative for the treatment of both HFW and WAS [16–21]. It is a complex microbially mediated process, in which the organic carbon is converted to its most oxidized state (carbon dioxide), and to its most reduced form (methane) in the form of biogas [22]. Biogas consists of methane (50–70%), carbon dioxide (30–50%) and minor amounts of other compounds, such as nitrogen, oxygen, hydrogen sulfide, ammonia and water vapor. The Calorific Value of methane is 50.4 MJ/kg. For biogas with a methane content in the range of 60–65% the Lower Calorific Value (LCV) is approximately 20–25 MJ/m^3-biogas [23]. Biogas is a versatile energy carrier that can be used directly for combined heat and electricity (CHP) generation or can be upgraded into biomethane through removal of CO_2 by processes such as water/amine scrubbing, pressure swing adsorption or the Sabatier reaction. It can then be fed to the natural gas grid or used after compression as a fuel (bioCNG) in the automotive sector [24]. Apart from biogas, digestate is also produced. The digestate is the stabilized nutrient-rich effluent of the AD process, which can be used either as a soil conditioner or as compost after being properly processed [25].

Although AD is currently used for FW treatment at industrial scale, its use is limited and still often faces several technical challenges, such as the need for feedstock pretreatment, VFA accumulation and process instability, foaming, low buffer capacity, and especially high cost of transportation and operation [17]. AD has been traditionally used for the stabilization and reduction of the solid content of WAS. During the AD of WAS energy in the form of biogas is produced [26] but due to the low biodegradability of WAS, the process is not cost effective [27]. Biogas production from AD of WAS can be improved by several pretreatment methods. Thermal, chemical, biological, enzymatic [28] and mechanical processes, as well as combinations of these, have been studied as possible pre-treatment methods of WAS. These methods

Table 2
Main characteristics of condensate, anaerobic sludge and WAS.

Parameter	Condensate		WAS		Anaerobic sludge	
	Average*	St.Dev.	Average*	St.Dev.	Average**	St.Dev.
tCOD (g O_2/L)	11.7	3.07	35.45	5.07	17.09	0.22
sCOD (g O_2/L)	11.7	0.00	0.60	0.28	0.15	0.02
TSS (g/L)	0.05	0.02	39.15	9.97	21.7	1.20
VSS (g/L)	-	-	21.70	1.98	12.7	1.10
pH	4.45	0.40	6.77	0.35	6.98	0.00
Acetate (mg/L)	1340.00	251.40	95.30	10.89	0.00	0.00
Propionate (mg/L)	49.08	13.23	85.60	14.71	0.00	0.00
Iso-butyrate (mg/L)	53.38	16.26	23.62	11.06	0.00	0.00
Butyrate (mg/L)	73.14	40.27	19.95	13.51	0.00	0.00
Iso-valerate (mg/L)	14.99	8.35	14.36	10.10	0.00	0.00
Valerate (mg/L)	0.00	0.00	2.85	1.82	0.00	0.00
Ethanol (mg/L)	3.09	0.85	0.00	0.00	0.00	0.00
TKN (mg/L)	10.90	4.44	1440.00	282.84	1200	120.20
Total alkalinity (mg $CaCO_3$/L)	***		1200.00	150.00	3750.00	250.00

* Average values of the characteristics of three different samples are depicted.
** Average values of the characteristics of three independent measurements of the same sample.
*** Cannot be measured due to low pH.

Table 3
Composition of the feedstocks used in the batch experiments in bench scale bioreactors. Different ratios of condensate to WAS were used in each experiment to investigate the applicability of co-digestion.

Composition (% v/v)			Nomenclature
Condensate	WAS	Anaerobic Sludge (Inoculum)	
19	76.25	4.75	CWA
-	95.25	4.75	WA
95.25	-	4.75	CA
-	-	100	CONTROL

cause disintegration of the cells contained in the WAS, permitting the release of their intracellular matter that becomes more accessible to anaerobic microorganisms. This improves the overall digestion process rate and the extent of sludge degradation, thus reducing the required retention time of the anaerobic digester and increasing the methane production rates [29]. However, these methods of pretreatment require extensive use of chemicals, heat, electricity, or some combination of these, so their application is limited for economic reasons. An alternative method for enhancement of AD of WAS is its co-digestion with other streams of organic waste [30].

It has been proved that for several feedstocks, co-digestion systems perform better than mono-digestion ones [31]. Several studies showed the benefits of co-digestion through mechanisms such as dilution of potential toxic compounds, improvement of nutrient balance, synergistic effects of microorganisms, increased load of biodegradable organic matter leading to higher biogas yields [32]. In particular, co-digestion of WAS with other organic wastes could increase the amount of biodegradable organic matter and at the same time provide a feedstock with an optimum C:N ratio [26]. The optimal C:N ratio for AD ranges from 20 to 30, depending on the feedstock used [33]. A lack of nitrogen has negative effects on the methane yield as it constitutes a structural element of many intracellular components (eg. DNA, RNA and proteins). Conversely, a high nitrogen concentration can imply an excess in the formation of ammonia which is toxic for the process of AD when present at high levels. Many different agricultural, industrial and municipal organic wastes have been used as co-substrates for the anaerobic co-digestion of WAS. The co-digestion of WAS with most of these substrates lead to higher biogas production, compared to the mono-digestion of WAS (Table 1) [9,34].

At municipal level, FW and WAS are currently being treated as separate waste streams, defined by the main phase in each case, solid and liquid, respectively. In the municipality of Halandri [35], in Attica, Greece an innovative FW valorization approach was developed and implemented at pilot-scale within the framework of the Horizon 2020 project WASTE4think [36]. The implemented waste management scheme included the source-separated collection of the household food waste from 250 households. The collected FW was then led to a drying/shredding facility of the Municipality. The drying/shredding process of the food waste results in a homogenized solid biomass product named FORBI (Food Residue Biomass). The mean moisture of FORBI is 10%, as almost 75-80% of the initial moisture of raw material is removed. Moisture is removed in the form of water vapors that are collected by a condenser. FORBI, rich in carbon and nitrogen with optimal C:N ratio is an ideal substrate for many biological processes, such as anaerobic digestion, dark fermentation [37], composting [38] and electricity production through microbial fuel cells [39]. The produced condensate is rich in organic carbon but poor in nitrogen which limits its biological treatment.

Based on the results of the project and the characteristics of condensate, an alternative scenario in which the condensate can be combined and co-managed with the WAS is proposed. In this research work, the feasibility of co-digesting the condensate with WAS is assessed as a novel approach for the valorization of these waste streams.

Through this novel approach for simultaneous treatment of WAS and condensate, the drying and shredding of the FW could take place nearby the existing anaerobic digesters in Wastewater Treatment Plants in order to increase their biogas yield and render the procedure of municipal wastewater treatment less energy demanding and more economical, reducing at the same time the transportation cost of FW treatment.

2. Material and methods

2.1. Analytical methods

The measurements of tCOD and sCOD, TSS and VSS and temperature were carried out according to Standard Methods [55]. The pH was measured using a digital pH-meter (WTW INOLAB PH720). For the quantification of VFAs, 1 ml of sample acidified with 30 μL of 20% H_2SO_4 was analyzed via a gas chromatograph (SHIMADZU GC-2010 plus) equipped with a flame ionization detector and a capillary column (Agilent technologies, 30 m x0.53 mm ID x1 μm film, HP-FFAP) using an autosampler (SHIMADZU AOC-20 s). The oven was programmed from 105 °C to 160 °C at a rate of 15 °C·min^{-1} and subsequently to 225 °C (held for 3 min) at a rate of 20 °C·min^{-1}. Helium was used as the carrier gas at 30 ml·min^{-1}, the injector temperature was set at 230 °C and the detector at 230 °C. For the quantification of the methane content of the biogas, a GC-TCD with Helium as carrier gas was used (SHIMADZU GC-2014). The separation column's (Supelco Carboxen 1000) length was 5 m and the interior diameter 2.1 mm. The initial temperature of the GC-TCD was 40 °C. For the estimation of the methane content a temperature program was used (total duration: 25 min.) during which the temperature was increasing 10 °C·min^{-1} until reaching 185 °C and staying stable at this temperature for 5 minutes. The methane content then was calculated using a standard calibration curve. The biogas production rate was measured using an oil displacement technique [56,57].

2.2. Drying and shredding

The drying and shredding of HFW took place in the commercially available Dryer-shredder GAIA GC-300. In each operation cycle, 130 kg

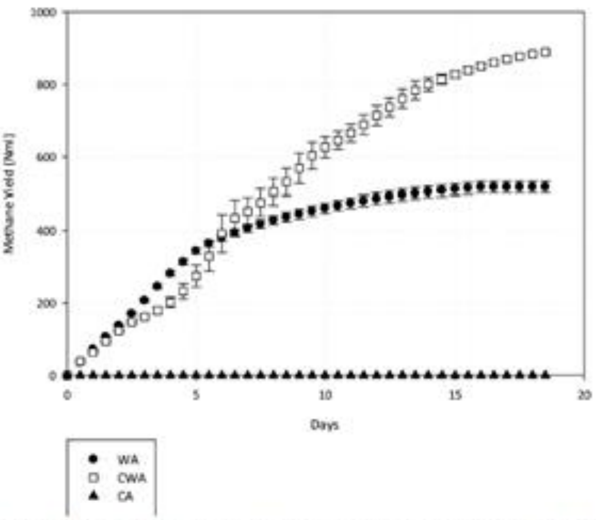

Fig. 1. Cumulative methane production from anaerobic digestion of WAS (WA), condensate (CA) and co-digestion of WAS and condensate (CWA). Each point is the mean of three different replicate experiments. Error bars indicate standard deviation.

Table 4
Main characteristics of each bench scale bioreactor during the start-up and after the end of the batch experiment. Data represent the mean (± standard deviation) of three independent experiments, each performed in triplicate. Total VFAs represent the cumulative concentration of acetate, propionate, isobutyrate, butyrate, isovalerate and valerate.

Sample	Parameter	Initial concentration	Final concentration
CWA	tCOD (g/L)	26.68 ± 1.04	20.02 ± 0.72
WA		28.43 ± 2.05	21.74 ± 1.19
CA		19.64 ± 0.03	20.00 ± 1.79
CWA	sCOD (g/L)	4.08 ± 0.08	0.15 ± 0.03
WA		0.42 ± 0.19	0.13 ± 0.04
CA		18.77 ± 0.99	18.35 ± 1.00
CWA	TKN (mg/L)	1083.69 ± 125	-
WA		1335.25 ± 143	
CA		74.15 ± 15.12	
CWA	TSS (g/L)	28.45 ± 1.74	19.78 ± 2.08
WA		35.12 ± 5.95	23.19 ± 3.94
CA		1.69 ± 0.25	0.29 ± 0.36
CWA	VSS (g/L)	13.68 ± 1.05	9.06 ± 3.24
WA		16.89 ± 2.39	10.13 ± 2.58
CA		0.80 ± 0.15	0.15 ± 0.08
CWA	Total VFAs (mg/L)	671.582 ± 20.05	0 ± 0.01
WA		159.69 ± 15.75	0 ± 0.01
CA		2905.92 ± 124	2878.176 ± 135
CWA	pH	6.4 ± 0.3	7.45 ± 0.2
WA		6.8 ± 0.2	7.52 ± 0.15
CA		4.5 ± 0.2	4.28 ± 0.2

of FW are used, producing 30 kg of FORBI with 10% humidity and 100 kg of condensate. The collected FW contains mainly kitchen waste including fruits, vegetables and cooked food. The food waste is placed inside the chamber of the dryer- shredder and the temperature of the chamber is increased up to 94 °C using an electrical resistance. The temperature is maintained at 94 °C for 9 hours until the drying procedure is complete. A shredder inside the machine is used for grinding. During the process the vapors generated from the chamber are passed through a condenser, generating a liquid condensate.

2.3. Substrates and inoculum

Anaerobic sludge obtained from the mesophilic anaerobic digester of the Municipal Wastewater Treatment Plant of Lycovrisi, Attica, Greece was used as inoculum for both bench and lab scale bioreactors.

The substrates for the co-digestion were condensate from the drying and shredding of FW and WAS from the abovementioned Municipal Wastewater Treatment Plant. Table 2 gives the main characteristics of anaerobic sludge, condensate and WAS.

The condensate: WAS ratio used throughout the experiments was 1:4. This ratio was determined considering the typical production of 0.04 kg of WAS in dry base per capita [58]. The average TSS of the samples taken from WAS and examined in this study was 39.15 ± 9.97 g/L, which is common for WAS, therefore almost 0.8 L of WAS are produced per capita per day. Regarding the production of HFW, almost 0.05- 0.06 kg of HFW on a dry basis are produced per capita per day [14] corresponding to 0.22 kg of raw HFW per capita per day. As mentioned before, 100 kg of condensate are produced from drying and shredding of 130 kilograms of raw HFW, which occupy a volume of 110 L. Therefore, almost 0.2 L of condensate are produced per capita per day.

2.4. Methane potential assessment

Batch experiments were performed using the Automated Methane Potential Test System II (AMPTS; Bioprocess Control AB, Lund, Sweden). Each of the AMPTS' bottles (500 ml total volume; 400 ml

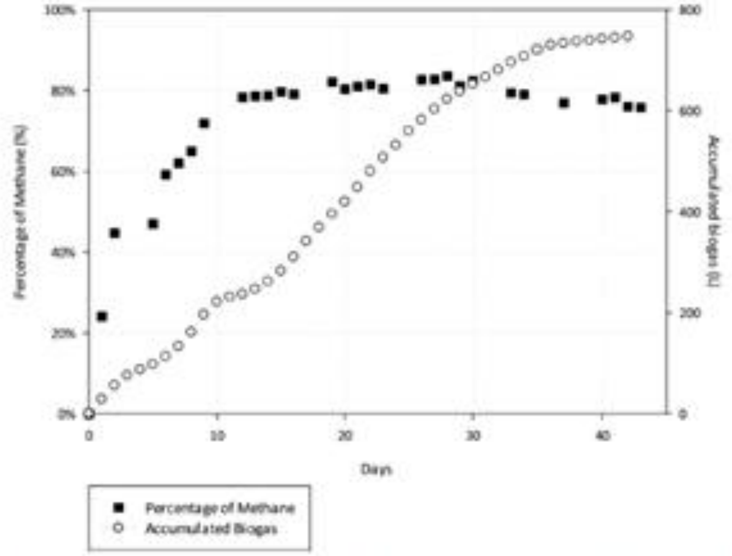

Fig. 2. Cumulative biogas production and percentage of methane during the batch operation of the lab scale anaerobic digester. For the batch operation of the bioreactor a mixture of WAS and condensate in a ratio 4:1 and the inoculum were added at once during start-up.

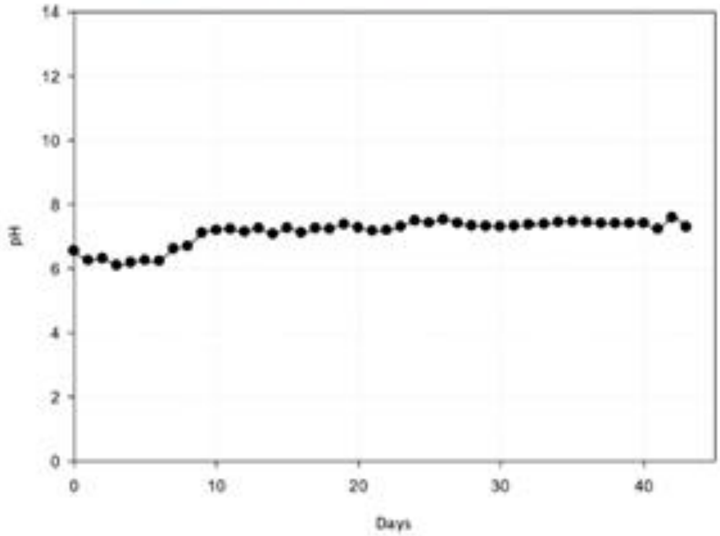

Fig. 3. pH of the bioreactor during the batch operation of the lab scale anaerobic digester. For the batch operation of the bioreactor the feedstocks and the inoculum were added at once during start-up.

working volume and 100 ml headspace) was equipped with an individual mechanical mixer and operated as a bench scale anaerobic bioreactor. The produced biogas from each of the bottles passed through a 3 M NaOH solution which retained CO_2 and H_2S, while allowing methane to pass though. Finally, the upgraded biogas passed through a flow meter device (one for each incubation bottle) which measured gas productivity through water displacement. The results of bench scale experiments are expressed as normalized mL [59]. All experiments started at the same time using the same inoculum and continued until no further biogas was produced. During start-up, flushing with N_2 took place and all samples were incubated at 35 °C throughout the experiment.

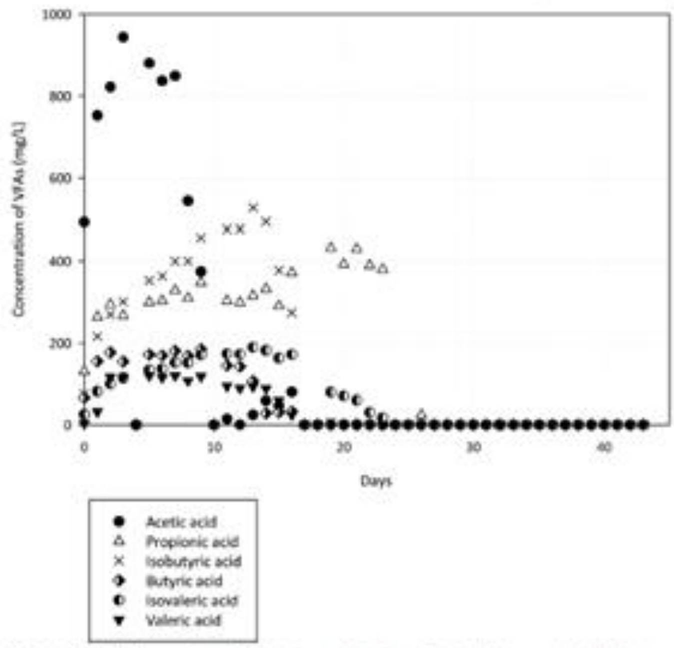

Fig. 4. Concentration of VFAs during the batch operation of the lab scale anaerobic digester. For the batch operation of the bioreactor the feedstocks and the inoculum were added at once during start-up.

Table 5
Main characteristics of the of the lab scale bioreactor during the start-up and after the end of the batch experiment. Total VFAs represent the cumulative concentration of acetate, propionate, isobutyrate, butyrate, isovalerate and valerate.

