

## Anaerobic digestion of dried/shredded food waste in a periodic anaerobic baffled reactor

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### ABSTRACT

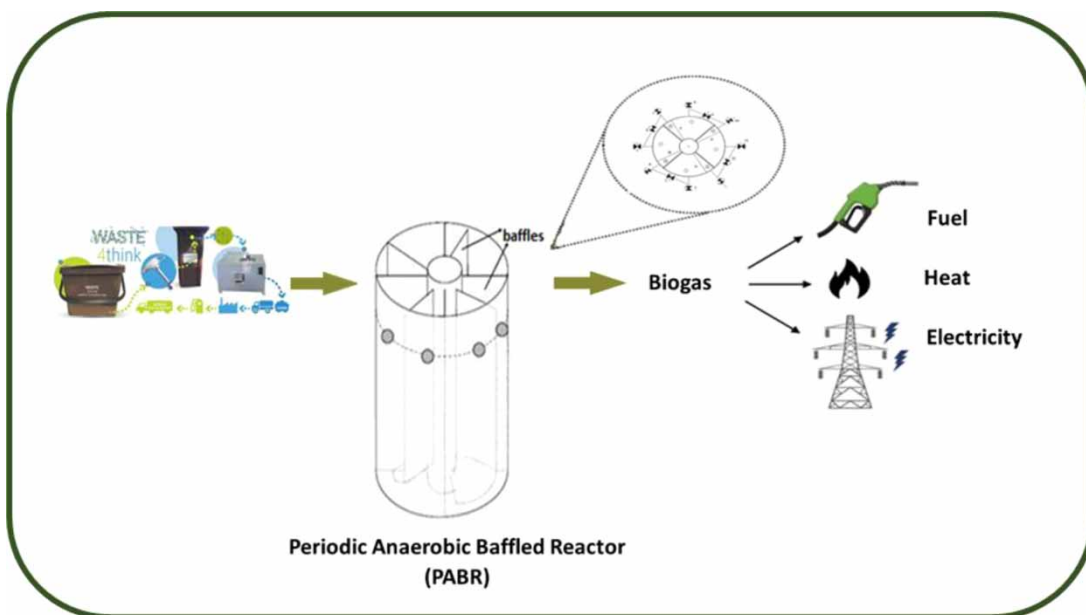
The objective of the current work is to study the impact of the operational parameters' variation (HRT, OLR and T) on biomethane productivity in a periodic anaerobic baffled reactor (PABR). The feedstock used was a biomass product named food residue biomass (FORBI), which is dried and shredded source-separated household food waste. The PABR is an innovative, high-rate bioreactor. Apart from the hydraulic retention time (HRT) and the organic loading rate (OLR), an important operational parameter is the switching period (T) of the feeding compartment: when T is high, the bioreactor operation is similar to an anaerobic baffled reactor (ABR), while when it is low, the operation approaches that of an upflow anaerobic sludge blanket reactor (UASBR). Nine distinct experimental phases were conducted, during which the operational parameters of the PABR were consecutively modified: the HRT varied from 9 to 2.5 days, T between 2 days and 1 and finally the OLR from  $1.24 \text{ g}_{\text{COD}}/\text{L}_{\text{bioreactor}}\text{d}$  to  $8.08 \text{ g}_{\text{COD}}/\text{L}_{\text{bioreactor}}\text{d}$ . The maximum biomethane yield was  $384 \text{ L}_{\text{CH}_4}/\text{kg}_{\text{FORBI}}$  corresponding to the operation at  $\text{HRT} = 5 \text{ d}$ ,  $\text{OLR} = 2.14 \text{ g}_{\text{COD}}/\text{L}_{\text{bioreactor}}\text{d}$  and  $T = 2 \text{ days}$ . Similar efficiency ( $333 \text{ L}_{\text{CH}_4}/\text{kg}_{\text{FORBI}}$ ) was achieved at higher OLR ( $4.53 \text{ g}_{\text{COD}}/\text{L}_{\text{bioreactor}}\text{d}$ ).

**Key words:** biogas, household fermentable waste, PABR, source separation, valorization

### HIGHLIGHTS

- The feedstock used was a biomass product food residue biomass (FORBI), which is dried and shredded food waste.
- Periodic anaerobic baffled reactor (PABR), a high-rate bioreactor.
- The switching period (T) of the feeding compartment gives the bioreactor the element of operational flexibility.
- The PABR can efficiently operate at HRTs as low as 2.5 days, however, the highest biomethane yield was achieved under HRT of 5 d.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

Population growth combined with the rapid urbanization that took place during the last decades were the accelerators leading to one of the most complex challenges of our days: waste management. It has been estimated that cities generate about 1.3 billion tons of solid waste per year, which is expected to increase to 2.2 billion tons before the middle of the current decade. The corresponding impacts at global scale are exponentially growing: greenhouse gases (GHGs) emissions are constantly increasing, the recycling industry is now a global business of many million euros annually, while local societies and economies can suffer from serious damages due to improper waste collection; flooding, local air pollution and public health impacts are only some of the major consequences (Hoorweg & Bhada-Tata 2012). The expected economic development, as well as population growth, will sharply increase the absolute numbers of waste generation during the coming decades (Melikoglu *et al.* 2013).