Parameter	Initial concentration	Final concentration
tCOD (g/L)	33.75	17.9
sCOD (g/L)	3.82	0.28
TSS (g/L)	42.8	25.1
VSS (g/L)	18.8	13.0
pH	6.55	7.29
Total VFAs (mg/L)	791.64	0
TKN (mg/L)	1100	-

These experiments were conducted to determine the methane yield of the individual substrates (condensate and WAS) and of the mixture of the condensate and WAS (ratio 1:4). Anaerobic mono-digestions of WAS and condensate were performed to assess the biomethane potential of each substrate. Anaerobic co-digestion was performed to assess the feasibility of co-digesting the two streams. The experimental design is shown in Table 3. All batch tests were performed in triplicate.

2.5. *Batch and fed-batch experiments in bioreactor*

A bioreactor made of stainless steel with a working volume of 100 L was used for the conduction of batch and fed-batch experiments. The content of the bioreactor was continuously stirred by a propeller agitator. The temperature was kept constant at 35 °C by circulating water from a thermostated bath through the bioreactor's jacket. In both cases, during start-up, 5 L of anaerobic sludge were used as inoculum. For the batch mode operation 20 L of condensate and 80 L of WAS were added at once during start-up. For the fed batch operation, 80 L of WAS were added at the start-up of the bioreactor and 1 L of condensate was added once a day for a time period of 20 days.

3. Results and discussion

3.1. *Methane potential experiments*

The cumulative methane yields during the anaerobic digestion of each substrate and co-digestion of both substrates are shown in Fig. 1. The batch experiments lasted 20 days until little or no biogas production was observed. The results presented are the net methane yield after subtracting the control yield.

According to Fig. 1, no methane was produced from anaerobic digestion of the condensate alone. Almost 518 Nml of methane were produced through anaerobic digestion of WAS, which corresponds to a methane yield of 193.6 Nml CH_4/g $tCOD_{consumed}$.

Co-digestion of WAS and condensate led to a higher methane yield of 334.1 Nml CH_4/g $tCOD_{consumed}$ producing almost 890 Nml of methane. Therefore, the co-digestion of WAS with condensate enhanced the methane yield from 193.6 to 334.1 Nml CH_4/g $tCOD_{consumed}$ that is an almost 72.5% increase in the methane yield compared with the anaerobic digestion of WAS.

The C:N ratio of the feedstock used in each experiment is an important factor that determines the methane yield. The C:N ratio of condensate is almost 1070:1 therefore the amount of nitrogen is a limiting factor for its anaerobic digestion. Through the addition of WAS

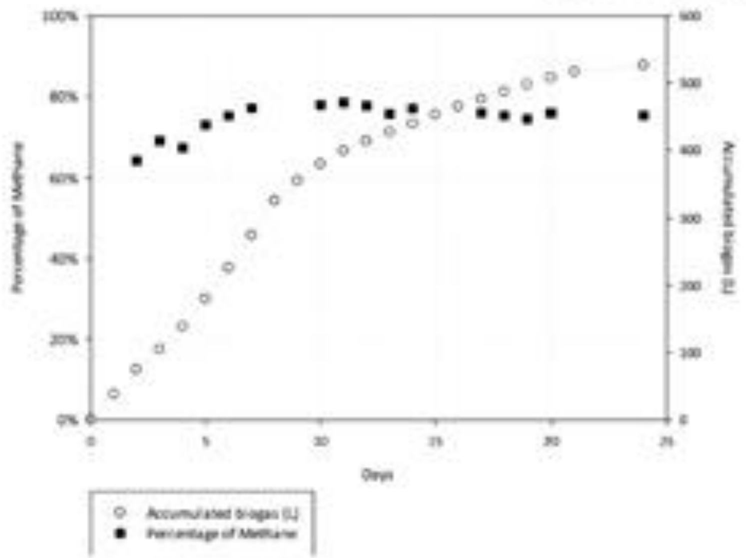

Fig. 5. Cumulative biogas production and percentage of methane during the fed batch operation of the lab scale anaerobic digester. For the fed batch operation, WAS and the inoculum were added at the start-up of the bioreactor and 1 L of condensate was added once a day for a time period of 20 days.

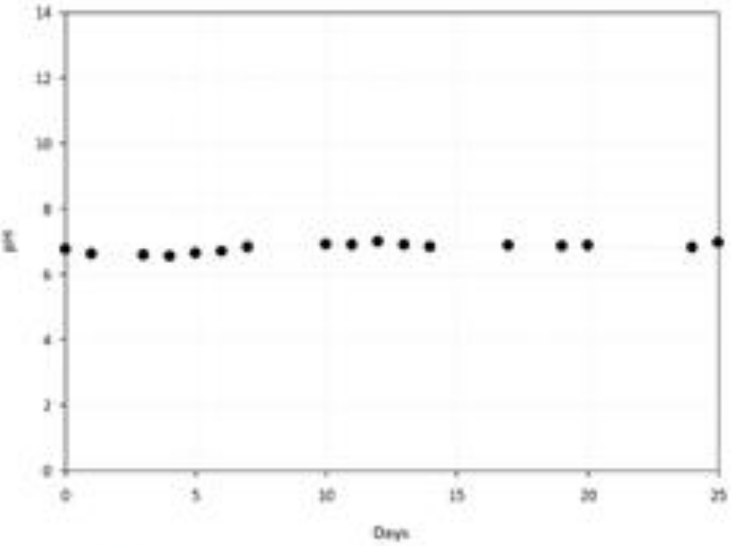

Fig. 6. pH of the bioreactor during the fed batch operation of the lab scale anaerobic digester.. For the fed batch operation, WAS and the inoculum were added at the start-up of the bioreactor and 1 L of condensate was added once a day for a time period of 20 days.

to condensate, the C:N ratio of the feedstock used for anaerobic digestion increased from 21.3 (WA) to 24.6 (CWA) (Table 4).

3.2. Batch experiment in bioreactor

A batch experiment in a bioreactor with a working volume of 100 L was also conducted. The batch experiment lasted for 42 days until no further biogas was produced. As seen in Fig. 2, almost 750 L biogas were produced during the operation of the bioreactor. The mean methane percentage was 71.6% and it remained above 59% after the sixth day.

During start-up of the bioreactor, the pH decreased sharply reaching 6.1, which is inhibitory for anaerobic digestion. Nevertheless, after the 7[th] day of operation the pH of bioreactor (Fig. 3) increased up to 7.

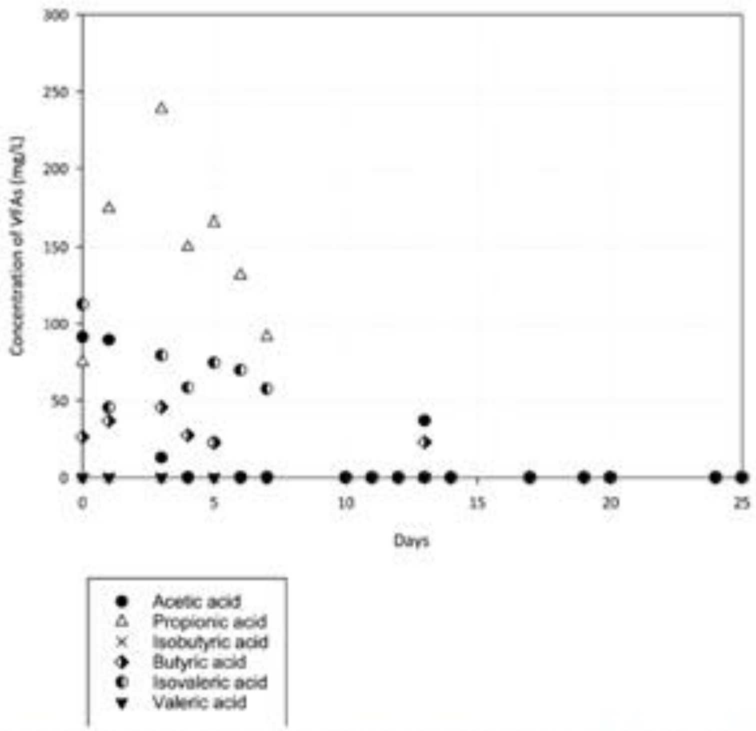

Fig. 7. Concentration of VFAs during the fed batch operation of the lab scale anaerobic digester. For the fed batch operation, WAS and the inoculum were added at the start-up of the bioreactor and 1 L of condensate was added once a day for a time period of 20 days.

Table 6
Main characteristics of the of the lab scale bioreactor during the start-up and after the end of the fed batch experiment. Total VFAs represent the cumulative concentration of acetate, propionate, isobutyrate, butyrate, isovalerate and valerate.

Parameter	Initial concentration	Final concentration
tCOD (g/L)	32.04	16.69
sCOD (g/L)	1.25	0.15
TSS (g/L)	33.22	21.73
VSS (g/L)	16.47	12.74
pH	6.76	6.96
Total VFAs (mg/L)	305.1	0
TKN (mg/L)	1250	-

Then, it remained stable and close to the optimum for anaerobic digestion pH range (6.8 to7.2) [60].

The significant decrease of pH during the start-up of the bioreactor coincided with a significant increase in the concentration of VFAs of bioreactor (Fig. 4). The concentration of acetate increased significantly during the start-up of the bioreactor and reached up to 945 mg/L. The accumulation of acetate is indicative of inhibition of acetotrophic methanogenesis. After a period of acclimation, the concentration of VFAs decreased significantly until no VFAs were detected.

Co-digestion of WAS and condensate in bioreactor led to a methane yield of 322.67 mL CH_4/ g $tCOD_{consumed}$ (Table 5). Therefore, the results obtained from the batch experiment in the lab scale bioreactor are in agreement with the findings of the methane potential experiments.

3.3. *Fed batch experiments in bioreactor*

According to Fig. 1 the cumulative methane production curve during the batch experiment appears to be sigmoid. The lag phase is indicative of inhibition. During the lag phase the pH of the bioreactor remained below the optimum for methanogens range of pH resulting in a low percentage of methane in the produced biogas. This inhibition could be attributed to the low pH and high concentration of VFAs of the condensate. In order to alleviate the possible inhibition due to addition of a high quantity of condensate, we also operated the bioreactor in a fed-batch mode.

The fed batch experiment lasted for 24 days until no further biogas was produced. Almost 525 L of biogas were produced during the fed-batch operation of the lab scale bioreactor (Fig. 5). The mean methane percentage was 74.3% and remained above 64% throughout the experiment.

The pH remained above 6.5 throughout the fed-batch experiment (Fig. 6) which is within the optimum pH range for anaerobic digestion. In addition, the concentration of VFAs remained below 310 mg/L throughout the experiment (Fig. 7). Therefore, VFAs did not accumulate in the bioreactor.

The fed-batch operation of the lab scale bioreactor led to a methane yield of 342.81 mL CH_4/ g $tCOD_{consumed}$ (Table 6), which is higher than the one obtained though the batch operation of the lab scale digester. The methane yield is close to the theoretical yield of methane which is equal to 350 ml/ g $tCOD_{removed}$. Therefore, the co-digestion of WAS with condensate proved to be a really promising alternative for the valorization of both streams.

3.4. Discussion

Co-digestion of WAS and condensate proved to be an effective way not only to enhance the methane yield of WAS but also to treat the condensate.

The condensate could not be used as feedstock for anaerobic microorganisms due to low concentration of TKN. The low C:N ratio of condensate hinders the biological treatment of this stream, as there is not enough nitrogen for the microorganisms to build up important biological molecules like proteins and nucleic acids. Apart from nitrogen, the condensate is also poor in other minerals and phosphate, which are important for the biological processes. Nevertheless, the condensate contains easily degradable carbon that can easily be consumed by microorganisms whenever sufficient amounts of nitrogen, phosphorus and minerals are secured.

During the batch operation of the 100 L bioreactor almost 320 mL CH_4/ g $tCOD_{consumed}$, which is close to the yield obtained from anaerobic co-digestion of FW with food wastewater. (Table 1). Even higher methane yield was achieved during the fed-batch operation of the bioreactor, reaching up to 342.81 mL CH_4/ g $tCOD_{consumed}$. In this research work the ratio of condensate: WAS used in the co-digestion process was calculated based on real data regarding the production of condensate and WAS at municipal level, so we did not attempt to optimize these ratios to get a better methane yield but to investigate the effect of several operational parameters on the methane yield.

This research work represents part of an innovative method for the combined treatment of the overall biodegradable organic wastes (HFW and wastewater) that are produced at Municipal level which is totally different from the current waste management scheme

4. Conclusion

In this study, WAS and condensate, produced through drying and shredding of source-separated collected FW, were co-digested in mesophilic conditions. Almost 322.67 mL CH_4/ g $tCOD_{consumed}$ and 342.81 mL CH_4/ g $tCOD_{consumed}$ were produced during the batch and the fed-batch operation of a lab scale anaerobic digester. The co-digestion of WAS and condensate enhanced the methane yield of WAS by 40% (batch operation) and by 43.5% (fed batch operation). This finding is important for the re-design of the current waste management scheme. Based on the obtained results, units for the drying and shredding of FW could be installed in existing wastewater treatment plants. The produced condensate could be co-digested with WAS, limiting the cost of treatment of wastewater treatment and the produced FORBI could be an ideal substrate for many biological processes.

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.

CRediT authorship contribution statement

G. Lytras: Methodology, Validation, Writing - review & editing. **E. Koutroumanou:** Investigation, Writing - original draft. **G. Lyberatos:** Conceptualization, Writing - review & editing, Supervision.

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Anaerobic Digestion of Synthetic Municipal Wastewater (MWW) in a Periodic Anaerobic Baffled Reactor (PABR): Assessment of COD Removal and Biogas Production

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Abstract: The benchmark approach for municipal wastewater treatment is based on biological oxidation. Due to high energy consumption, alternative treatment schemes are proposed, among which anaerobic digestion is the most promising. In this work, the direct anaerobic digestion of municipal wastewater in a high-rate system is examined. The reactor utilized for the study is the periodic anaerobic baffled reactor (PABR). Two distinct experimental cycles were conducted, during which the operational parameters of the PABR were consecutively modified: in the first cycle, six phases were conducted where the hydraulic retention time (HRT) varied from 10 to 1 days, the period T between 2.5 days and 0.25, while the OLR remained constant at values near 1.0 gsCOD/L/d. During the second cycle, four distinct phases were conducted with no switching imposed. The HRT varied from 4 to 1 d. The last experimental phase of both cycles was the most significant, due to feedstock resemblance to raw wastewater. The biogas and the biomethane production rates reached 66.8 L/d and 41.1 L/d, respectively, while the COD reduction rate reached 73.7%. Conclusively, the PABR is a high-rate AD system, capable of treating MWW under extreme operational conditions.

Keywords: high-rate anaerobic digestion; municipal wastewater; PABR

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1. Introduction

Wastewater treatment is a key process in ensuring public health and environmental well-being. The environmental aspect of this process is based on removing pollutants, such as organic matter and nutrients (N, P), before disposal. The energy cost of the activated sludge process, the most widely used municipal wastewater treatment process, is quite high (0.69–3.01 kWh/kg COD) [1]. The increase in the cost of energy has led to research on more environmental and economically efficient methods. The new approaches of domestic wastewater management are based on circular ways to recover valuable nutrients and energy, as opposed to the traditional linear methods [2]. Currently, the benchmark approach to municipal wastewater management consists of sewer collection, treatment in a facility aimed at removal of suspended solids through primary sedimentation, biological oxidation of organic matter under aerobic conditions, biological nutrient (N and P) removal, and disposal of the clarified effluent following disinfection by chlorination. The process generates a mixture of primary and excess secondary sludge, which are typically mixed, stabilized by anaerobic digestion, and dewatered before disposal [3]. The key operating costs lie in the aeration and in sludge (biosolids) management [4]. Anaerobic digestion emerges as a feasible solution that aims to reduce the energy requirements of WW treatment and is already globally implemented in WW treatment plants. However, AD is most commonly used as a side process in WWTPs, mostly for stabilization of the sludge generated during primary and secondary sedimentation. The efficiency of direct AD of

MWW has been proposed by many researchers, and notable is the installment of a full-scale expanded granular sludge bed reactor (EGSBR) in a WWTP in Ireland, during the operation of which a high BOD removal rate (85%) was accomplished [5]. Another management scheme that is a substantial departure from the conventional activated sludge process is the low-energy mainline (LEM) process [6]. This scheme is based on direct low-strength anaerobic digestion of municipal wastewater after primary sedimentation and use of the reactor's effluent as irrigation water, as no significant amount of nitrogen and phosphorus would be consumed in the anaerobic process, based on the same concept by examining the capabilities of an innovative high-rate anaerobic system to treat municipal wastewater.

The aim of this work is to examine the suitability of a novel high-rate anaerobic system—the periodic anaerobic baffled reactor (PABR)—to treat municipal wastewater directly.

2. Materials and Methods

2.1. Experimental Process

The PABR is a high-rate anaerobic system designed by Skiadas and Lyberatos [7]. It consists of two concentric cylinders, as shown in Figure 1, with the inner one operating as heat exchanger. The space between the two cylinders is divided into four compartments, each of which is divided in two sections, one downflow and one upflow, thus resembling a simple anaerobic baffled reactor (ABR), only arranged in a circular structure.

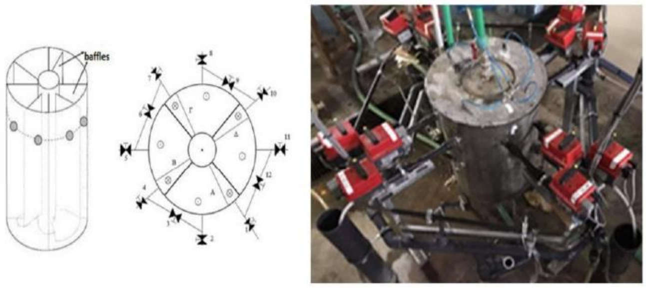

Figure 1. Experimental setup of the PABR used in the experiments. A,B,Γ,Δ indicate the compartments of the reactor. Valves 1,4,7,10 are the inlet valves of compartments A,B,Γ,Δ while valves 2,5,8,11, are their effluent valves. Valves 3,6,9,12 control the communication between the compartments.

The innovative approach of this bioreactor is its ability to periodically change the inflow and outflow compartments. The PABR introduces a novel operational parameter called switching period (T), which along with the hydraulic retention time (HRT) rearranges the flow patterns of the reactor. T is the period for one complete switching of compartment roles. Through this parameter, the time each compartment will be used as the inlet and the outlet is determined. The switching between the compartments is achieved with valves fitted on the external piping, which determine whether the compartment will be used as the inlet or outlet or as an intermediate compartment. This flexibility gives the biomass the opportunity to withstand fluctuations of the feed concentration, leading to easier culture adaptation under extreme or varying conditions.