The major fraction of municipal solid waste (MSW) corresponds to food waste (FW), reaching between 40% and 50% of the total. According to estimations 30% of the total quantities of food produced ends up wasted, which raises environmental, ethical and economic issues (FAO 2009; Gustavsson *et al.* 2011). The traditional FW management approaches lead to huge environmental, social and economic burdens (Eriksson *et al.* 2015). The extent of the challenge can be fathomed when considering that 12% of the methane emissions globally are originating from carbon decomposition in landfills (Ellen MacArthur Foundation 2017). Furthermore, FW based on its physicochemical properties could evolve to be one of the most important resources in the foreseeable future, if only sound management will be implemented. Considering these figures, it is apparent that innovative (FW) valorization approaches are necessary to be developed in order to face this challenge in an environmentally sound and economically rational direction, via maximum nutrients valorization and recovery (Zhang *et al.* 2014).

Among the alternatives, the most prominent currently is anaerobic digestion (AD). Implementing this specific technology, FW diversion from landfills, biogas generation – as an energy carrier leading to energy recovery – and nutrients recovery (through digestate treatment and use-on-land) could concurrently be achieved (Carlsson *et al.* 2015; Michalopoulos *et al.* 2017a). During the last few years, research has been focussed on optimizing AD processes, in order to maximize environmental and economic benefits by minimizing capital and operation expenditures (Hagos *et al.* 2017). The critical parameters towards this are maximizing the biogas/biomethane productivity efficiency, while minimizing the hydraulic retention time (HRT) (Chiu & Lo 2016).

### 1.1. The periodic anaerobic baffled reactor, PABR

The PABR was designed by Skiadas and Lyberatos, to become an innovative high-rate anaerobic digestion system, capable of anaerobically processing high organic-loaded feedstocks at low HRTs (Skiadas & Lyberatos 1998). As shown in Figure 1, it consists of two concentric cylinders, from which the inner compartment is used as a temperature-control bath. The space between the two cylinders is divided into four compartments, each one of which is further divided into two sub-compartments (downflow and upflow sections), thus resembling a simple ABR, only arranged in a circular structure. The downflow section of each compartment is the one from which the feed enters, descending, passing through the microbial biomass layer at its bottom and then ascending through the upflow section of the same compartment. Then it exits the compartment and, through an external pipeline system, which links the compartments, it goes to the next one. After following the same route inside the last compartment, it flows outside of the system as effluent. An important property of the specific bioreactor is the ability to periodically change the inflow compartment. This important operating parameter, the switching period ( $T$ ), represents the time required for all four compartments to have served as feed compartment. 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 (Michalopoulos *et al.* 2017a). The flow of the feedstock throughout the compartments as well as the switching of the feeding compartment is achieved through the utilization of a system of 12 solenoid valves, which open and close in a suitable way.

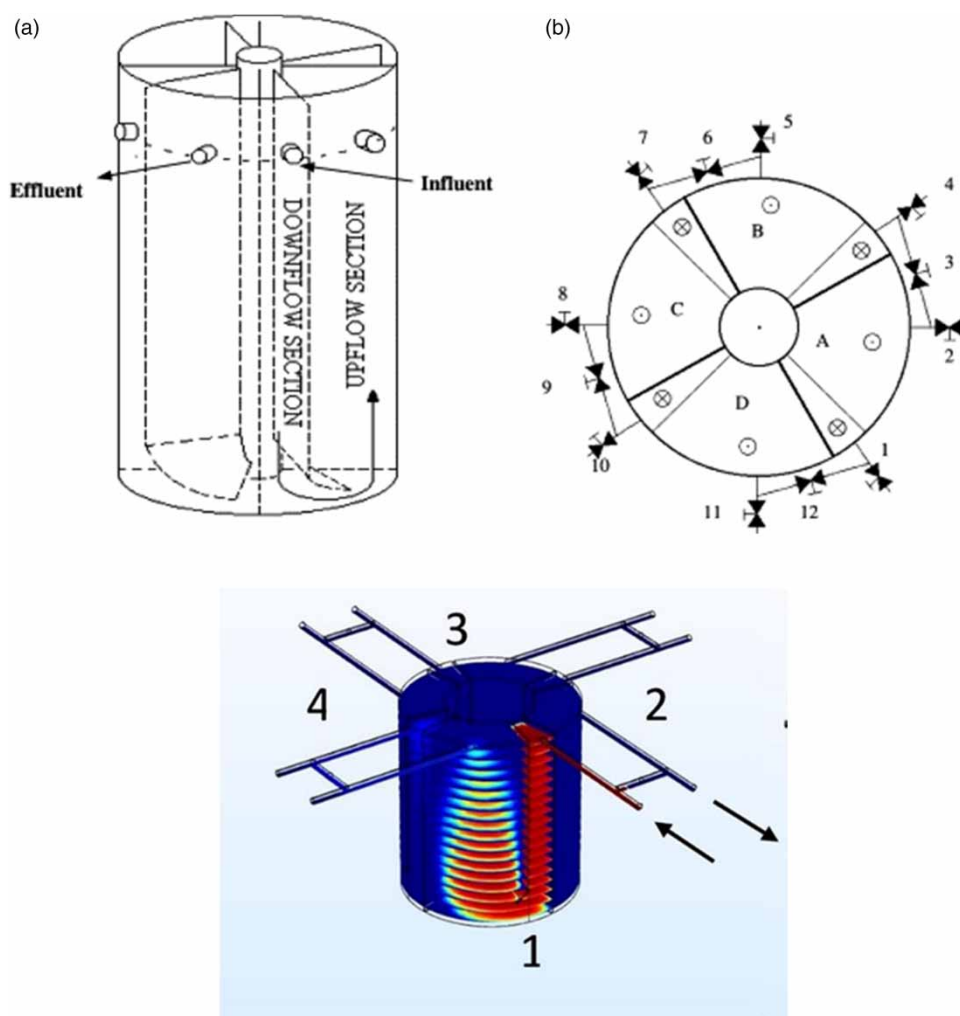


Figure 1 | Front and top views of PABR (Michalopoulos *et al.* 2018).

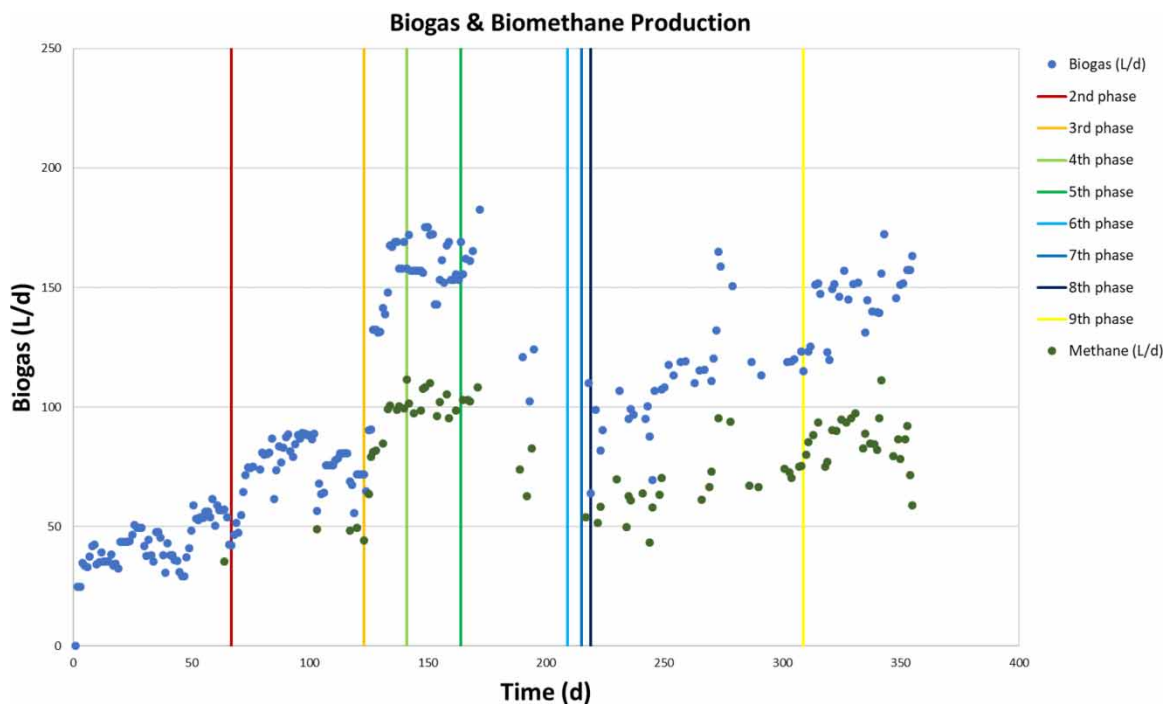
This specific operational parameter gives the bioreactor the element of operational flexibility: when T is high, the bioreactors operation is similar to an ABR, while when it is low the operation approaches the one of an upflow anaerobic sludge blanket reactor (UASBR).

A number of studies have examined the performance of the PABR under various organic loading rates (OLRs), HRTs and Ts and by utilizing different types of feedstocks (Liu *et al.* 2009; Michalopoulos *et al.* 2017a, 2019; Skiadas *et al.* 2000). A recent work by Michalopoulos *et al.* 2018, described the hydraulic behaviour of a pilot-scale PABR concluding in a relation between HRT/T values and the operation of the bioreactor. Specifically, they found that the reactor operates similarly to a plug-flow one at low HRT/T values, and as a continuous stirred-tank reactor (CSTR) at high HRT/T values (Michalopoulos *et al.* 2018).