When the HRT/T ratio is equal to 1, every compartment receives the same amount of untreated substrate. On the other hand, if we do not switch periodically the role of each compartment, the flow pattern of the reactor resembles that of a four-compartment anaerobic baffled reactor. A pilot-scale 77L active volume PABR was utilized and both operation modes (switching and ABR mode) were examined and evaluated for similar organic loading rates and HRTs.

A number of studies have examined the performance of the PABR under various OLRs, HRTs, and TS and by utilizing different types of feedstock other than typical municipal wastewaters [8–12].

2.2. Feedstock Composition

In order to secure a constant composition of the feed, instead of real raw municipal wastewater, a synthetic mixture was used that resembles its main characteristics. The synthetic wastewater used for the PABR in the present study consists of: 10 to 1.0 g/L glucose, 0.306 to 0.0285 g/L NH_4Cl (regarding the experimental phase), 0.08 g/L CH_3COONa, 0.044 g/L KH_2PO_4, 0.0275 g/L $MgSO_4{\cdot}7H_2O$, 0.0025 g/L $CaCl_2$, 0.004 g/L KCl, 0.125 g/L $NaHCO_3$, 1.875 mg/L $FeCL_3{\cdot}6H_2O$, 0.1875 mg/L H_3BO_3, 0.225 mg/L KI, 0.15 mg/L $MnSO_4$, 0.0275 mg/L $ZnSO_4{\cdot}7H_2O$, 0.0375 mg/L $CuSO_4{\cdot}5H_2O$ and 12.5 mg/L EDTA [13]. Every experimental phase had different concentration of glucose and ammonium chloride so that the OLR would be kept constant while reducing the HRT. The relative concentrations of these two substances were chosen so that the C/N ratio was maintained constant close to 50 [14].

2.3. Analytical Methods

The scope of the experimental process was to evaluate the efficiency of the PABR under different conditions in terms of organic load reduction and biogas and biomethane productivity. Initially, the COD was high (10,000 mg/L) in order to achieve good anaerobic digestion operation and then, as the municipal wastewater typically has COD concentrations under 1000 mg/L, the organic load of the feed mixture was progressively reduced while keeping the organic loading rate constant. Therefore, the bioreactor operated under various HRTs and T while the organic loading rate was kept at values near 1 gsCOD/L/d (as outlined in Tables 1 and 2).

Table 1. Operational parameters imposed during the first experimental cycle.

First Experimental Cycle	Experimental Phases					
Operational Parameters	**First**	**Second**	**3rd**	**4th**	**5th**	**6th**
Duration (d)	21	33	20	10	69	9
HRT (d)	10	6	4	3	2	1
T (d)	10	6	4	3	2	1
OLR (g sCOD/L/d)	0.91	0.96	0.95	0.90	0.91	1.06

Table 2. Operational parameters imposed during the second experimental cycle.

Second Experimental Cycle	Experimental Phases			
Operational Parameters	**First**	**Second**	**3rd**	**4th**
Duration (d)	28	15	15	22
HRT (d)	4	3	2	1
OLR (gCOD/L/d)	0.97	0.97	1.02	1.06

The reactor was fed with the synthetic wastewater and operated under mesophilic conditions (35 °C), for 242 consecutive days. Two distinct experimental cycles were conducted, as shown in Tables 1 and 2. During the first cycle, six consecutive experimental phases were conducted, with the reactor operating in a switching mode with constant HRT/T and OLR/HRT ratios. During the second experimental cycle, four experimental phases were conducted with similar OLR/HRT ratios, but the reactor operated in the ABR mode with no switching imposed. Throughout the experimental process, pH, total alkalinity, total suspended solids (TSS), volatile suspended solids (VSS), soluble chemical oxygen demand (sCOD), biogas production and methane content were monitored at regular intervals. TSS, VSS, sCOD and alkalinity were measured according to standard methods (APHA, 1995), while a GC-TCD (Shimadzu GC-2014, Duisburg, Germany) was used for the measurement of the methane content of the generated biogas.

3. Results and Discussion

3.1. First Experimental Cycle

The overall efficiency of the PABR throughout the whole experimental cycle is presented in Table 3. The HRT reduction from 10 d to 1 d affected the biogas yield, as well as the COD removal achieved. Furthermore, the experimental phase with the lowest HRT showed the highest amount of biogas (1d HRT—44.3 L/d) and biomethane production (1d HRT—26.5 L/d). On the other hand, the average COD removal rate during the HRT 1 d phase is reduced to 69.4%. The highest COD removal occurred during the fourth experimental phase (HRT 3 days) where the COD consumption of the process reached 89%. As shown in Table 3, during all experimental phases the PABR effluent had significant deviations in COD concentrations.

Table 3. Average daily results of the first experimental cycle phases.

First Experimental Cycle	Experimental Phases					
Characteristics	1st	2nd	3rd	4th	5th	6th
Biogas Production (L/d)	25.6 ± 4.2	33.8 ± 3.7	37.0 ± 3.2	35.6 ± 2.5	32.3 ± 4.9	44.3 ± 1.8
Biomethane Production (L/d)	6.9 ± 3.4	15.2 ± 5.4	18.7 ± 3.7	18.5 ± 5.8	21.1 ± 4.2	26.5 ± 1.6
CH_4 Biogas content (%)	27.0 ± 10.7	44.5 ± 13.4	50.9 ± 10.5	54.3 ± 17.6	66.5 ± 8.4	59.6 ± 0.6
sCOD Feedstock (g/L)	9.11 ± 0.75	5.74 ± 0.23	3.78 ± 0.59	2.71 ± 0.29	1.81 ± 0.16	1.06 ± 0.06
sCOD Effluent (g/L)	1.86 ± 1.20	0.94 ± 0.94	0.50 ± 0.91	0.28 ± 0.12	0.25 ± 0.15	0.37 ± 0.12
Average COD removal (%)	79.5	83.7	86.9	89.6	85.30	64.9

As shown in Figure 2, the daily biogas production increased as the HRT was reduced from 10 days to 6 days and remained at the same daily production levels when the HRT took the values of 4, 3 and 2 d. During the last experimental phase, the average daily biogas increased to 44.3 L/d. The biomethane production is calculated by the concentration of methane in the daily generated biogas. Generally, it is concluded that as the HRT is lowered, the methane concentration of biogas increases, with the exception of the last experimental phase, as shown in Figure 3. In Figure 3, the daily concentration of methane in biogas is presented. It is clear that as the HRT is lowered, the methane content of the biogas increases.

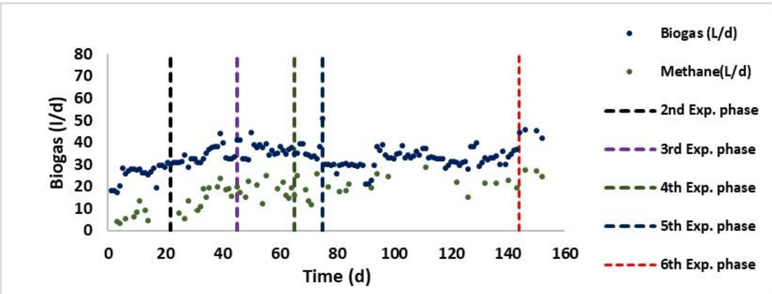

Figure 2. Daily biogas and biomethane production of PABR.

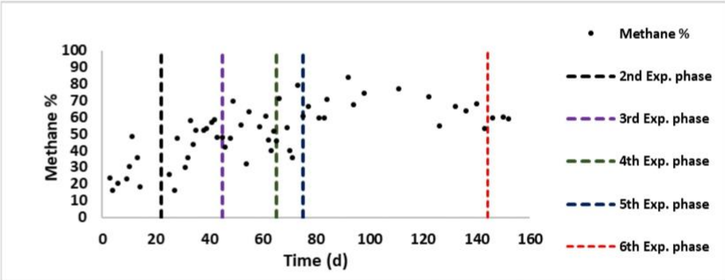

Figure 3. Daily methane concentration of the biogas generated in the PABR.

Regarding the behavior of the process in removing the organic content of the waste, two aspects are examined. First, the COD removal is examined between the feedstock and the effluent of the reactor, and second, the concentration distribution of the COD between the four compartments of the PABR. Figure 4 shows the variation of sCOD with time during the consecutive six phases of the PABR switching mode operation. In all cases, the process shows significant sCOD reduction. The only experimental phase presenting significant sCOD at the effluent is the first experimental phase (HRT 10 d). This happens due to the time required for acclimation to the new feedstock type. The inoculum used for the PABR startup was obtained from a CSTR reactor operating in higher HRTs and with excess activated sludge as feedstock. By observing the COD reduction of the last experimental phase (HRT 1 d), where the synthetic waste resembles as much as possible the characteristics of MWW, it is concluded that although the effluent is not yet directly disposable due to its COD concentration, a significant reduction is achieved without consuming the equivalent energy needed for aeration in biological oxidation.

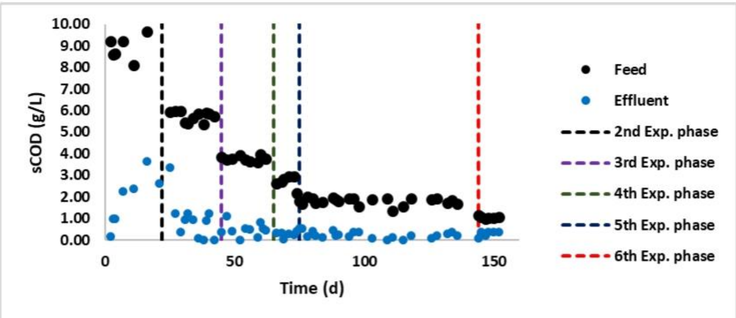

Figure 4. Daily sCOD of the reactor's feedstock and effluent.

Figure 5 shows the average sCOD concentration and also the variation in sCOD in the four compartments of the PABR. It has been demonstrated that when switching is frequent enough (low switching period T), the PABR resembles the behavior of a UASBR (upflow anaerobic sludge blanket reactor) [7]. This was indeed verified also in this case when operating with a constant HRT/T ratio.

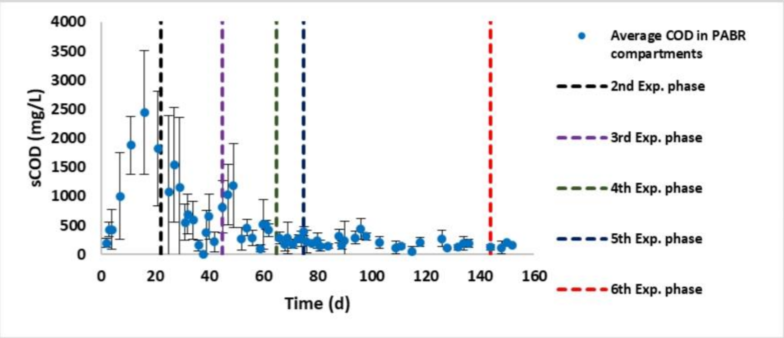

Figure 5. Average daily sCOD concentration and variation of in the four PABR compartments.

Similar variation in the COD concentration was also noticed for other process parameters, such as the pH and the total alkalinity, as shown in Figures 6 and 7, respectively. The pH values have strong fluctuations during the higher HRT phases and after the third experimental phase are stabilized at values between 7 and 8. Due to the characteristics of the feedstock, the pH did not cause inhibition of the process as the pH of the feedstock is in the favorable range for anaerobic digestion. On the other hand, the alkalinity of the synthetic MWW proposed by the literature is significantly low (0.125 g/L $NaHCO_3$ = 78mg $CaCO_3$/L), and due to the water used in feedstock preparation, the total alkalinity of the feedstock was 913 mg$CaCO_3$/L in the first experimental phase. As the HRT is lowered, the low alkalinity of the feedstock could introduce a limitation for the process. In order to avoid this problem, the proposed alkalinity of the synthetic mixture was changed and more $NaHCO_3$ was added as alkalinity buffer in order to stabilize the alkalinity of the process above the value of 2000 mg$CaCO_3$/L. As the total alkalinity of the feedstock increased, the alkalinity of the reactor's compartments increased also. During the first experimental phase feeding the reactor with 912.50 mg$CaCO_3$/L on average, the compartments average alkalinity was 1147 mg/L. Increasing the alkalinity of the feedstock to 2500 mg$CaCO_3$/L led to an average alkalinity of 1821 mg $CaCO_3$/L in the reactor. Further increase in the feedstock alkalinity led to higher increase inside the reactor compartments, with the highest amount noticed during the fourth experimental phase (3560 mg $CaCO_3$/L). It is observed that as the alkalinity took higher values, the productivity of the reactor in biogas generation and biomethane concentration increased. This is an indication of the significant role of alkalinity for process efficiency. It can be concluded that if high-rate anaerobic digestion is to replace the activated sludge process for MWW treatment, the alkalinity of the feedstock can be a major limitation parameter for the process. In Table 4, the average daily pH and total alkalinity values are given for the reactor, the feedstock and the effluent.

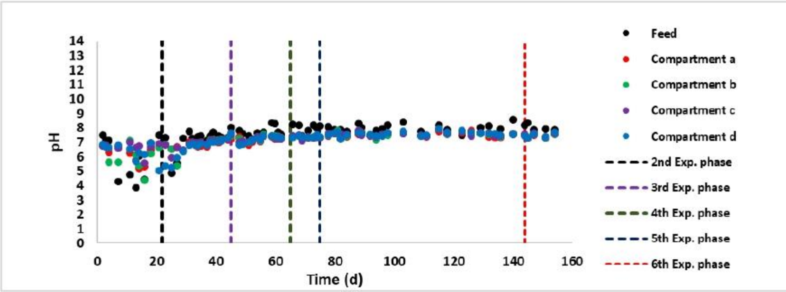

Figure 6. Daily pH values of feedstock and reactor compartments.

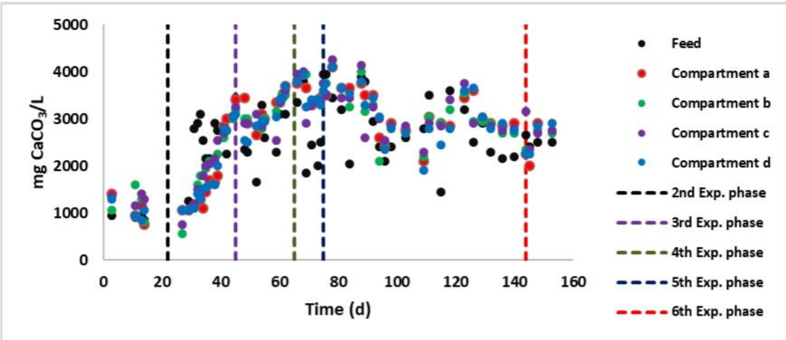

Figure 7. Daily total alkalinity value of the feedstock and reactor compartments.

Table 4. Average daily pH and total alkalinity of the feedstock, compartments and effluent.

	Feedstock		Compartment a		Compartment b		Compartment c		Compartment d		Effluent	
Exp. Phase	pH	Alkalinity mg$CaCO_3$/L	pH	Alkalinity mg$CaCO_3$/L	pH	Alkalinity mg$CaCO_3$/L	pH	Alkalinity mg$CaCO_3$/L	pH	Alkalinity mg$CaCO_3$/L	pH	Alkalinity mg$CaCO_3$/L
1st	5.97	912.5	6.23	1063	6.00	1188	6.64	1300	6.53	1038	6.26	1147
2nd	7.11	2500	6.87	1719	6.86	1896	6.89	1919	6.49	1750	6.87	1821
3rd	7.75	2770	7.23	3240	7.31	3140	7.27	3090	7.26	3050	7.36	3130
4th	8.00	2658	7.36	3583	7.42	3667	7.39	3475	7.38	3517	7.51	3560
5th	7.94	2880	7.55	3555	7.56	3095	7.59	3145	7.60	3127	7.65	3130
6th	8.15	2512	7.46	2125	7.51	2300	7.49	2738	7.44	2563	7.53	2431

Regarding the concentration of the biosolids, it seems that the solid content in the PABR compartments was reduced during the experiment. This phenomenon can lead to the assumption that as the HRT is reduced, the reactor reduces its biomass. However, the low concentrations of suspended solids and volatile suspended solids in the compartments, the effluent is caused due to biomass sedimentation in the reactor lower parts, and this is typical for a high-rate system such as this. As shown in Figure 8, in each PABR compartments a two-phase system is formed between the biomass (solid phase) and the treated effluent (liquid phase). The sampling and the effluent valve of each compartment are placed in the higher parts of the reactor.

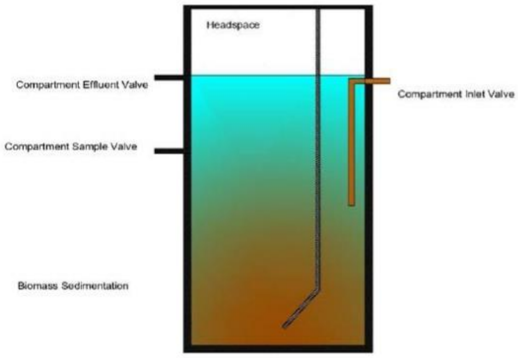

Figure 8. PABR compartment cut.

In Figures 9 and 10, the daily concentrations of the TSS and VSS measured from samples obtained from the four separate compartments are presented. In general, we can conclude that as the HRT is reduced, both TSS and VSS are also reduced. In the first experimental phase (10 d HRT), the average TSS and VSS concentrations were 0.83 g/L and 0.63 g/L respectively, while in the last experimental phase the same concentrations were 0.22 g/L and 0.14 g/L, respectively. In Table 5, the average TSS and VSS concentration of every compartment and that of the effluent for all experimental phases is presented.

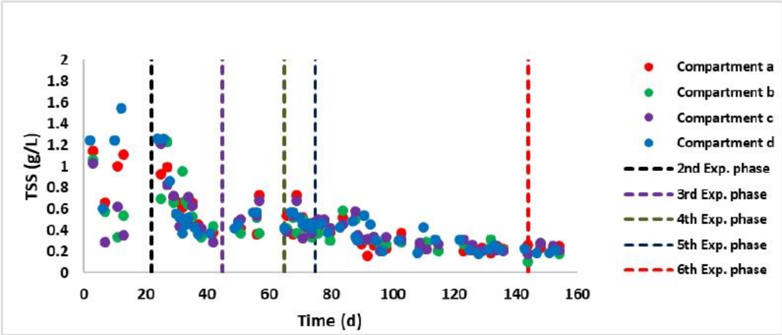

Figure 9. Daily TSS concentration in reactor compartments.