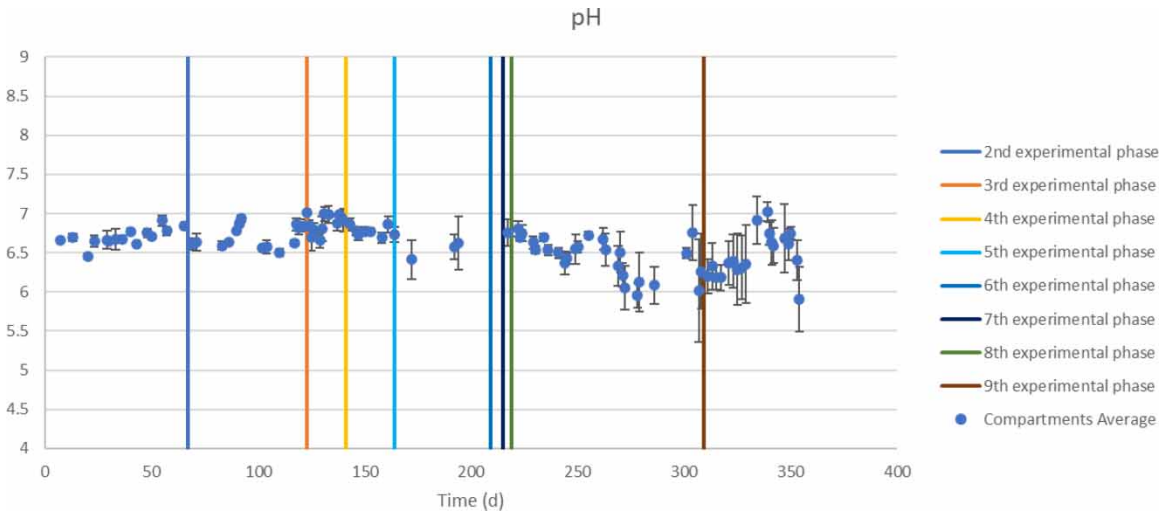
The scope of the current working paper is to assess the operational efficiency of a PABR under various operational parameters, as well as to prove the robustness of the specific anaerobic digestion system against abrupt operational modifications. Furthermore, this study aims at assessing the biomethane yield and COD removal efficiency of the bioreactor treating food waste under various HRT and OLR values, in comparison with a variety of other types of bioreactors as presented in a previous study conducted by Lytras *et al.* (2020). To achieve this, we fed the PABR with various concentrations of FORBI suspension and under various HRTs. The biogas productivity, biomethane content and effluent COD concentration were regularly determined aiming at identifying the optimum operational parameters in terms of HRT minimization and biomethane production maximization.

## 2. MATERIALS AND METHODS

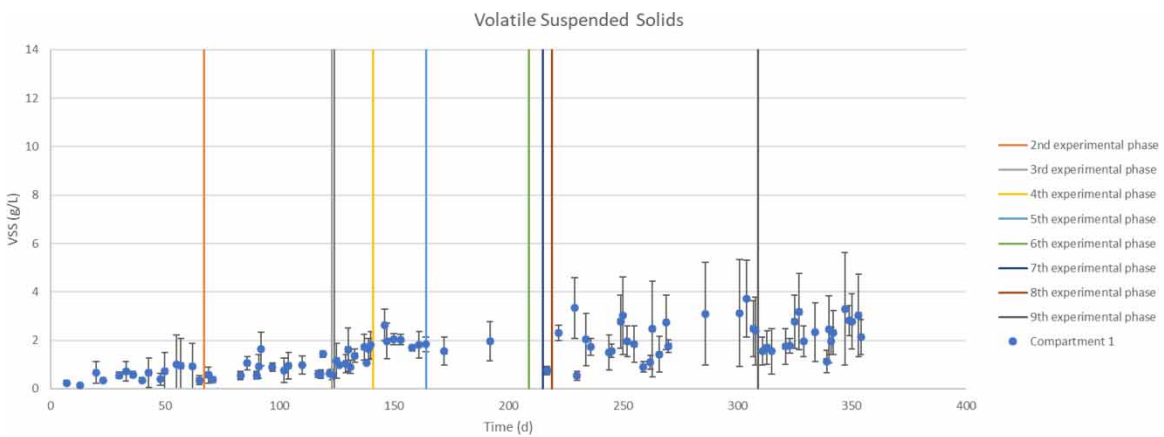
The scope of this work was to study the effect of the basic operational parameters (HRT, OLR and T) in the operational efficiency of a PABR, considering the biogas and methane productivity. Nine distinct experimental phases were carried out, during which the operational parameters were being successively modified. Specifically, the HRT ranged between 9 and 2.5 days, T between 2 and 1 days and the OLR between  $1.24 \text{ g}_{\text{COD}}/\text{L}_{\text{bioreactor}}^* \text{d}$  and  $8.08 \text{ g}_{\text{COD}}/\text{L}_{\text{bioreactor}}^* \text{d}$ . 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), biogas production and methane content were monitored at regular intervals, to assess the efficiency of the process (Figures 2–7).



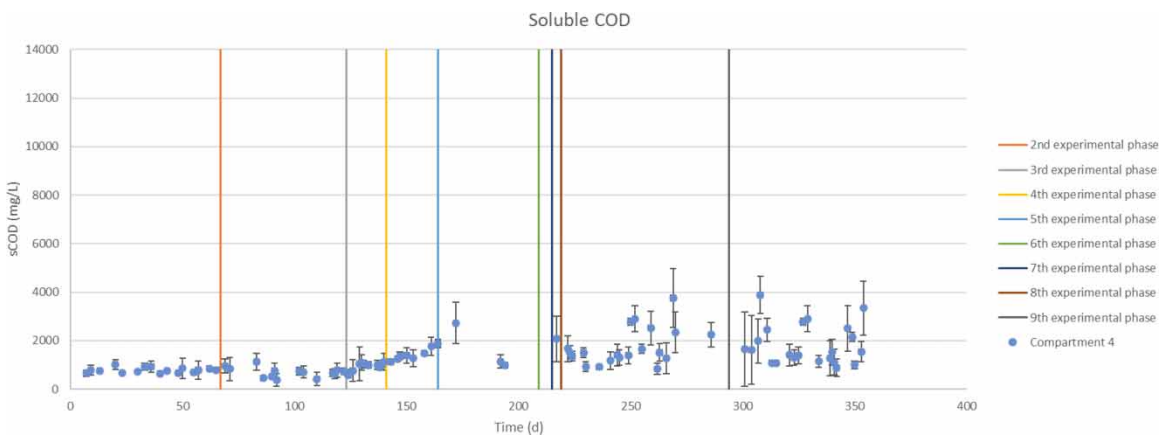
**Figure 2** | Biogas and biomethane production throughout the nine experimental phases.



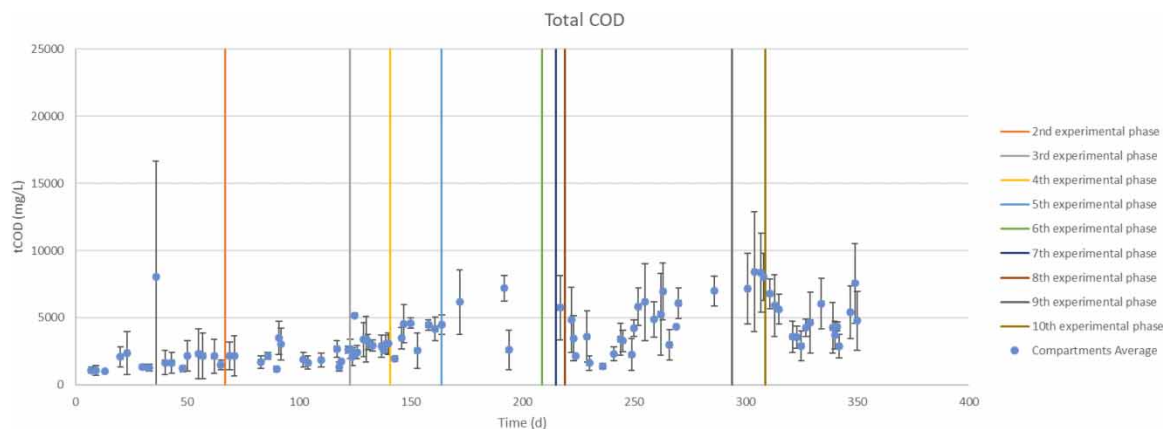
**Figure 3** | Average pH and per compartment fluctuation in the four PABR's compartment throughout the nine experimental phases.



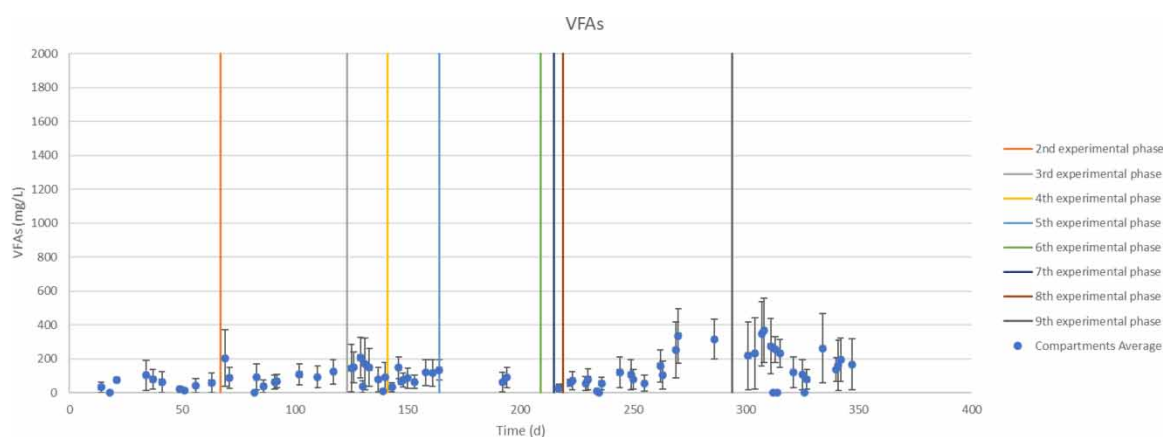
**Figure 4** | VSS average value and compartments fluctuation in the four PABR's compartment throughout the nine experimental phases.