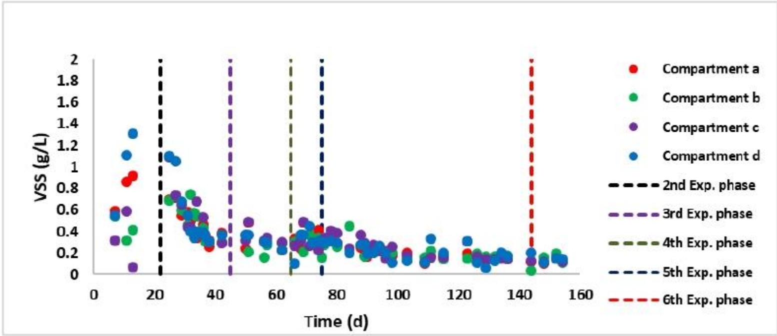

Figure 10. Daily VSS concentration in reactor compartments.

Table 5. Average daily TSS and VSS concentration in feedstock, reactor's compartments and effluent.

	Compartment a		Compartment b		Compartment c		Compartment d		Effluent	
Exp. Phase	**TSS (g/L)**	**VSS (g/L)**	**TSS (g/L)**	**VSS (g/L)**	**TSS (g/L)**	**VSS (g/L)**	**TSS (g/L)**	**VSS (g/L)**	**TSS (g/L)**	**VSS (g/L)**
1st	0.98	0.79	0.63	0.43	0.57	0.33	1.16	0.99	0.75	0.63
2nd	0.61	047	0.64	0.52	0.60	0.54	0.63	0.54	0.58	0.49
3rd	0.50	0.31	0.44	0.26	0.55	0.35	0.50	0.31	0.48	0.32
4th	0.50	0.35	0.43	0.31	0.46	0.31	0.50	0.32	0.48	0.32
5th	0.30	0.20	0.32	0.31	0.33	0.23	0.34	0.21	0.45	0.28
6th	0.12	0.24	0.20	0.13	0.24	0.13	0.20	0.15	0.25	0.16

3.2. *Second Experimental Cycle*

The average results and their standard deviation for every phase of the second experimental cycle are presented in Table 6.

Table 6. Average daily results of the second experimental cycle phases.

Second Experimental Cycle	Experimental Phases			
Characteristics	**1st**	**2nd**	**3rd**	**4th**
Biogas Production (L/d)	58.1 ± 3.1	68.0 ± 4.1	71.6 ± 8.6	66.8 ± 2.3
Biomethane Production (L/d)	42.9 ± 7.4	44.6 ± 6.4	42.3 ± 4.5	41.1 ± 3.5
CH_4 Biogas content (%)	71.7 ± 11.2	65.07 ± 7.5	60.01 ± 5.3	61.6 ± 4.7
sCOD Feedstock (g/L)	3.89 ± 0.10	2.92 ± 0.30	2.05 ± 0.12	1.03 ± 0.15
sCOD Effluent (g/L)	0.82 ± 0.04	0.48 ± 0.17	0.24 ± 0.10	0.27 ± 0.06
COD removal (%)	78.9	83.5	88.3	73.7

In Figure 11, the daily production of biogas and biomethane in the reactor per experimental phase shows increase in biogas production after the first experimental phase and then a significant reduction in the beginning of the third experimental phase. In the middle of the third experimental phase, the reactor increased again its biogas generation, and during the 56th day of operation reached the maximum production recorded (81.3 L biogas). During the last experimental phase (HRT 1 d) the reactor showed greater stability both in terms of biogas and biomethane production. The same pattern is shown in Figure 12, where the daily methane percentage in the generated biogas is depicted.

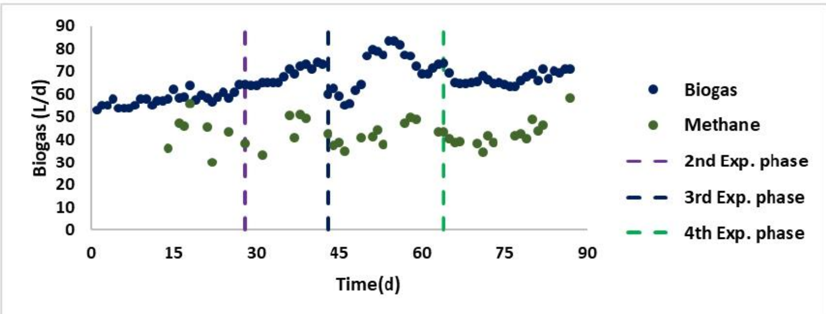

Figure 11. Daily biogas and biomethane production.

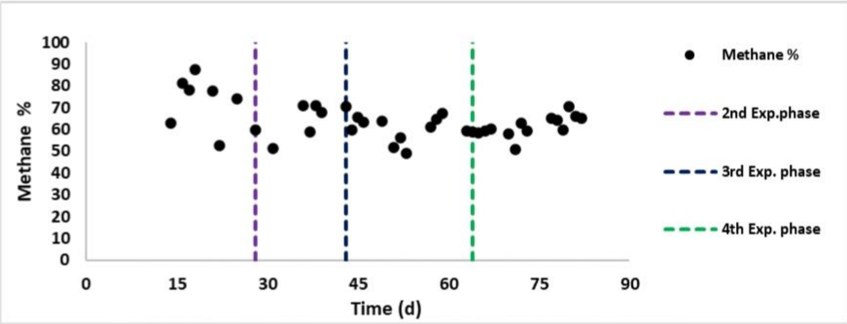

Figure 12. Daily methane concentration of biogas generated from the PABR.

Regarding the COD consumption in this experimental cycle, again a significant reduction was presented in the reactor's effluent. Although reduction levels reached 88.3% (2d HRT), the effluent still does not reach the criteria for disposal. The lower effluent COD concentration achieved is that of 240 mg/L in the third experimental phase and the highest value in COD effluent was observed during the first experimental phase 820 mg/L. The daily sCOD values of each compartment are presented in Figure 13, while the daily sCOD values of the feedstock and the effluent are presented in Figure 14. The sCOD concentration of the effluent in the last experimental phase shows that a significant reduction is obtained (73.7%). However, as in the previous cycle, the effluent is not directly disposable.

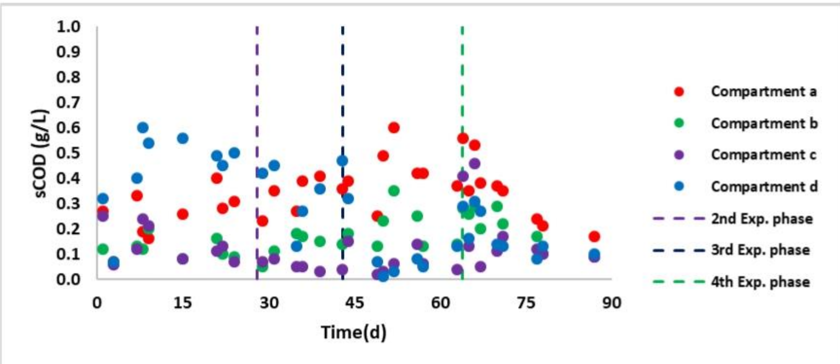

Figure 13. Daily sCOD values of PABR compartments.

The pH of the process observed in Figure 15 was fairly constant during all experimental phases of the cycle for all compartments, without any significant fluctuation. Also, by adding $NaHCO_3$ as alkalinity buffer in the feedstock, the alkalinity of the process remained at the desired levels of 2000–2500 mg$CaCO_3$/L for all experimental phases, as shown in Figure 16. The average daily pH and total alkalinity values are presented in Table 7.

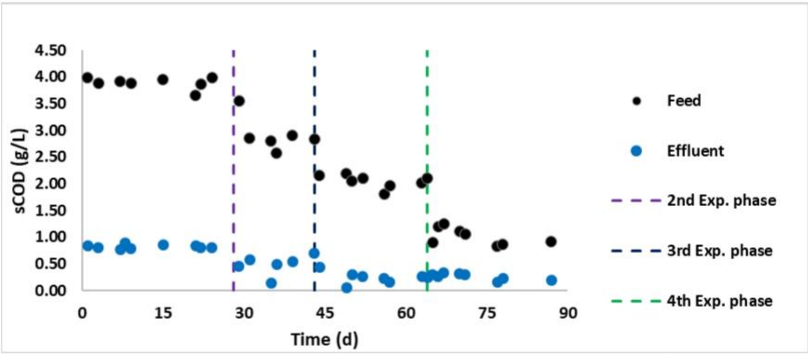

Figure 14. Daily sCOD values of the reactor's feedstock and effluent.

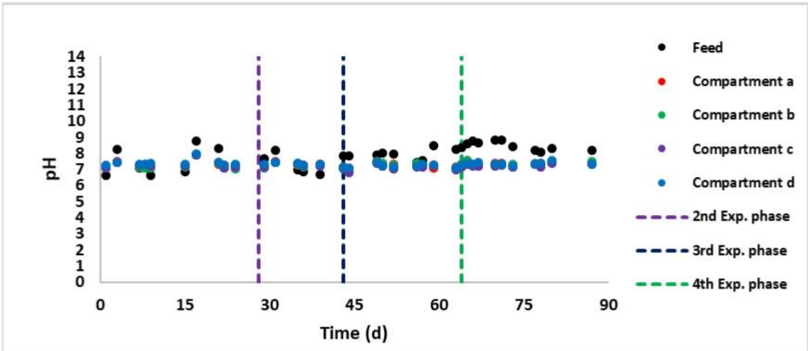

Figure 15. Daily pH values of the feedstock and the reactor compartments.

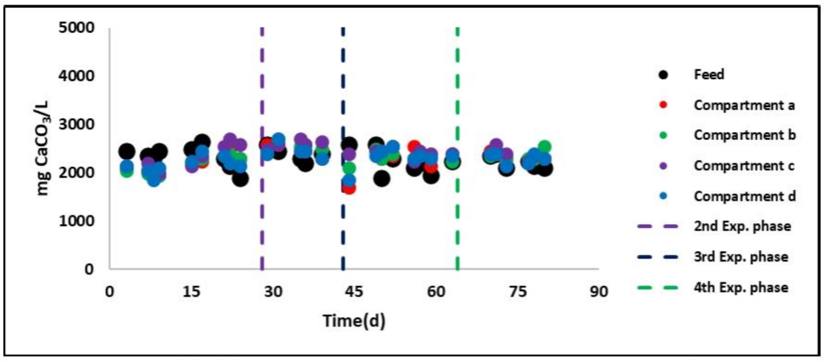

Figure 16. Daily total alkalinity value of the feedstock and the reactor's compartments.

Table 7. Average daily values of pH and total alkalinity of the reactor's feedstock, compartments and effluent.

	Feedstock		Compartment a		Compartment b		Compartment c		Compartment d		Effluent	
Exp. Phase	pH	Alkalinity $mgCaCO_3/L$	pH	Alkalinity $mgCaCO_3/L$	pH	Alkalinity $mgCaCO_3/L$	pH	Alkalinity $mgCaCO_3/L$	pH	Alkalinity $mgCaCO_3/L$	pH	Alkalinity $mgCaCO_3/L$
1st	7.41	2339	7.30	2188	7.40	2172	7.31	2294	7.25	2172	7.41	2100
2nd	7.37	2390	7.24	2480	7.31	2560	7.29	2610	7.22	2460	7.31	2410
3rd	7.98	2238	7.14	4806	7.22	2319	7.25	2419	7.28	2312	7.47	2287
4th	8.51	2225	7.24	2333	7.37	2367	7.36	2383	7.37	2308	7.60	2375

The average amount of TSS and VSS per compartment at every experimental phase is presented in Table 8, while their daily concentrations are presented in Figures 17 and 18, respectively.

Table 8. Average daily values of reactor's compartment and effluent.

Exp. Phase	Compartment a		Compartment b		Compartment c		Compartment d		Effluent	
	TSS (g/L)	VSS (g/L)	TSS (g/L)	VSS (g/L)	TSS (g/L)	VSS (g/L)	TSS (g/L)	VSS (g/L)	TSS (g/L)	VSS (g/L)
1st	0.38	0.26	0.24	0.17	0.24	0.17	0.43	0.33	0.48	0.34
2nd	0.39	0.34	0.30	0.21	0.22	0.21	0.49	0.40	0.52	0.38
3rd	0.66	0.43	0.31	0.21	0.26	0.17	0.40	0.27	0.26	0.19
4th	0.32	0.23	0.19	0.11	0.16	0.11	0.30	0.23	0.18	0.13

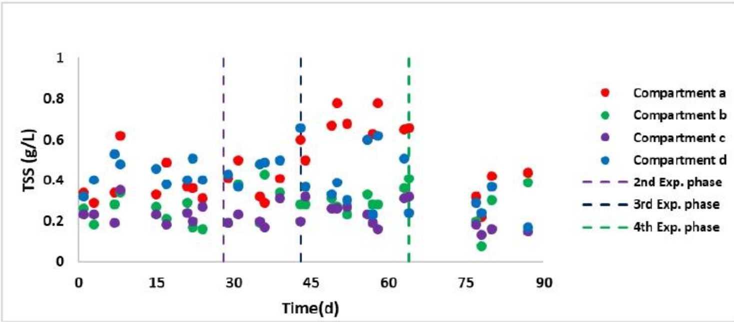

Figure 17. Daily TSS concentration in the reactor's compartments.

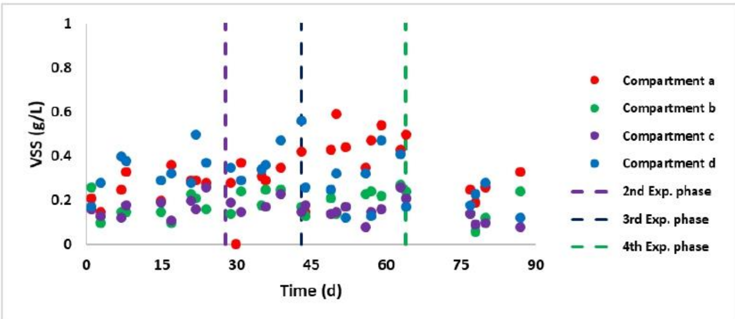

Figure 18. Daily VSS concentration in the reactor's compartments.

Comparing the two operational modes, it is concluded that in both switching and ABR mode, the process shows significant efficiency, especially during the last phase of each cycle, where the feedstock resembles the most the composition of municipal wastewater. In terms of possible energy recovery, during the sixth phase of the first cycle biogas generation reached 44.3 L/d with almost 60% methane content, while during the fourth phase of the second cycle with similar conditions imposed, biogas generation reached 66.8 L/d and methane content 61.5%. On the other hand, in terms of waste treatment, during the last phases of the first and second cycles, the COD removal rate reached 64.9% and 73.7%, respectively. In both aspects the ABR operational mode presents better results.

4. Conclusions

In this paper, we evaluated the efficiency of a PABR for the treatment of synthetic municipal wastewater operating under different conditions and assessed biogas and biomethane productivity along with COD removal. During both experimental cycles, the reactor showed high potential both in terms of biomethane generation and of organic matter reduction. The most significant results were obtained during the last phase of each experimental cycle, where the feedstock resembled the most the municipal wastewater characteristics.

During the PABR operation (first experimental cycle) the process was efficient in terms of energy recovery, but the organic content of the effluent in the last experimental phase was higher than the environmental limit. During the ABR operation (second experimental cycle), biogas and biomethane production reached 66.8 L/d and 41.1 L/d, respectively. However, similarly to the first experimental cycle, the COD concentration of the reactor's effluent is over the environmental limit.

As a conclusion, the PABR is a high-rate anaerobic digestion system capable of operating in low organic loadings and low HRTs. This capability gives the PABR the potential of reducing the energy consumption of MWW management by operating as a pretreatment step before the aeration tank in MWW treatment plants.

Author Contributions: Methodology, A.Z., C.K., A.M., K.P. and G.L.; investigation, G.L. and K.P.; writing—original draft preparation, A.Z., K.P. and G.L.; writing—review and editing, G.L. and K.P.; supervision, K.P. and G.L. All authors have read and agreed to the published version of the manuscript.

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CODIGESTION OF THE LIQUID FRACTION OF FOOD WASTE WITH WASTE ACTIVATED SLUDGE

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Keywords

Anaerobic Digestion, CSTR, Biofuels, Food Waste, Biogas

Highlights

• Suitable mixing of different waste streams to achieve high performing Anaerobic Digestion.

• CSTR achieves >90% COD removal for mixed feed of wastes.

• Biogas productivity >20L/d, with a methane content of up to 80%.

Purpose

Anaerobic Digestion (A.D.) is the biological process during which complex organic compounds of wastes are decomposed in the absence of oxygen, by anaerobic microorganisms. Through the intricate sequence of actions of these microorganisms (disintegration, hydrolysis, acidogenesis, acetogenesis, methanogenesis), the organic substrates are converted into renewable energy, in the form of biogas, while the residue meets the specifications for disposal in the soil or conversion into useful by-products [1]. This study aims to suggest a novel approach for simultaneous treatment of municipal waste sludge and the liquid fraction of food waste, in order to render the A.D. process more stable, increase the biogas yield and treat the mixed waste stream more effectively.

Materials and methods

Anaerobic Sludge obtained from the Municipal Wastewater Treatment Plant of Attica, Greece was used as inoculum for the A.D. reactor during start-up. The substrates to be co-digested were Waste Activated Sludge (W.A.S.), obtained from the same treatment plant, and the liquid fraction of household food waste. The food waste undergoes a rapid shredding, drying and condensation process and the liquid fraction (condensate), rich in organic load, is mixed with W.A.S. and used as substrate to be fed in the bioreactor. The digestion process of the mixed substrates takes place in a 100 L anaerobic bioreactor in continuous operation mode. The CSTR is kept at a constant hydraulic retention time (HRT) of 20 days, constant temperature at mesophilic conditions of 35^{o}C and is monitored through frequent observation of various measurements according to Standard Methods. The Analytical methods used for characterizing the mixed feedstock and digested outlet of the bioreactor include pH, alkalinity, solids, total and soluble Chemical Oxygen Demand (COD) measurements, Total Organic Carbon (TOC) and Total Nitrogen (TN), dissolved and Total Kjeldahl Nitrogen (TKN), Volatile Fatty Acids and alcohols [2]. The biogas production is measured through an oil displacement technique and the methane content is quantified using a GC-TCD.

Results and discussion

Condensate samples are extracted every hour of the pretreatment process in order to analyze the temporal distribution of the waste characteristics. Figure 1a depicts the tCOD of condensate extracted in relation to its moisture content, while Figure 1b shows the TOC and TN of the samples. These results are utilized for the determination of the mixed feedstock characteristics. During startup, the inoculum included a mixture of Anaerobic Sludge, W.A.S. and Condensate in ratios 1:17:2 respectively, based on previous studies [3].