**Figure 5** | Average sCOD and compartments fluctuation in the four PABR's compartments throughout the nine experimental phases.



**Figure 6** | Average tCOD and compartments fluctuation in the four PABR's compartment throughout the nine experimental phases.



**Figure 7** | Average VFAs and compartments fluctuation in the four PABR's compartments throughout the nine experimental phases.

## 2.1. Food residue biomass product, FORBI

The current research work, pursued within the framework of Waste4think, a Horizon2020 project, is based on previous work on the anaerobic digestion of food waste (Stamatelatou & Antonopoulou 2011; Pham *et al.* 2015; Zamanzadeh *et al.* 2016; Michalopoulos *et al.* 2019). The Horizon2020 Waste4think project involved four European cities (Zamudio, Cascais, Seveso and Halandri) aiming at developing and integrating eco-solutions in the waste management value chain. The Municipality of Halandri, in collaboration with the National Technical University of Athens (NTUA), proposed an innovative management approach of the Household Fermentable Waste (HFW that included source separation and separate collection of this fermentable fraction of household food waste, followed by drying and shredding of the collected waste.

The scope of the project was to evaluate the generated product, named FORBI as a potential feedstock for the production of biofuels, among various valorization alternatives. FORBI is a high quality homogenized and dry biomass product weighing approximately 20–25% of the original food waste collected and may be stored for prolonged periods of time without deterioration (Papanikola *et al.* 2019).

The proposed HFW management scheme offers a variety of benefits, since FORBI exhibits numerous advantages:

- Volume and weight are reduced by as high as 75–80% compared to the initial raw food waste.
- It is a homogenized product, with highly repeatable physicochemical characteristics.
- Odors have been removed.
- It is highly stable, as it can be saved for prolonged periods of time without deteriorating.

In previous studies, the physicochemical properties of FORBI, as well as the potential valorization routes have been presented (Papadopoulou & Lyberatos 2015; Michalopoulos *et al.* 2017; Mathioudakis *et al.* 2018). Lytras *et al.* present the methane productivities that can be achieved from FORBI in various bioreactors (Lytras *et al.* 2020).

## 2.2. Analytical methods

TSS, VSS, tCOD, sCOD and alkalinity were measured based on the relevant methodologies described in the Standard Methods for the Examination of Water and Wastewater (APHA *et al.* 1995). A digital pH-meter (WTW, INOLAB, pH720) was used to carry out pH measurements. VFAs were measured using a gas chromatograph (SHIMADZU GC-2010 plus) equipped with a flame ionization detector and a capillary column (Agilent technologies, 30 m × 0.53 mm ID × 1 μm film, HP-FFAP) and a SHIMADZU AOC-20 s autosampler. The samples were acidified using a 20% H<sub>2</sub>SO<sub>4</sub> solution prior to the analysis. A temperature programme was set ranging from 105 °C to 160 °C at a rate of 15 °C/min and subsequently reaching 225 °C at a rate of 20 °C/min. The carrier gas was helium at a 30 mL/min flow, while the injector's and detector's temperature were both set at 230 °C (Michalopoulos *et al.* 2019). Moreover, a GC-TCD (SHIMADZU GC-2014) was used for the measurement of methane content in the biogas generated. A 5-m separation column (Carboxen 1,000) with a 2.1 mm interior diameter was used. The initial temperature of the GC-TCD was 40 °C. For the estimation of the methane content a temperature programme was used (duration: 25 min) during which the temperature was increasing 10 °C·min<sup>-1</sup> until reaching 185 °C and staying stable at this temperature for 5 min. The methane content then was calculated using a standard calibration curve (Michalopoulos *et al.* 2019). The biogas production rate was measured using an oil displacement technique (Michalopoulos *et al.* 2017a, 2017b).

## 2.3. Experimental process

A pilot-scale 77-L active volume PABR was utilized for the AD experiments. The system was fed with a FORBI as a suspension at various solids concentrations (TS 10–20 g/L). The temperature of the process was 35 °C during the whole experimental period corresponding to mesophilic anaerobic digestion. The feedstock was kept at low temperature (5–6 °C) prior to being fed to the bioreactor in the storage tank shown in Figure 8. Samples were taken throughout the experimental procedure from all four compartments of the bioreactor, through sampling valves located in the middle of each compartment, and without any prior mixing of the compartments.

Furthermore, samples were taken and analysed from the feedstock and the effluent of the bioreactor. It is important to mention that the bioreactor was already operating for two years before starting the current experimental process. Specifically, it started up being filled with inoculum taken from the Metamorphosis Waste Processing Centre, Athens, Greece. Then for approximately two years it was fed with different feedstocks (expired baby products and animal manure), before its operation was adjusted to be fed with FORBI.

As mentioned, the scope of the experimental process was to evaluate the efficiency of PABR operation under different conditions and to assess the optimum conditions in terms of biogas and biomethane productivity. Therefore, the bioreactor operated at various HRTs, OLRs and T<sub>s</sub> (as outlined in Table 1). The transition from one experimental phase to the next was only implemented after a steady periodic state was achieved. The only exceptions were for the 6th and 7th phases, because of the system's instability observed in the extreme conditions imposed.



**Figure 8** | The experimental setup: PABR, programmable logic computer (PLC) and feedstocks storage tank.

**Table 1** | Operational parameters, nine experimental phases, PABR

| Operational parameters/experimental phases | 1st   | 2nd  | 3rd   | 4th   | 5th  | 6th  | 7th  | 8th  | 9th  |
|--|-------|------|-------|-------|------|------|------|------|------|
| Operation duration (days)                  | 67    | 56   | 18    | 23    | 45   | 6    | 4    | 75   | 15   |
| HRT (days)                                 | 8.7   | 5    | 5     | 5     | 2.5  | 2.5  | 2.5  | 2.5  | 2.5  |
| T (days)                                   | 2     | 2    | 2     | 1     | 2    | 2    | 1    | 1    | 1    |
| TS <sub>in</sub> (g/L)                     | 10    | 10   | 20    | 20    | 10   | 15   | 15   | 10   | 15   |
| Average feedstock's tCOD (g/L)             | 10.83 | 10.7 | 22.63 | 22.63 | 12.9 | 20.2 | 19.8 | 14.1 | 19.5 |
| OLR (g <sub>COD</sub> /L*d)                | 1.24  | 2.14 | 4.53  | 4.53  | 5.16 | 8.08 | 7.92 | 5.64 | 7.80 |

The biogas was collected from the top of the PABR and passed through a device for biogas production rate measurement and finally recorded to programmable logic computer (PLC) (Figure 8). The custom-made device used for the quantification of biogas production rate and for biogas sampling is described in previous works (Michalopoulos *et al.* 2017a, 2017b).

### 3. RESULTS AND DISCUSSION

The PABR operated being fed with FORBI suspension for 350 consecutive days. During the first two experimental phases, the methane content was not quantified on a regular basis. As shown in Figure 2 maximum biogas production was observed during the 3rd and 4th experimental phases, reaching 531 and 517 L/kg<sub>FORBI</sub> respectively, while the biomethane production reached 333 and 325 L/kg<sub>FORBI</sub>. During these two phases, the basic operational parameters were: HRT: 5 d and OLR: 4.53 g<sub>COD</sub>/L\*d for both experimental phases, while T was reduced from 2 d in phase 3 to 1 d in phase 4. Hence, it is obvious that for the specific HRT and OLR, reducing T to the half did not have an important impact.

During the 5th phase, the HRT was further reduced to 2.5 d with the OLR being increased to 5.16 g<sub>COD</sub>/L\*d and then to 9.08 and 7.92 g<sub>COD</sub>/L\*d during phases 6 and 7, respectively. As a consequence, significant decrease in biogas and biomethane production was observed. At this HRT, we started observing several operational problems, as will be discussed further below where the pH and VSS variations are presented. In order to remedy the reactor, the OLR was reduced to 5.64 during the 8th phase, by feeding a more dilute feed. The biogas gradually increased and this trend was maintained during phase 9 when the OLR was increased to 7.8 g<sub>COD</sub>/L\*d. Overall, it is obvious that the PABR can efficiently operate under HRTs as low as 5 d and can even operate at an HRT of 2.5 d, albeit at lower efficiency and not without operational problems.

The variation of pH is presented in Figure 3 and it is apparent that for all the compartments it was sufficiently constant throughout the experimental procedure. However, after day 250, a sharp decrease was observed in compartment 4 and it seems that for an HRT of 2.5 days the system tended to operational failure. This happened most probably due to hydraulic malfunction of the system. However, interesting was the fact that when the loading was reduced in phase 8, the productivity of biogas recovered without the need for any external pH adjustment. This highlights one of the most important benefits of the specific type of bioreactor: its robustness against sharp operational modifications.

The level of VSS as shown in Figure 4 remained remarkably low in all compartments during the first five periods of the experimental procedure and specifically under 1.5 g/L. Nevertheless, when the HRT was significantly reduced, a gradual increase of VSS reaching an average of 3.5 g/L was observed and this was maintained also after the reduction of T from 2 to 1 d. In addition, the difficulty of compartment 3 to lower its level of VSS in conjunction with the slower recovery to normal pH values of compartment 4 possibly shows that a flow malfunction occurred in the piping system which links those two compartments. Therefore, the hypothesis that the organic solids' overloading most probably was caused by hydraulic malfunction is reinforced.

A similar trend with VSS was observed for the soluble chemical oxygen demand (sCOD). Specifically, it remained below 1 g/L during the first five phases of the experimental procedure and followed a gradual increase up to 5 g/L (Figure 5) afterwards. This clear upward trend of sCOD when the HRT was reduced to 2.5 d indicated once more that the system approached its limits of functional operation under those conditions.