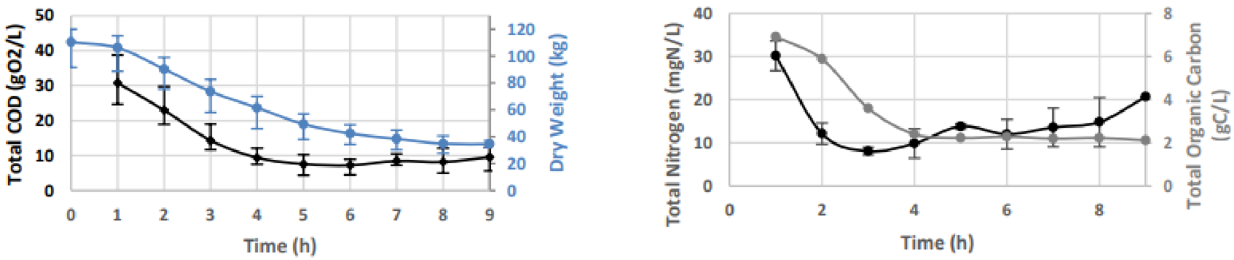

Figure 1: The condensate effluent characteristics versus time showing a) its dry weight (right y-axis) and tCOD (left y-axis) content and b) its TOC (right yaxis) and TN (left y-axis) load.

Following the start-up in batch mode, the bioreactor was shifted to continuous mode. The influent was maintained constant at 5 L of mixed W.A.S. and condensate in 2:1 ratio, based on the annual global Municipal Solid Waste generation rate [4]. Figure 2 shows the continuous operation sCOD at the inlet and outlet of the bioreactor, indicating that the organic matter COD removal exceeds 90% .

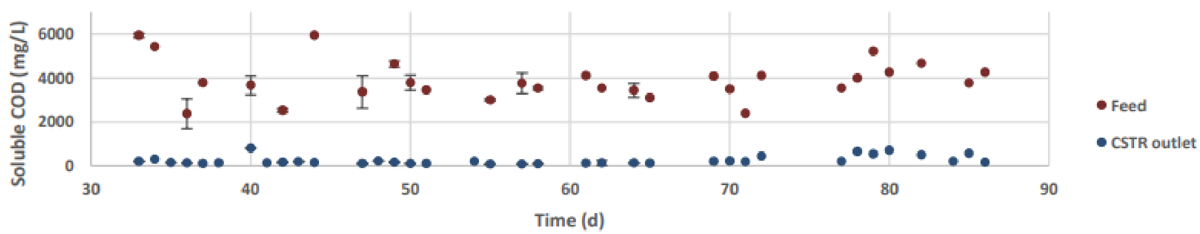

Figure 2: The sCOD of the CSTR inlet and outlet versus operation time.

As a result of the digestion of the mixed feed, biogas is produced. Figure 3 depicts the total biogas productivity, as well as its methane content.

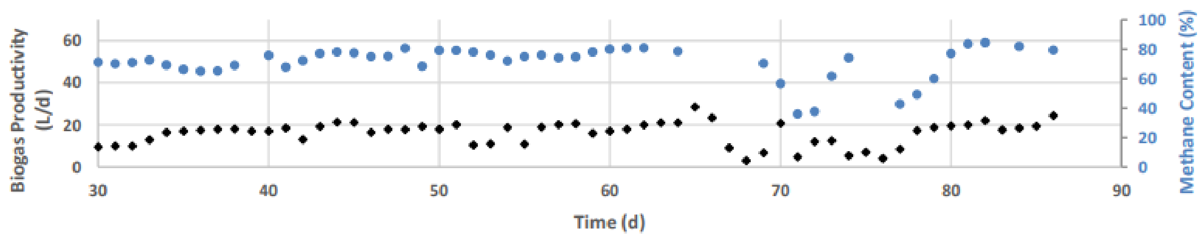

Figure 3: The CSTR daily biogas productivity (left y-axis) and its methane content (right y-axis) versus operation time.

Conclusions and perspectives

Most of the organic matter of the mixed feed is digested. The COD removal was over 90%. The steady state operation yielded over 20L biogas per day with a methane content of 80%. Future perspectives include the optimization of the CSTR operation, in terms of Organic Loading Rate, search for optimal C:N ratio for digestion of the mixed feedstock, HRT, biogas productivity and methane content within the biogas. In addition, supplementary BioMethane Potential measurements will be performed in smaller scale bioreactors for optimization of the abovementioned parameters.

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Anaerobic Digestion of Municipal Wastewater (MWW) in a Periodic Anaerobic Baffled Reactor (PABR)

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Abstract

The scope of this work is to study the treatment of municipal wastewater in a Periodic Anaerobic Baffled Reactor (PABR). PABR is an innovative, high-rate bioreactor, designed to operate under high organic loadings. Apart from the Hydraulic Retention Time (HRT) an important operational parameter is the Switching Period (T). The current research work aims to study the impact of the operational parameters variation (HRT and T) in the biogas and biomethane productivity.

Six distinct experimental phases were conducted, during which the operational parameters of the PABR were consecutively modified: HRT varied from 10 to 1 day, T between 2.5 and 0.25 days while the OLR remained constant at values near 1 $g_{sCOD}/L_{bioreactor}*d$. The maximum CH_4 productivity was 26.5 LCH_4/d corresponding to the operation under HRT=1d, OLR=0.89 $g_{sCOD}/L_{bioreactor}*d$ and T=0.25 days. Conclusively, the PABR is a high-rate AD system, capable of treating MWW under extreme operational conditions.

Keywords: Anaerobic Digestion; Bioreactor; High-rate; Methane; Municipal Wastewater; PABR

1. Introduction

Currently, the benchmark approach to municipal wastewater (MWW) management consists of sewer collection, treatment in a facility aiming at removal of suspended solids through primary sedimentation, biological oxidation of organic matter, biological nutrient (N and P) removal and disposal of the clarified effluent following disinfection by chlorination. The process generates a mixture of primary and excess secondary sludge which are typically mixed, stabilized by anaerobic digestion and dewatered before disposal (Chan et al., 2009). The key operating costs lie in the aeration and in sludge (biosolids) management (Mohan et al., 2008).

Alternative approaches that would reduce the energy requirements have been contemplated in the recent years. Indeed, it is possible to produce energy from the dissolved organic matter in wastewater, rather than consuming energy for aeration, followed by a partial recovery through anaerobic digestion of the biosolids. Among them, direct anaerobic digestion (AD) of the wastewater has been examined (Sosnowski et al., 2003).

The PABR was designed by Skiadas and Lyberatos (1998). It is an innovative high-rate anaerobic digestion system capable of anaerobically processing high organic-loaded feedstocks at low HRTs. As shown in Figure 1 it consists of two concentric cylinders. The space between the two cylinders is divided into four compartments, each one of which is further divided into two sections, one downflow and one upflow, thus resembling a simple ABR, only arranged in a circular structure. However, an important property of the specific bioreactor is the ability to periodically change the inflow and (outflow) compartment.

The time required for all the compartments to act as feeding compartments is the switching period T. This specific operational parameter gives the bioreactor the element of operational flexibility: when T is high, the bioreactors operation is similar to an ABR, while when it is low the operation approaches the one of an Upflow Anaerobic Sludge Blanket (UASB).

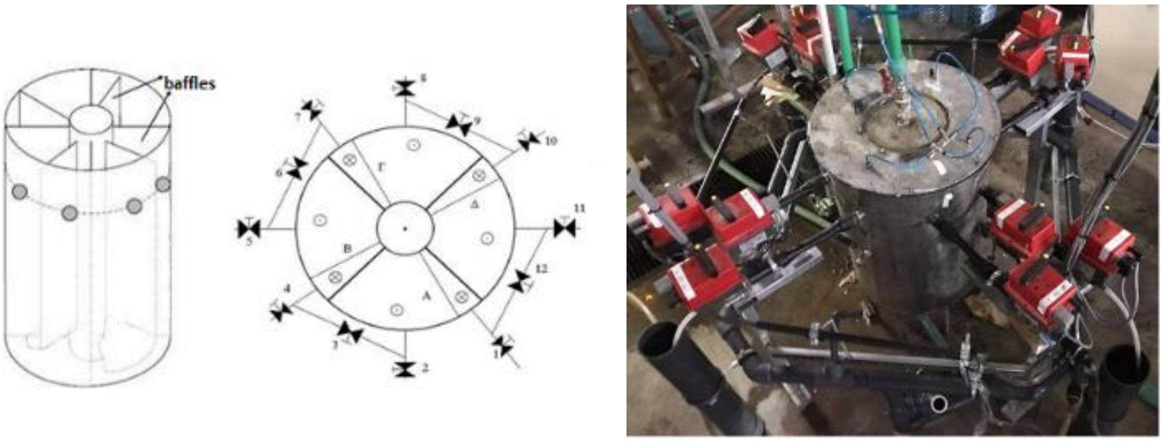

Figure 1. PABR experimental setup

2. Materials and Methods

A pilot-scale 77-L active volume PABR was utilized for the AD experiments. The system was fed with a synthetic municipal wastewater, operating under mesophilic conditions 35°C, for 147 consecutive days.

The synthetic wastewater used for the PABR in the present study consists of: 10 to 1.0 g/L glucose, 0.306 to 0.0285 g/L NH_4Cl (regarding the experimental phase), 0.08 g/L CH_3COONa, 0.044 g/L KH_2PO_4, 0.0275 g/L $MgSO_4*7H_2O$, 0.0025 g/L $CaCl_2$, 0.004 g/L KCl, 0.125 g/L $NaHCO_3$, 1.875 mg/L $FeCL_3*6H_2O$, 0.1875 mg/L H_3BO_3, 0.225 mg/L KI, 0.15 mg/L $MnSO_4$, 0.0275 mg/L $ZnSO_4*7H_2O$, 0.0375 mg/L $CuSO_4*5H_2O$ and 12.5 mg/L EDTA (Shuli Liu et al., 2020). Every experimental phase had different concentration of glucose and ammonium chloride so that the OLR would be kept constant while reducing the HRT. The concentrations of the above mentioned substances, were chosen by calculating the C/N ratio that would occur so that it remained constant near the value of 50.

The scope of the experimental process was to evaluate the efficiency of the PABR under different conditions in terms of organic load reduction and biogas and biomethane productivity. Municipal wastewaters tend to have COD concentration lower than 1000mg/L, so by reducing the organic load of the feed mixture we tried to approach that value as much as possible.

Therefore, the bioreactor operated under various HRTs and T while the organic loading rate was kept at values near 1 g_{sCOD}/L*d (as outlined in Table 1). In all cases, the ratio of HRT/T was kept constant and equal to 1.

Table 1. Operational Parameters, 6 phases, PABR

Operational Parameters	Experimental Phases					
Phases	1	2	3	4	5	6
Operation Duration (days)	21	23	20	10	69	4
HRT (days)	10	6	4	3	2	1
T switching period (days)	2.5	1.5	1	0.75	0.5	0.25

Six distinct experimental phases were carried out as shown in Table 1. Throughout the experimental process pH, total alkalinity, Total Suspended Solids (TSS), Volatile Suspended Solids (VSS), total and soluble Chemical Oxygen Demand (tCOD, sCOD), Volatile Fatty Acids (VFAs) TOC, TN and TKN (data not shown), biogas production and methane content were monitored in regular intervals, to assess the efficiency of the process. TSS, VSS, tCOD, sCOD and alkalinity were measured according to Standard Methods (APHA, 1995), VFAs were measured using a gas chromatograph (SHIMADZU GC-2010 plus), while a GC-TCD (SHIMADZU GC-2014) was used for the measurement of the methane content in the generated biogas. Moreover TOC-L Shimadzu was used for the measurement of total organic carbon and total nitrogen.

3. Materials and Methods

The overall efficiency of the PABR throughout the experimental phases is presented in Table 2:

Table 2. Experimental results, 6 phases, PABR

	Experimental Phases					
Phases	**1**	**2**	**3**	**4**	**5**	**6**
OLR (gsCOD/L*d)	0.91	0.96	0.95	0.90	0.85	0.89
tCOD removal (%)	79.5	83.7	86.9	89.6	85.3	64.9
Biogas productivity (L/d)	25.6	33.8	37.0	35.6	32.3	44.3
CH4 productivity (L/d)	6.9	15.2	18.7	18.5	21.1	26.5

From table 2 it is apparent that HRT reduction from 10 to 1 days significantly affected the biogas and methane productivity, as well as the tCOD removal achieved in the PABR respectively.

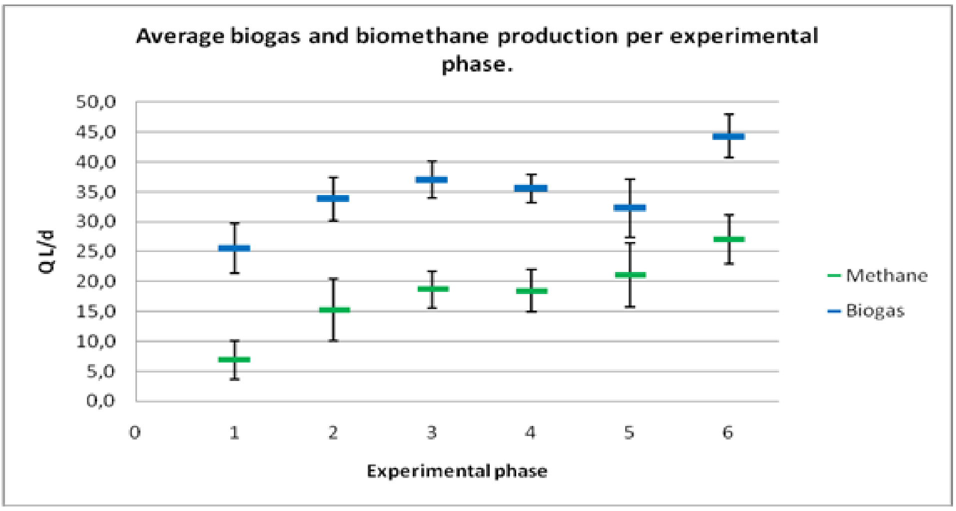

Figure 2. Biogas and biomethane average production throughout the six experimental phases.

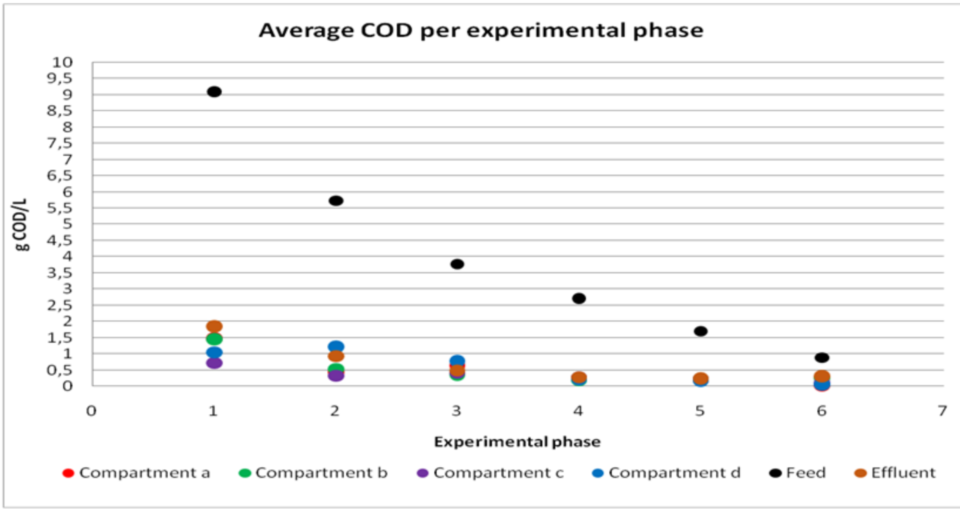

Figure 3. COD concentration in the PABR compartments, Feed and Effluent at every operational experimental phase.

As shown in Figure 2 maximum biogas production observed during the 6th experimental phase, reaching 44.29, while the biomethane production reached 26.5 L/d. As shown in Figure 3 the PABR reactor managed to reduce the effluent COD at every experimental phase that operated.

4. Conclusion

In this paper, we evaluated the efficiency of a PABR for the treatment of a synthetic municipal wastewater operating under different conditions and assessed biogas and biomethane productivity.

It was shown that the PABR can efficiently operate under HRTs as low as 1 day. Specifically, maximum biogas production was observed in the experimental phase when the basic operational parameters were HRT: 1 d and the OLR: 0.89 g_{sCOD}/L*d. In those phases biogas production reached 44.3 L/d, while the biomethane production reached 26.5 L/d. Furthermore, the reduced organic load of the PABR effluent leads to the conclusion that can replace the benchmark approach for treating similar wastes, even though the biogas production is not suitable for energy recovery. For example, at the fourth experimental phase were the COD removal was the highest, the average daily bio-methane production was 30% lower from that of experimental phase 6. This approach would be efficient with liquid wastes of high organic load (10-6 g/L) if the PABR anaerobic system was used as a pretreatment method to aerobic oxidation tanks.

Acknowledgments

The research work was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "First Call for H.F.R.I. Research Projects to support Faculty members and Researchers and the procurement of high-cost research equipment grant" (Project Number: 2797).

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Condensate originating from household food waste as a substrate for Microbial Fuel Cells

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Keywords

Microbial Fuel Cell, Condensate, Household food waste, Wastewater treatment, Energy production

Abstract

A microbial fuel cell (MFC) is a bioreactor that converts the chemical energy of the bonds of organic compounds to electrical energy, through the catalytic reactions of microorganisms. Under anaerobic conditions various substrates have been examined using MFC technology. This study examines the potential use of the liquid fraction of fermentable household waste (source-sorted food waste), which results from condensation of the vapors generated during drying, as a feed to the MFC. The main characteristics of this substrate are: 13 g COD/L, pH=3.5, conductivity=262 μS/cm. Condensate was fed to two single-chamber air cathode MFCs, using mullite and GoreTex as cathodic electrodes, respectively. The oxygen reduction catalyst was MnO_2 in both cases, while graphite granules were used as anodic electrodes. The units were operated in batch mode. Linear sweep voltammetry was carried out in order to conduct electrochemical characterization. The maximum power output was 0.52 $\mu W/m^3$ for the mullite cell and 0.28 $\mu W/m^3$ for the GoreTex cell, respectively. High COD removal efficiencies (>75%) were achieved for both cells.

Introduction

Efficient municipal waste management (MW) is a key factor that contributes to the overall waste management [European Commission Proposal 2015]. Although the amount of MW is not the same across EU countries [EUROSTAT 2017], food waste is the major fraction of MW [European Parliament News 2017], 53 % of which is produced in households [Stenmark 2016]. Food waste (FW) is rich in various substances with high energetic and nutritional content [Antonopoulou et al 2019], making an excellent supply for many biological processes [Ng et al 2020]. In the municipality of Halandri, in Attica, Greece, an innovative FW valorization approach has been developed and implemented at pilot-scale within the framework of the Horizon 2020 project WASTE4think [Antonopoulou et al 2019, Tremouli et al. 2019, Lytras et al. 2020]. The implemented waste management scheme included the source-separated collection of the household FW from 250 households. The collected FW was then led to a drying/shredding facility of the Municipality. The produced condensate is rich in organic carbon but poor in nitrogen which limits its biological treatment. An exploitation approach of condensate is its mixing with waste activated sludge as a feed for an anaerobic digester, in order to enhance the methane yield [Lytras et al. 2020].

Another approach of condensate exploitation is bioelectricity production using the microbial fuel cell (MFC) technology. This is an innovative approach to wastewater treatment with direct electricity output [Logan 2009]. The MFC is comprised of an anode and a cathode compartment. In the anode the effluent is oxidized by bacteria, under anaerobic conditions. The produced electrons are collected through the anodic electrode and transferred to the cathodic electrode by an external resistance. The produced protons are transferred through the separator to the cathodic chamber. On the cathodic electrode an electron acceptor is reduced [Obileke et al. 2021]. Depending on the acceptor the presence of a catalyst may be needed; such is the case of O_2. The separator between the anode and the cathode may increase the cost of the system, especially when membranes are used [Daud et al. 2015]. More feasible options than membranes have been researched and provided comparable results at lower costs, such as ceramic electrodes [Winfield et al. 2016] and GoreTex cloth [Tremouli et al. 2019].

In this study, the performance of two single chamber MFCs with alternative cathode assemblies (ceramic and GoreTex) was studied. Two MFCs were acclimated and operated using raw condensate as the substrate.

Materials and Methods

Two similar Plexiglas single chamber MFCs were constructed, as described elsewhere [Tremouli et al. 2021]. Each cell had four tubes running through the anodic compartment. The same anode electrode setup was used for both cells, graphite granules (250 g) and an embedded graphite rod. Different cathode electrodes were used for the two cells. For the first cell, four cathodic electrodes with GoreTex cloth were assembled as specified in Tremouli *et al.* [2019]. For the second cell, the four cathodic mullite electrodes were internally coated with the oxygen reduction catalyst by mixing graphite paint (12 g), xylene (3 ml), ethanol (3 ml) and 3 g MnO_2. An external resistance set at 100 Ω was connected between the anode and the cathode electrodes.

The cells were operated in batch mode, each filled up with 150 cm^3 anodic liquid. The cells were placed in a temperature-controlled room, at 27 ^oC. During the acclimation period both cells were fed with synthetic wastewater consisting of phosphate buffer (3.67 g/L NaH_2PO_4 and 3.45 g/L Na_2HPO_4), potassium chloride (0.16 g/L KCl), sodium bicarbonate (5 g/L $NaHCO_3$), trace elements (1% v/v, described elsewhere [Skiadas & Lyberatos 1998]) and glucose (1.5 g COD/L) as the electron donor. During the first three acclimation cycles the cells were inoculated with anaerobic sludge (10 % v/v) obtained from the Likovrisi, Athens, Greece sewage treatment plant.

Following the acclimation period, glucose was replaced with condensate. Condensate was produced by condensing the vapors that are generated during the drying and shredding of the pre-sorted fermentable fraction of household food waste collected door-to-door in the Municipality of Halandri, Greece [Ntaikou et al 2018]. The characteristics of condensate were 13 g COD/L, pH=3.5, conductivity=262 µS/cm cm and contained the following volatile fatty acids (VFAs) acetic 1008 ± 720 mg/L, propionic 75 ± 25 mg/L, iso-butyric 40 ± 28 mg/L, butyric 144 ± 68 mg/L and iso-valeric 13 ± 4 mg/L. The VFAs concentrations are the average values of four different feed samples. In order to improve the low conductivity and pH, phosphate buffer was added in the raw condensate. After the mixing the improved pH and conductivity were 4.9 and 6.6 mS/cm, respectively. The condensate feeding presented fluctuations because it originated from gathered HFW, which varied each batch.

The voltage of the cells was recorded every two minutes by a Keysight LXI Data Acquisition. Linear sweep voltammetry was conducted by a Potentiostat – Galvanostat (PGSTAT128N – AUTOLAB) with an Ag/AgCl reference electrode. The pH and conductivity were measured by digital instruments (WTW INOLAB PH720) and (WTW INOLAB) respectively. Soluble COD was measured according to the standard methods [Standard

Methods 2012]. For the quantification of VFAs, 1 ml of sample acidified with 30 μL of 20% H2SO4 was analyzed via a gas chromatograph (SHIMADZU GC-2010 plus) equipped with a flame ionization detector and a capillary column (Agilent technologies, 30m x0.53mm ID x1 μm film, HP-FFAP) using an auto sampler (SHIMADZU AOC-20 s).

Coulombic efficiency (CE) was calculated according to Eq.1. CE is the charge produced to the charge that is contained in the substrate and is calculated by [Logan 2009]:

$$CE = \frac{M_{O2} \cdot \int_0^t Idt}{F \cdot b \cdot V \cdot \Delta COD} \text{ Eq. 1}$$

MO^2 is the molar weight of Oxygen (=32), F is the Faraday constant (=96485 C/mol), b is number of electrons per O^2 mole (=4), V is the effective volume of the cell (=150 ml) and ΔCOD is the difference between the initial and the final COD measurements for each batch cycle.

Results

GoreTex cell operation

The duration of the acclimation period of the GoreTex cell was 660 h. For the acclimation to be considered complete, there had to be repeatable current peaks and high COD removal, implying development of the electrogenic active biofilm. The maximum current output for the acclimation cycles was 0.5 mA.

Following the acclimation period, the glucose synthetic feed was replaced with raw condensate and the results are presented in Figure 1. Five cycles were carried out; the detailed results of each cycle are presented in Table 1. The current output was comparable to the maximum current achieved during the acclimation, approximately 0.5 mA. However, the maximum current output was decreased over time, 1^{st} cycle 0.62 mA and 4^{th} cycle 0.42 mA.

Table 1 Measurements and calculations of the GoreTex cell operation.

Cycle #	**CODin (g/L)**	**Inlet pH**	**Imax (mA)**	**COD Removal (%)**
1^{st}	9.9	5.9	0.62	95%
2^{nd}	9.2	4.0	0.52	96%
3^{rd}	12.7	4.9	0.44	94%
4^{th}	14.7	3.8	0.47	92%
5^{th}	13.8	4.3	0.42	77%

The GoreTex cell achieved high COD removal (>92%) in all five cycles, but a decrease was observed in the last cycle (77%). The inlet characteristics in terms of COD and pH have possibly affected the performance of the cell, as the inlet COD is increased and the pH is lowered through the cycles. The maximum current output (0.62 mA) was achieved in the first cycle, where both a low inlet COD (9.9 mg/L) and highest pH (5.9) were measured. Coulombic efficiencies calculated for the five cycles were very low, approximately 2%.

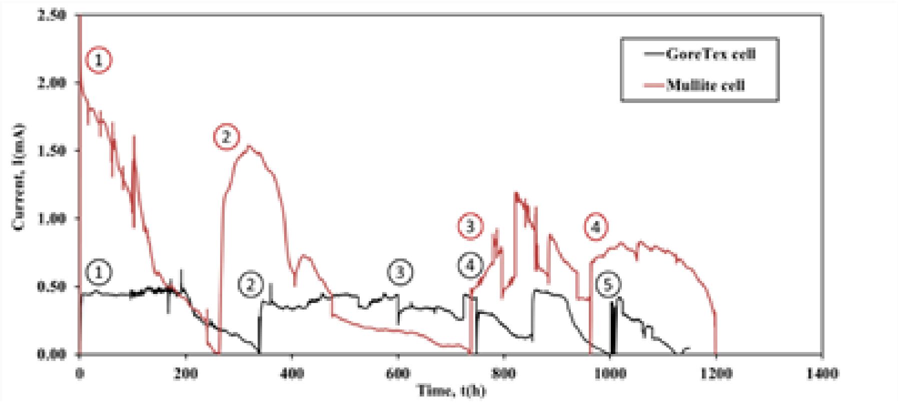

Figure 1: Current output versus time during operation of the two cells (Black = GoreTex cell, Red = mullite cell). The cycles have been numbered with the respective colors.

Mullite cell operation

The duration of the acclimation of the mullite cell was 2010 h. The maximum current output for the acclimation cycles was 2.28 mA. Following the acclimation period, the synthetic glucose feed was replaced with raw condensate and the results are presented in Figure 1. Four cycles were carried out, the detailed results of each cycle being presented in Table 2. In particular, the maximum current output achieved was 2.02 mA, similar to the acclimation maximum current output (2.28 mA). However, the maximum current output decreased with time, as it can be seen in Figure 1 and Table 2 (current output for the 1st cycle 2.02 mA and 0.83 mA for the 4th cycle, respectively). As it can be seen from Figure 1, during the 3rd cycle the current output of the mullite cell (red line) presented fluctuations which are attributed to the electrical connection issues.

The COD removal (>91%) was high for the mullite cell. The maximum current output is affected by the low pH and the high COD of the raw condensate while a drop is observed in its maximum value during time (2.02 mA 1st cycle, 1.54 mA 2nd cycle, 1.26 mA 3rd cycle and 0.83 mA 4th cycle). Coulombic efficiencies calculated for the four cycles ranged between 4% - 9%.

The VFAs were almost completely consumed by the microorganisms, leading to an increase in the pH in both cells at the end of every cycle (e.g. GoreTex cell 1st cycle inlet pH=5.9, outlet pH=7.13, mullite cell 4th cycle inlet pH 3.8, outlet pH=4.36).

Table 2 Measurements and calculations of the mullite cell operation.

Cycle #	**CODin (g/L)**	**Inlet pH**	**Imax (mA)**	**COD Removal (%)**
1st	10.9	5.9	2.02	96%
2nd	6.2	6.1	1.54	91%
3rd	10.5	4.8	1.26	95%
4th	12.5	3.8	0.83	94%

Electrochemical Characterization

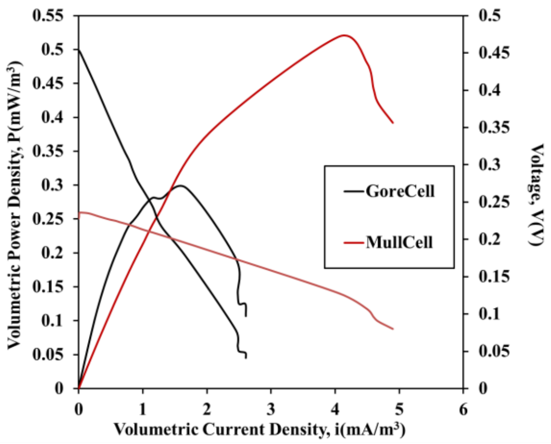

Figure 2 Volumetric power density versus volumetric current density versus voltage as extracted by LSV experiment on the two cells. (Black = GoreTex cell, Red = mullite cell)

Figure 2 presents the polarization curves of the two cells. The maximum power output was achieved by the GoreTex cell P_{max} = 0.52 mW/m^3, while the mullite cell achieved P_{max} = 0.3 mW/m^3. The OCVs (open circuit voltages) obtained were 0.228 V and 0.452 V for the GoreTex and mullite cell, respectively. The voltage versus volumetric current density curves indicate that, in both cells, ohmic resistances dominated, but were greater for the GoreTex cell, due to a higher slope (698 Ω internal GoreTex cell resistance, 211 Ω internal mullite cell resistance). Despite the facts that acclimation was not as fast and the OCV was not as high as for the GoreTex cell, the mulite cell overall performed better in terms of power output, waste treatment efficiency and coulombic efficiency.

Conclusion

The liquid fraction of dried fermentable household waste was treated using two single chamber MFCs using different cathode assemblies (GoreTex and mullite assembly, respectively). The mullite cell performed better than the GoreTex cell in terms of COD removal and power output. The results indicated that both cells had difficulty treating the raw condensate wastewater, because of its high COD 13 g/L and low pH 3.5 and conductivity 2.62 mS/cm.

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Development of a Novel concept for Integrated Management of Municipal Wastewater and Biowaste

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1. Keywords

Municipal wastewater, biowaste, condensate, anaerobic digestion, Periodic Anaerobic Baffled Reactor (PABR)

2. Highlights

- Revolutionize the field of waste and wastewater management
- Develop an innovative approach in the field of municipal waste and wastewater management
- Co-manage the liquid fraction of the Fermentable Municipal Solid Waste (condensate) and the Municipal Wastewater streams
- PABR is a high-rate bioreactor, designed to operate under high organic loadings in low HRTs

3. Purpose

Historically, the management of municipal solid waste and that of wastewater have evolved in two independent streams, defined by the main phase in each case: solid and liquid, respectively.

Currently, the benchmark approach to municipal wastewater management consists of sewer collection, treatment in a facility aiming at removal of suspended solids through primary sedimentation, biological oxidation of organic matter, biological nutrient (N and P) removal and disposal of the clarified effluent following disinfection by chlorination. The process generates a mixture of primary and excess secondary sludge which are typically mixed, stabilized by anaerobic digestion and dewatered before disposal [1,2].

Concerning solid waste management, for many years, the fermentable organic matter, mostly food waste, is collected usually mixed with recyclables in a commingled bin and then led to the landfill. Separate collection of food waste at the source allows for (a) high quality food waste that can be valorized and (b) cleaner recyclables [3].

The purpose of present work is to develop an innovative approach in the field of municipal waste and wastewater management. More specifically, it focuses on the Fermentable Municipal Solid Waste (FMSW) and the Municipal Wastewater (MWW) streams. These two streams are currently being treated as separate waste streams; FMSW is collected as part of the mixed solid waste and landfilled and MWW is led to a wastewater treatment facility through the sewer. We hereby propose to explore an alternative that is much more meaningful and sustainable: To co-manage the liquid fraction of the Fermentable Municipal Solid Waste (condensate) and the Municipal Wastewater streams. We have recently developed a method to separate the solid and the liquid fraction of the Fermentable Municipal Solid Waste (drying and shredding process) and we aim to build upon this experience to develop an innovative and sustainable treatment framework that can revolutionize the field of waste and wastewater management [4].

4. Materials and methods

The Periodic Anaerobic Buffled Reactor (PABR) is a novel bioreactor, designed to operate at high organic loading rates [5, 6, 7]. The PABR is a high-rate digester, suitable for municipal sewage treatment because of its low construction, operation and maintenance costs, low excess sludge production, and high capacity for biogas production at a small retention time.

We evaluated the anaerobic digestion potential of a mixture of the condensate resulting from drying food waste and of municipal wastewater mixture using a PABR with an operating volume 77L. Biogas productivity, methane content, pH, alkalinity, sCOD, tCOD, TSS, VSS and VFAs were measured routinely.

We developed also an activated sludge system (a sequencing batch reactor, SBR) for the treatment of the effluent of the PABR digester. The specific system was a 15L sequencing batch reactor. The SBR operation secure both COD and (N) removal. During the experiments soluble and total COD, total nitrogen (TN), alkalinity, TSS and VSS were measured regularly both in the feed and the effluent of the SBR.

5. Results and discussion

The PABR exhibited great stability in the effluent with a mean sCOD removal rate was 77%. The VSS remained below 520mg/L and TSS 610mg/L respectively. The mean biogas productivity was 51mg/L and the mean methane composition of the biogas was 66%.

For the SBR, the pH levels in the effluent remained close to 8 (range between 7.7-8.3 - basic conditions), while the total alkalinity was around 1100mg_{CaCO3}/L. SBR showed satisfactory behavior in removing organic loading below the environmental discharge limit of 120mg/L. The COD of the effluent remained approximately 100 mg/L. Total nitrogen was 12.4mg/L while the TS and VSS were 0.25 mg/L and 0.2 mg/L respectively.

6. Conclusions and perspectives

Overall, the PABR proved to efficiently operate under HRTs as low as 4 days. Specifically, biogas production observed when the basic operational parameters were HRT 4 d and organic loading rate (OLR) 0.94g_{COD}/L*d. Biogas production was 51L/d.

The work contributes to the development of a framework in which the liquid fraction (condensate) of the municipal fermentable household waste will be combined and co-managed with either the municipal wastewater in a common collection sewer system or will be transported and mixed with the excess sludge generated in conventional treatment plants, enhancing the generation of biogas. At the same time the dried and shredded food waste (food residue biomass) can be exploited in various ways as developed and described in [4].

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Development of an innovative scheme for the simultaneous treatment of wastewater and the condensate from drying food waste

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Abstract The objective of this work is the development of a new treatment scheme for Municipal Wastewater (MWW) along with the condensate from drying and shredding food waste. These two streams are currently collected and treated separately from each other. The new environmentally efficient treatment scheme proposed here is based on the chemical similarity of these two waste streams due to their mainly organic nature. Food waste was collected separately from households and led to a drier/shredder, where the liquid phase (condensate) is separated from the solid phase. The condensate is mixed with MWW and led to a high-rate anaerobic reactor, where both streams are treated. In this work a 77L high-rate digester, a Periodic Anaerobic Baffled Reactor (PABR) was utilized. The PABR effluent is fed in a Sequencing Batch Reactor (SBR) for further treatment until the final effluent meets the environmental criteria for safe disposal. The biogas generated from the PABR was 36.6 L/d with a methane content of 65%. The SBR operated utilizing the Anaerobic – Aerobic -Anoxic (AOA) process for simultaneous organic carbon and nutrient removal. The process generated an effluent suitable for disposal in terms of organic matter, nitrogen and phosphorus content.

Keywords: Anaerobic Digestion; Food Waste; Municipal Wastewater; PABR; SBR

5. Introduction

Food Waste (FW) is defined as the food lost in the final stages of the Food Supply Chain (FSC), which includes the distribution and retail sector along with the final consumer [1]. Food loss is also observed along the previous food productions stages although, in the developed countries, households are responsible for most of the food waste [2].

Currently the majority of food waste in Greece is collected along with the rest of the non-recyclable municipal solid wastes and is led to landfills and incineration plants [3]. This management scheme results in biogas emissions from landfills impacting climate change and loss of potential energy or nutrient recovery from the fermentable fraction of municipal solid waste.

On the other hand, Municipal Wastewater (MWW) is collected through the sewage system and led to Wastewater Treatment Plants (WWTP). The benchmark approach for MWW consists of primary sedimentation, biological oxidation utilizing aeration and secondary sedimentation. This “activated sludge” process is characterized by high energy costs especially for aeration and high biosolids generation [4]. Concerning food waste alternative treatments schemes along with food prevention policies are introduced in order to reduce its negative environmental impact. An alternative approach was proposed by the Horizon 2020 “Waste4Think” research program where Food Residue Biomass (FORBI) resulting from drying and shredding food waste collected separately from households was valorized through Anaerobic Digestion for energy recovery among various alternatives [5].

Novel WW management schemes focus on processes with lower energy consumption and higher nutrient recovery [6] AD is gaining ground, as it has low energy requirements but also the potential of energy recovery in the form of methane. While AD is currently used in WWTPs as a side process mostly for the treatment of the excess sludge generated by biological oxidation, there are recent projects examining the feasibility of AD as a direct MWW treatment process. A significant limitation is the low efficiency of anaerobic digestion for low organic strength wastewaters such as municipal wastewater. High-rate AD systems may be used as the only viable option. A notable effort towards this goal is the installment of a full scale Expanded Granular Sludge Bed Reactor (EGSBR) in a WWTP in Ireland, during the operation of which, high BOD removal rate (85%) was accomplished [7]. It is, however, desirable to co-treat municipal wastewater with other higher strength wastewater streams in the effort to increase the potential of methane recovery. The liquid fraction of food waste is such a stream.

While food waste is treated as solid waste, it contains high amounts of humidity (70-80%) [8] [9] [10] and MWW contains significant amount of biosolids [11]. This study is based on the approach proposed by the Horizon 2020 "WASTE4Think" research program where the drying process divided food waste in two streams: a) the solid part called FORBI and b) the liquid part containing the majority of the moisture content of food waste and other volatile compounds such as Volatile Fatty Acids (VFAs) and Ethanol [12].

It is then a reasonable option to consider the co-treatment of MWW with the condensate generated upon drying food waste in a high-rate anaerobic digester. The high-rate anaerobic system utilized in this study is the Periodic Anaerobic Baffled Reactor (PABR), while the digestate was treated in a Sequencing Batch Reactor (SBR) in order to attain effluent characteristics that are suitable for discharge to receiving water bodies.

6. Materials and Methods

A synthetic wastewater for testing the idea of co-digestion was formulated based on the literature and had the following composition: 0.7g/L glucose, 0.019 g/L NH_4Cl, 0.08 g/L CH_3COONa, 0.044 g/L KH_2PO_4, 0.0275 g/L $MgSO_4*7H_2O$, 0.0025 g/L $CaCl_2$, 0.004 g/L KCl, 0.125 g/L $NaHCO_3$, 1.875 mg/L $FeCL_3*6H_2O$, 0.1875 mg/L H_3BO_3, 0.225 mg/L KI, 0.15 mg/L $MnSO_4$, 0.0275 mg/L $ZnSO_4*7H_2O$, 0.0375 mg/L $CuSO_4*5H_2O$ and 12.5 mg/L EDTA (Liu et al. 2013). The FW condensate resulting from drying and shredding FW for the restaurant of the National technical University of Athens. FW was collected separately daily and led to a dryer where the liquid part (condensate) was separated from the solid residue. The condensate was then mixed with the synthetic municipal wastewater at a ratio of 10% /90% respectively and fed to a PABR. The PABR is a high-rate anaerobic system developed by Skiadas and Lyberatos (Skiadas, I. V., Lyberatos 1998). It consists of two concentric cylinders as shown in Figure 1, with the inner one operating as heat exchanger. The space between the two cylinders is divided into four compartments, each of which is divided in two sections, one down- flow and one up-flow, thus resembling a simple Anaerobic Baffled Reactor (ABR), only arranged in a circular structure. The innovative approach of this bioreactor is its ability to periodically change the inflow and outflow compartments. The Switching Period T (the period for one complete switching of compartment roles), along with the Hydraulic Retention Time (HRT) determine the flow patterns of the reactor. In this work, a 77L PABR was utilized and operated under ABR mode (compartment switching was not imposed.). From previous experiments the PABR showed higher efficiency both in terms of COD removal and biogas production operating without Switching Period imposed for this type of waste(Zarkaliou et al. 2022).

In this work a 15 L SBR was used. to treat the PABR effluent so as to reach the required effluent quality for discharge. The SBR had an external jacket for temperature control via water circulation. Every operation cycle of the SBR was divided in four phases. The first phase was the feeding phase followed by the reaction period that consisted of distinct Anaerobic, Aerobic and Anoxic conditions. The final phases of the operation cycle were the sedimentation phase and the discharge.

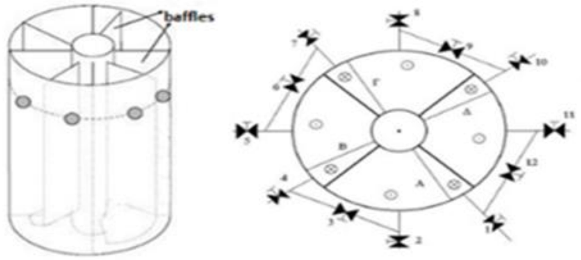

Figure 3 PABR experimental set-up

The PABR operated under 1 day HRT with no switching period imposed. The reactor was fed with 77L of feedstock daily. The Feedstock was a mixture of 90% synthetic Municipal Wastewater and 10% Fermentable Municipal Solid Waste condensate. The temperature was kept constant at 35 ^{o}C. The effluent of the PABR was then mixed again with condensate in a ration of 85 % PABR effluent and 15% condensate and led to the SBR reactor. The reactor was fed at the 2/3 of its active volume in every cycle. The 1/3 of the volume was constantly occupied by the activated sludge. The operational parameters of the Anaerobic Digestion process are presented in Table 1 and those of the Activated Sludge Process in Table 2**.**

3. Results and Discussion

Concerning the AD process, the mixture of FW condensate and synthetic MWW constituted a suitable feedstock for the PABR. Especially in terms of biogas the average daily production reached the value of 36.6 L/d with a methane content of 65 %. In terms of COD removal, the process reached a rate of 92% which is similar to that of biological oxidation process but without consuming equivalent energy. Figure 2 shows the daily biogas and biomethane production. While the digestate COD was low other nutrients had concentrations higher than the environmental limit. Especially Nitrogen (TN) was close to 50 mg/L, while Total Phosphorus (TP) between 4-5 mg/L. The digestate was led to the SBR in order to achieve a total TN below 12 mg/L and TP below 2 mg/l. After the Anaerobic-Aerobic- Anoxic (AOA) process in the SBR the final effluent had an average TN and TP value of 6 mg/L and 1.9 mg/L respectively. The daily measurements of the TN concentration in the SBR feed and effluent are shown in Figure 3.

It can be concluded that while the Anaerobic co – digestion of the FW condensate along with municipal wastewater can reduce their organic content at a sufficient rate, it is not effective regarding other nutrients such as nitrogen and phosphorus. However, high-rate AD could serve as a first step before the activated sludge process in WWTP's and reduce the energy consumption of aeration needed for the oxidation of the organic matter while also producing methane.

Table 3 Operational parameters of the Anaerobic Digestion process.

HRT	1 d
Switching Period T	-
Organic Loading Rate OLR	1,035 (gCOD/L/d)
Feedstock Temperature	4 (ºC)
Reactor Temperature	35 (ºC)

Table 4. Operational parameters of biological oxidation process

HRT	0.69 d
Cycle Duration	11 hrs
Feedstock Fed per Cycle	10 L
Feedstock Temperature	4 (ºC)
Reactor Temperature	25 (ºC)

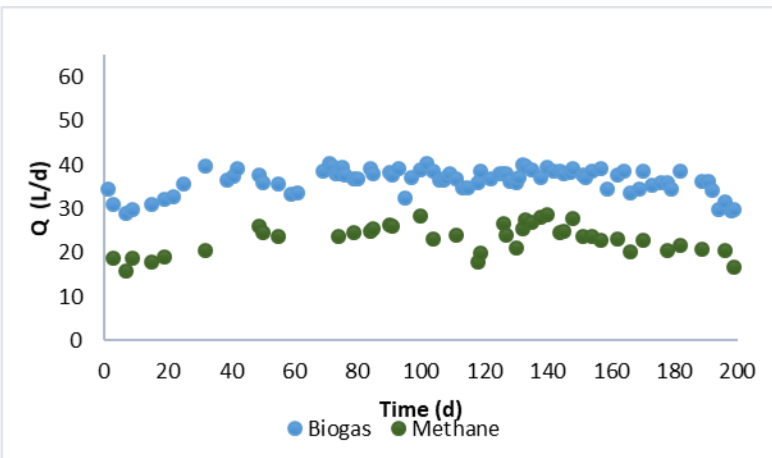

Figure 4. Daily production of biogas and bio-methane in the PABR

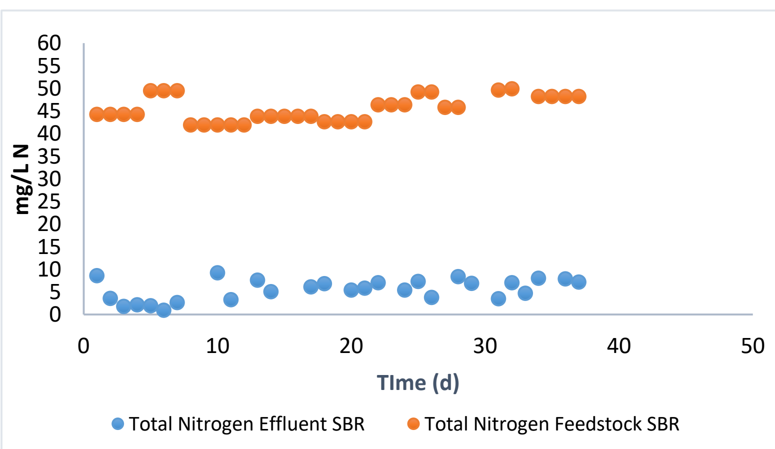

Figure 5. TN concentration in SBR feedstock and effluent.

4. Conclusion

This work proposed a novel management scheme where two municipal waste streams are co-treated by utilizing their similar chemical nature (organic) in comparison with the physical phase approach which has been traditionally used for collection and disposal of solid and liquid wastes, respectively.

The proposed novel management scheme includes the co-digestion of FW condensate with MWW in a high-rate anaerobic system with potential energy recovery and treatment of the digestate by biological oxidation in order to reach the environmental safety disposal criteria.

Acknowledgment

The research work was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "First Call for H.F.R.I. Research Projects to support Faculty members and Researchers and the procurement of high-cost research equipment grant" (Project Number: 2797).

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ΑΝΑΠΤΥΞΗ ΚΑΙΝΟΤΟΜΟΥ ΠΡΟΣΕΓΓΙΣΗΣ ΓΙΑ ΤΗΝ ΟΛΟΚΛΗΡΩΜΕΝΗ ΔΙΑΧΕΙΡΙΣΗ ΤΩΝ ΑΣΤΙΚΩΝ ΥΓΡΩΝ ΑΠΟΒΛΗΤΩΝ ΚΑΙ ΒΙΟΑΠΟΒΛΗΤΩΝ

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ΠΕΡΙΛΗΨΗ

Διαχρονικά, η διαχείριση των Στερεών και Υγρών Αστικών Αποβλήτων έχει εξελιχθεί σε δύο ξεχωριστά ρεύματα, με βάσει τη κύρια φάση του κάθε ρεύματος: υγρή και στερεή. Αντικείμενο της παρούσας εργασίας αποτελεί η ανάπτυξη μίας καινοτόμου προσέγγισης στον τομέα της διαχείρισης των Αστικών Αποβλήτων. Πιο συγκεκριμένα, εστιάζει στη συν-διαχείριση του υγρού κλάσματος των Βιοαποικοδομήσιμων Αστικών Στερεών Αποβλήτων (συμπύκνωμα) που προκύπτει από την ξήρανση τροφικών υπολειμμάτων και των Αστικών Υγρών ΑποβλήτωνΗ αύξηση του οργανικού φορτίου στο νέο ρεύμα που προκύπτει, σε σχέση με τυπικό αστικό υγρό απόβλητο επιτρέπει την επεξεργασία του με αναερόβια χώνευση προς παραγωγή βιοαερίου αντί για τη συμβατική ενεργοβόρο διεργασία ενεργού ιλύος.

Στην παρούσα εργασία χρησιμοποιήθηκε ένας Περιοδικός Αναερόβιος Χωνευτήρας με Ανακλαστήρες, Periodic Anaerobic Baffled Reactor (PABR) για την επεξεργασία του αποβλήτου που προκύπτει από τη συνένωση των δύο ρευμάτων. Ο

Ο PABR παρουσίασε μεγάλη σταθερότητα με μέσο ποσοστό απομάκρυνσης διαλυτού COD (sCOD) 92%, μέση παραγωγικότητα βιοαερίου 35.8 L/d και ποσοστό μεθανίου 64%. Αποδείχθηκε ότι ο PABR μπορεί να λειτουργήσει αποτελεσματικά με υδραυλικό χρόνο παραμονής (HRT) έως και 1 ημέρα.

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: PABR, αναερόβια χώνευση, συμπύκνωμα, τροφικά υπολείμματα, υγρά αστικά απόβλητα.

1. ΕΙΣΑΓΩΓΗ

Σήμερα η κύρια προσέγγιση της διαχείρισης των Αστικών Υγρών Αποβλήτων αφορά τη συλλογή τους μέσω αποχετευτικού δικτύου και την επεξεργασία τους σε μονάδες βιολογικού καθαρισμού για την αφαίρεση των αιωρούμενων στερεών και των θρεπτικών συστατικών τους (άζωτο, φώσφορο) μέσω διεργασιών καθίζησης, βιολογικής οξείδωσης του οργανικού φορτίου και απολύμανσης μέσω χλωρίωσης. Στη συνέχεια ένα μείγμα πρωτογενούς και δευτερογενούς ιλύος που παράγεται από την παραπάνω διεργασία οδηγείται για αναερόβια χώνευση πριν την τελική του διάθεση. Το κύριο λειτουργικό κόστος που φέρει το παραπάνω σύστημα επεξεργασίας βασίζεται, στον αερισμό της ιλύος που απαιτείται για την οξείδωση του οργανικού της φορτίου [1]. Για την εξομάλυνση του συγκεκριμένου κόστους έχει προταθεί, συνολική ή μερική σταθεροποίηση των αποβλήτων μέσω αναερόβιας χώνευσης με σκοπό την παραγωγή ενέργειας [2]. Ωστόσο, η συγκεκριμένη πρόταση έχει αποτελεσματική εφαρμογή μόνο για περιοχές με θερμό κλίμα, λόγω της χαμηλής συγκέντρωσης σε οργανικό φορτίο που περιέχεται στον συγκεκριμένο τύπο αποβλήτων .

Όσον αφορά στη διαχείριση των βιοαποικοδομήσιμων στερεών αποβλήτων και ιδιαίτερα των οικιακών τροφικών αποβλήτων, έχει διαπιστωθεί ότι περιέχουν αρκετά υψηλό υγρό περιεχόμενο, (τυπικά 70-80%) διαχείρισή τους από τα υπόλοιπα στερεά απόβλητα με αποτέλεσμα να συμβάλουν αρνητικά τόσο στην απώλεια σημαντικού ποσοστού καθαρών ανακυκλώσιμων υλικών όσο και στην απελευθέρωση μεγάλων ποσοτήτων βιοαερίου μέσω των ΧΥΤΑ, συμβάλλοντας σημαντικά στο φαινόμενο του θερμοκηπίου. Κοινοτικές Οδηγίες (Ευρωπαϊκή Ένωση), πιέζουν προς την ορθολογική διαχείριση του συγκεκριμένου τύπου αποβλήτων που αφορούν αρχικά τη χωριστή συλλογή τους στη πηγή και τηνδιαφοροποίησή τους από το ρεύμα που οδηγείται στους ΧΥΤΑ με σκοπό την ενεργειακή τους αξιοποίηση μέσω μεθόδων όπως αυτή της αναερόβιας χώνευσης [4, 5].

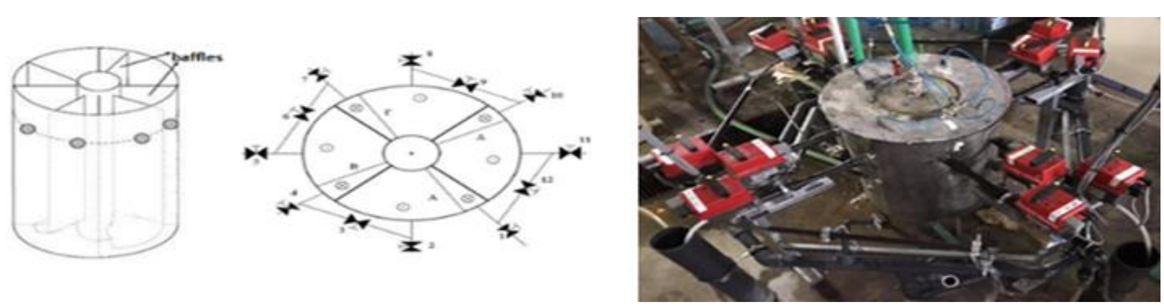
Ένα πρώτο στάδιο για την ορθολογική αξιοποίηση των βιοαποικοδομήσιμων στερεών αποβλήτων επιτεύχθηκε στο πλαίσιο του Προγράμματος Horizon2020 (Waste4Think) όπου το ΕΜΠ, σε συνεργασία με τον Δήμο Χαλανδρίου εφάρμοσαν ένα πιλοτικό πρόγραμμα χωριστής συλλογής των οικιακών τροφικών αποβλήτων, προ-επεξεργασίας και ενεργειακής αξιοποίησης αυτών μέσω αναερόβιας χώνευσης. Η προ-επεξεργασία αφορά τον τεμαχισμό και την ξήρανση της μάζας των αποβλήτων χωρίζοντάς το σε δύο ρεύματα, το στερεό (Food Residue Biomass, FORBI) που οδηγείται για αναερόβια χώνευση και το αρκετά πλούσιο σε οργανικό φορτίο υγρό συμπύκνωμα (condensate). Η παρούσα εργασία στοχεύει στην συνεπεξεργασία του υγρού αυτού κλάσματος και ενεργειακή αξιοποίησή του μέσω αναερόβιας χώνευσης μαζί με συνθετικό απόβλητο που προσομοιάζει τα χημικά χαρακτηριστικά των κοινών υγρών αστικών λυμάτων.

Για την μελέτη της παραπάνω διεργασίας επιλέχθηκε ένας Περιοδικός Αναερόβιος Αντιδραστήρας με Ανακλαστήρες τύπου PABR (Periodic Anaerobic Baffled Reactor) [6, 7, 8, 9]. Ο PABR είναι ένας καινοτόμος ταχύρρυθμος αντιδραστήρας και μια ελκυστική διαδικασία για τα αστικά λύματα λόγω του χαμηλού κόστους κατασκευής, λειτουργίας και συντήρησης, της χαμηλής παραγωγής ιλύος και της υψηλής παραγωγής βιοαερίου σε μικρό χρόνο παραμονής τόσο σε υψηλές όσο και σε χαμηλές οργανικές φορτίσεις. Ο PABR αποτελείται από δύο ομόκεντρους κυλίνδρους, όπως φαίνεται στην (Εικόνα 1), με τον εσωτερικό να λειτουργεί ως εναλλάκτης θερμότητας, ώστε να διατηρείται το σύστημα σε σταθερή θερμοκρασία. Ο χώρος ανάμεσα στον εσωτερικό και τον εξωτερικό κύλινδρο αποτελείται από τέσσερα, ίδιου όγκου διαμερίσματα, κάθε ένα από τα οποία χωρίζεται σε ένα ανοδικό και ένα καθοδικό τομέα. Κάθε διαμέρισμα προσομοιάζει υδραυλικά, έναν αναερόβιο αντιδραστήρα με ανακλαστήρες ABR παραμέτρου λειτουργίας η οποία ονομάζεται Περίοδος Εναλλαγής (Switching Period) T. Η συγκεκριμένη παράμετρος καθορίζει το χρονικό διάστημα για το οποίο κάθε διαμέρισμα του αντιδραστήρα λειτουργεί ως διαμέρισμα Εισροής. Η περίοδος εναλλαγής T μαζί με τον υδραυλικό χρόνο παραμονής, Hydraulic χαμηλές τιμές της παραμέτρου T ο PABR προσεγγίζει την συμπεριφορά ενός αντιδραστήρα Upflow μεταξύ των διαμερισμάτων, ο αντιδραστήρας προσομοιάζει τη συμπεριφορά τεσσάρων αντιδραστήρων ABR συνδεδεμένων σε σειρά. Στην συγκεκριμένη εργασία εξετάζεται η αποτελεσματικότητα του PABR, ως προς την αναερόβια συγχώνευση μίγματος Αστικών Υγρών Αποβλήτων, municipal wastewater (MWW) και Συμπυκνώματος Τροφικών Αποβλήτων (condensate).

2. ΜΕΘΟΔΟΛΟΓΙΑ

Χρησιμοποιήθηκε συνθετικό μίγμα που προσομοιάζει τα φυσικοχημικά χαρακτηριστικά των MWW. Η συνταγή για το συγκεκριμένο διάλυμα αντλήθηκε βιβλιογραφικά και είναι η εξής: 0,7g/L $C_6H_{12}O_6$, 0.124 g L N H C l g L C H C O O N a g L K H P O g L M g S O H O g L C a C l g L

Οι παράμετροι λειτουργίας για κάθε πειραματική φάση παρουσιάζονται στον Πίνακα 1. Ο αντιδραστήρας λειτούργησε χωρίς περιοδική εναλλαγή (ως ABR). Καθ' όλη την διάρκεια των πειραμάτων διεξάγονταν καθημερινές αναλύσεις διαλυτού χημικώς απαιτούμενου οξυγόνου (sCOD). Η παραγωγή βιοαερίου και Μεθανίου παρακολουθούνταν ημερησίως. Όλες οι αναλύσεις διενεργήθηκαν σύμφωνα με τις Πρότυπες Μεθόδους [11], ενώ για τη μέτρηση της περιεκτικότητας σε μεθάνιο στο παραγόμενο βιοαέριο χρησιμοποιήθηκε αέριος χρωματογράφος (SHIMADZU GC-2010 plus).



Εικόνα 1 Πειραματική διάταξη PABR

Πίνακας 1 Παράμετροι λειτουργίας για κάθε πειραματική φάση

Λειτουργικές Παράμετροι	Εγκλιματισμός	Πειραματική φάση
Υδραυλικός Χρόνος Παραμονής	2 Μέρες	1 Μέρα
Ρυθμός Οργανικής Φόρτισης	0,98 gCOD/(L*d)	0,97 gCOD/(L*d)
Περίοδος Εναλλαγής Διαμ/των	-	-
Θερμοκρασία Λειτουργίας	35^{o}C	35^{o}C

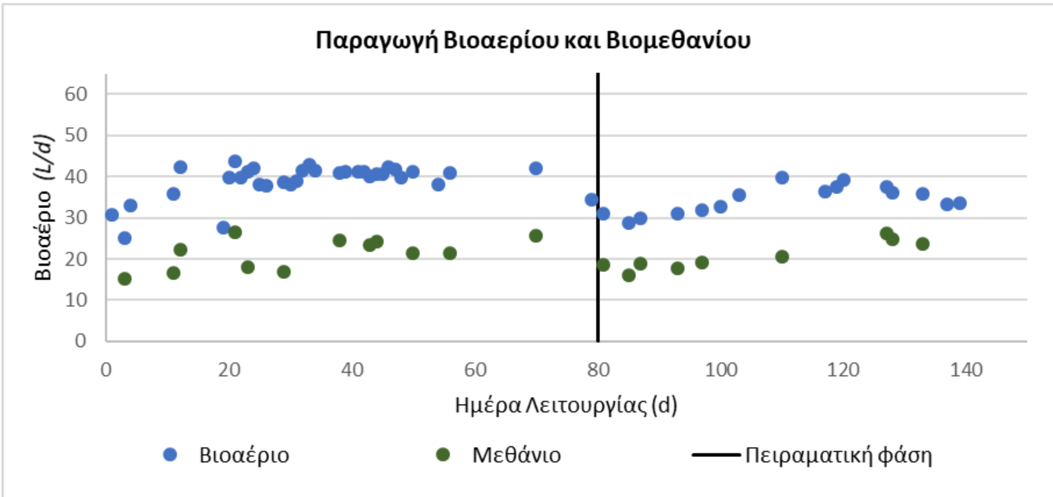
3. ΑΠΟΤΕΛΕΣΜΑΤΑ ΚΑΙ ΣΥΖΗΤΗΣΗ

Στον Πίνακα 2 παρουσιάζονται τα συγκεντρωτικά αποτελέσματα της φάσης εγκλιματισμού και της πειραματικής φάσης λειτουργίας. Λόγω της χαμηλής συγκέντρωσης σε COD του τελικού διαλύματος ανάμειξης των δύο αποβλήτων, ο HRT του αντιδραστήρα μειώθηκε στην μία μέρα με σκοπό η πειραματική φάση λειτουργίας να έχει τον ίδιο ρυθμό οργανικής φόρτισης με την φάση εγκλιματισμού. Όσον αφορά την παραγωγή βιοαερίου και βιομεθανίου ο αντιδραστήρας δεν φαίνεται να επηρεάζεται σημαντικά από την προσθήκη του condensate και την μείωση του HRT όπως φαίνεται στο (Διάγραμμα 1). Ενδιαφέρον παρουσιάζει η σύγκριση του παραγόμενου μεθανίου με το θεωρητικό μέγιστο της διεργασίας που εξαρτάται από την κατανάλωση οργανικού φορτίου (Διάγραμμα 2). Στο Διάγραμμα 2 παρατηρείται ότι ο αντιδραστήρας παρουσιάζει χαμηλές αποδόσεις κατά την πρώτη φάση λειτουργίας ενώ στην συνέχεια παρουσιάζει ικανοποιητική απόδοση για τον ρυθμό οργανικής φόρτισης στον οποίο λειτουργεί. Όσον αφορά στην κατανάλωση του οργανικού φορτίου, η πειραματική φάση λειτουργίας παρουσιάζει αρκετά ικανοποιητικό βαθμό απόδοσης. Επίσης επιτυγχάνεται σημαντική μείωση του οργανικού φορτίου του μίγματος μέσω της αναερόβιας χώνευσης, όπως φαίνεται στο (Διάγραμμα 3).

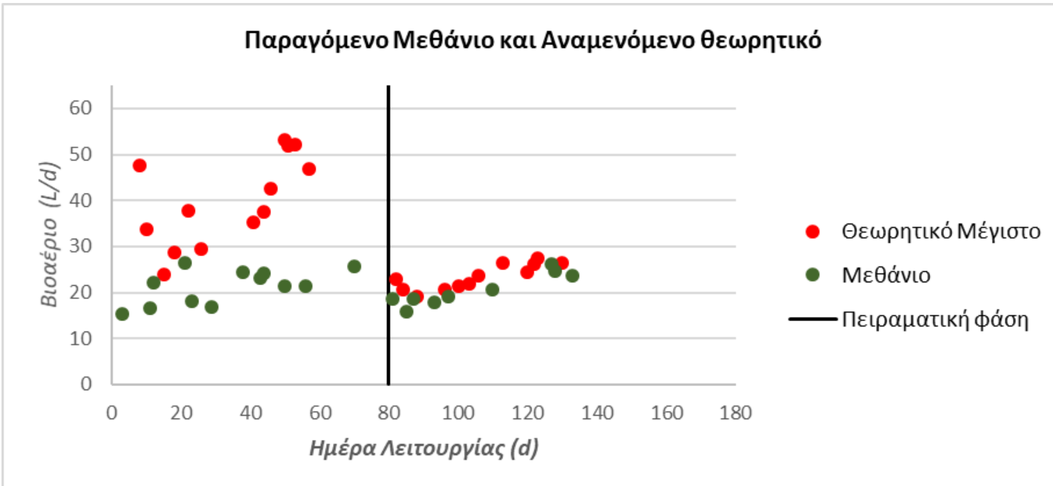
Πίνακας 2 Συγκεντρωτικά αποτελέσματα λειτουργίας του αντιδραστήρα.

	Εγκλιματισμός	Πειραματική φάση
Αποτελέσματα	Μέση τιμή	Μέση τιμή
Παραγωγή Βιοαερίου (L/d)	38,7 ± 4,4	34,5 ± 3,2
Παραγωγή Μεθανίου (L/d)	21,1 ± 3,5	20,6 ± 3,3
Ποσοστό Μεθανίου (%)	56,2 ± 6,9	63,1 ± 7,5
COD υποστρώματος (g/L)	1.98 ± 0.2	0.97± 0.08

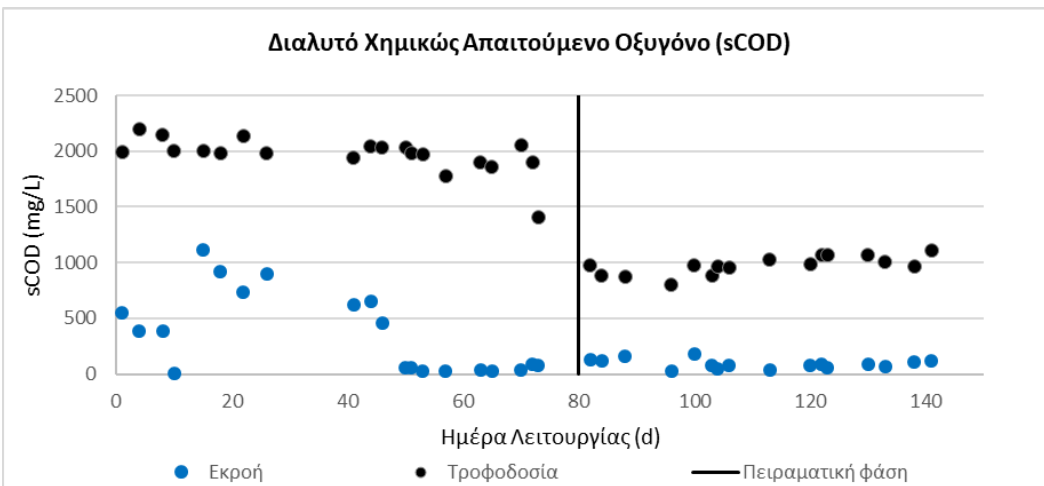
Κατανάλωση COD (%)	78 ± 17,7	91± 4,5
Απόδοση ως προς CH_4 (%)	53 ± 19,7	88 ± 16,3



Διάγραμμα 1 Παραγωγή Βιοαερίου και βιομεθανίου ανά ημέρα λειτουργίας.



Διάγραμμα 2 Παραγόμενο μεθάνιο και αναμενόμενο θεωρητικό ανά ημέρα λειτουργίας.



Διάγραμμα 3 Διαλυτό COD στην τροφοδοσία και στην εκροή του αντιδραστήρα.

Το συγκεκριμένο αποτέλεσμα είναι ενθαρρυντικό καθώς δείχνει ότι η συγκεκριμένη μεθοδολογία θα μπορούσε να αντικαταστήσει την ενεργειακά ασύμφορη διεργασία της βιολογικής οξείδωσης αν όχι για την πλήρη γραμμή επεξεργασίας των αστικών λυμάτων, για ένα ποσοστό της. Συγκεκριμένα παρατηρείται ότι με την πάροδο της διεργασίας η κατανάλωση οργανικού φορτίου ξεπερνάει το 90%. Το γεγονός αυτό σε συνδυασμό με την ταχύρρυθμη λειτουργία του αντιδραστήρα δηλαδή την ικανότητα του να επεξεργάζεται μεγάλους όγκους αποβλήτων ημερησίως καθιστά την διεργασία βιώσιμη.

ΕΥΧΑΡΙΣΤΙΕΣ

Η ερευνητική εργασία υποστηρίχτηκε από το Ελληνικό Ίδρυμα Έρευνας και Καινοτομίας (ΕΛ.ΙΔ.Ε.Κ.) στο πλαίσιο της Δράσης «1η Προκήρυξη ερευνητικών έργων ΕΛ.ΙΔ.Ε.Κ. για την ενίσχυση των μελών ΔΕΠ και Ερευνητών/τριών και την προμήθεια ερευνητικού εξοπλισμού μεγάλης αξίας» (Αριθμός Έργου: 2797).

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Ζαρκαλίου, Κ. Παπαδοπούλου*, Γ. Λυμπεράτος Ολοκληρωμένη διαχείριση των βιοαποβλήτων και αστικών υγρών αποβλήτων για παραγωγή βιοαερίου, ΕΛΛΗΝΙΚΗ ΕΤΑΙΡΕΙΑ ΔΙΑΧΕΙΡΙΣΗΣ ΣΤΕΡΕΩΝ ΑΠΟΒΛΗΤΩΝ σε συνεργασία με την International Solid Waste Association (ISWA), «Επιτάχυνση της Μετάβασης στην Κυκλική Οικονομία - Ευκαιρίες & Κίνδυνοι», 28—29 Σεπτεμβρίου 2022 (Πολυτεχνείο, Πατησίων)

7ο ΣΥΝΕΔΡΙΟ ΕΕΔΣΑ

7th HSWMA CONFERENCE

ΟΛΟΚΛΗΡΩΜΕΝΗ ΔΙΑΧΕΙΡΙΣΗ ΤΩΝ ΒΙΟΑΠΟΒΛΗΤΩΝ ΚΑΙ ΑΣΤΙΚΩΝ ΥΓΡΩΝ ΑΠΟΒΛΗΤΩΝ ΓΙΑ ΠΑΡΑΓΩΓΗ ΒΙΟΑΕΡΙΟΥ

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ΠΕΡΙΛΗΨΗ

Αντικείμενο της παρούσας εργασίας αποτελεί η ανάπτυξη μίας καινοτόμου προσέγγισης στον τομέα της διαχείρισης των Αστικών Αποβλήτων. Πιο συγκεκριμένα, εστιάζει σε δύο από τα ρεύματα των Αστικών Αποβλήτων: τα Βιοαποικοδομήσιμα Αστικά Στερεά Απόβλητα και τα Αστικά Υγρά Απόβλητα. Η διαχείριση των συγκεκριμένων ρευμάτων σήμερα βασίζεται στην αρχή ότι αποτελούν δύο ξεχωριστά ρεύματα. Προτείνουμε την μελέτη μίας εναλλακτικής προσέγγισης: Τη συνδιαχείριση του υγρού κλάσματος των Βιοαποικοδομήσιμων Αστικών Στερεών Αποβλήτων (συμπύκνωμα) και των Αστικών Υγρών Αποβλήτων.

Δεδομένης της υψηλής συγκέντρωσης οργανικού φορτίου στο νέο ρεύμα, οδηγήθηκε για αναερόβια χώνευση προς παραγωγή βιοαερίου. Χρησιμοποιήθηκε ένας Περιοδικός Αναερόβιος Χωνευτήρας με Ανακλαστήρες, Periodic Anaerobic Baffled Reactor (PABR). Ο PABR είναι ένας καινοτόμος αντιδραστήρας και μια ελκυστική διαδικασία για τα αστικά λύματα λόγω του χαμηλού κόστους κατασκευής, λειτουργίας και συντήρησης, της χαμηλής παραγωγής ιλύος και της υψηλής παραγωγής βιοαερίου σε μικρό χρόνο παραμονής ακόμα και σε υψηλές οργανικές φορτίσεις. Στην παρούσα εργασία ο PABR παρουσίασε μεγάλη σταθερότητα με μέσο ποσοστό απομάκρυνσης sCOD 77%. Η μέση παραγωγικότητα βιοαερίου ήταν 51 L/d και το ποσοστό μεθανίου ήταν 66%.

Συνολικά, ο PABR αποδεικνύεται ότι είναι ένα καινοτόμο σύστημα αναερόβιας χώνευσης ικανό να επεξεργάζεται αναερόβια πρώτες ύλες υψηλού οργανικού φορτίου σε χαμηλούς χρόνους παραμονής HRT. Αποδείχθηκε ότι ο PABR μπορεί να λειτουργήσει αποτελεσματικά με HRT έως και 1 ημέρα.

Λέξεις Κλειδιά: PABR, αναερόβια χώνευση, συμπύκνωμα, τροφικά υπολείμματα, υγρά αστικά απόβλητα

ΕΥΧΑΡΙΣΤΙΕΣ

ΕΛ.ΙΔ.Ε.Κ. Ελληνικό Ίδρυμα Έρευνας & Καινοτομίας

Η ερευνητική εργασία υποστηρίχτηκε από το Ελληνικό Ίδρυμα Έρευνας και Καινοτομίας (ΕΛ.ΙΔ.Ε.Κ.) στο πλαίσιο της Δράσης «1η Προκήρυξη ερευνητικών έργων ΕΛ.ΙΔ.Ε.Κ. για την ενίσχυση των μελών ΔΕΠ και Ερευνητών/τριών και την προμήθεια ερευνητικού εξοπλισμού μεγάλης αξίας» (Αριθμός Έργου: 2797).

Integrated management of municipal wastewater with source collected biowaste

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Abstract

Historically, the management of municipal solid waste and that of wastewater have evolved as two independent streams, defined by the main phase in each case; solid and liquid, respectively. Of course, liquid effluents contain substantial amounts of solid matter in suspension, while municipal solid wastes, especially food waste, have a very high moisture content (typically 70-80% by weight). An alternative much more sustainable approach, based on the chemical composition, is presented. Source-sorted food waste is dried and shredded, generating a homogeneous, odor-free biomass that may be stored without deterioration for prolonged periods of time and used in alternative ways for the production of biofuels and/or compost. In parallel, the liquid fraction generated from the drying process may be combined with the municipal wastewater stream opening interesting and novel treatment and valorization possibilities.

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