This work shows how essential it is to measure all the required analytical characteristics of the samples in order to properly evaluate the efficiency of the reactor's operation, as it is not necessary that an operational malfunction will become apparent



in all characteristics' measurements at once and on time. Thus, while VFA measurements did not indicate any problem of PABR operation, the evaluation of the other analytical characteristics indicated several operational problems.

The overall efficiency of the PABR throughout the experimental phases is presented in Table 2. From this table it is apparent that HRT reduction from 5 to 2.5 days significantly affected the specific biogas and methane yield per kg of FORBI fed, as well as the tCOD removal achieved in the bioreactor. On the other hand, a high specific methane productivity was achieved during phases 1–4, reaching 348 L/kg<sub>FORBI</sub> or 429 L/kg<sub>Vs</sub>. The OLR seems to play a significant role in terms of biogas/biomethane productivity. Specifically, when the OLR increased from 4.53 g<sub>COD</sub>/L\*d to 5.16 g<sub>COD</sub>/L\*d, which corresponds to a 14% increase, the biogas/biomethane productivity was decreased by as high as 37%.

Furthermore, as far as the effect of HRT/T on the methane yield is concerned only two T values (T = 1 and T = 2) were assessed. The effect of HRT/T on methane yield is shown on Table 3.

It seems that the increase of the HRT/T ratio leads to increase of the CH<sub>4</sub> yield, which comes in agreement with the conclusions of a previous study assessing the hydraulic behavior of the PABR (Michalopoulos *et al.* 2018).

#### 4. CONCLUSIONS

In this paper, we evaluated the efficiency of the high-rate PABR operating under different conditions and assessed the optimum conditions in terms of biogas and biomethane productivity. The feedstock used was the biomass product FORBI which is dried and shredded source separated household food waste, a type of waste which corresponds to the major fraction of MSW.

It was shown that the PABR can efficiently operate at HRTs as low as 5 days. Specifically, maximum biogas production observed in two of the experimental procedure's phases when the basic operational parameters were HRT 5 d and OLR 4.53 g<sub>COD</sub>/L\*d. For the specific HRT and OLR reducing T to the half (from 2 to 1 d) did not have an important impact. In these phases biogas production reached 531 and 517 L/kg<sub>FORBI</sub>, while the biomethane production reached 333 and 325 L/kg<sub>FORBI</sub>, respectively. In addition, under these conditions, the pH was sufficiently steady and VSS, sCOD and VFAs remained remarkably low in all the compartments, indicating an efficient operation of AD inside the reactor.

On the other hand, several operational issues were observed when the HRT was further decreased to 2.5 d. In particular, the decrease in biogas and biomethane production, the sharp and continuous reduction of pH and the clear upward trend of both VSS and sCOD indicated that the system was pushed beyond its limits for safe functional operation under those conditions. Moreover, the drop in pH values of compartment 4 in conjunction with the rise of VSS in compartment 3

**Table 2** | PABR operational efficiency, nine experimental phases

| Phase  | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    |
|--|------|------|------|------|------|------|------|------|------|
| OLR (g <sub>COD</sub> /L*d)                    | 1.24 | 2.14 | 4.53 | 4.53 | 5.16 | 8.08 | 7.92 | 5.64 | 7.80 |
| Average effluent tCOD (g/L)                    | 1.86 | 2.03 | 3.44 | 5.43 | 3.01 | 3.8  | 3.9  | 3.4  | 4.6  |
| tCOD removal (%)                               | 86.4 | 80.5 | 85.6 | 74.3 | 76.7 | 81.2 | 80.3 | 75.9 | 76.4 |
| Biogas productivity (L/L/d)                    | 0.56 | 0.98 | 2.09 | 2.07 | 1.32 | 1.46 | 1.55 | 1.75 | 0.9  |
| Biogas yield (L/kg <sub>FORBI</sub> )          | 484  | 500  | 531  | 517  | 330  | 243  | 258  | 438  | 150  |
| %CH <sub>4</sub>                               | 67.5 | 69.6 | 62.7 | 62.8 | 62   | 54   | 55   | 62   | 57.5 |
| CH <sub>4</sub> yield (L/kg <sub>FORBI</sub> ) | 327  | 348  | 333  | 325  | 205  | 131  | 142  | 271  | 86   |
| CH <sub>4</sub> yield (L/kg <sub>Vs</sub> )    | 403  | 429  | 411  | 401  | 253  | 162  | 175  | 335  | 106  |

**Table 3** | HRT/T effect on CH<sub>4</sub> yield

|  |      |     |      |     |
|--|------|-----|------|-----|
| CH <sub>4</sub> yield (L/kg <sub>FORBI</sub> ) | 168  | 236 | 327  | 333 |
| HRT/T  | 1.25 | 2.5 | 4.35 | 5   |

indicate a flow malfunction in the piping system which links those two compartments. Notably, VFA measurements did not show any significant increase in spite of the evaluation of the other analytical characteristics pointing out several operation problems. This made clear how essential it is to measure all the key parameters in order to properly evaluate the efficiency of reactor's operation, as it is not necessary that an operational malfunction will become apparent in all characteristics' measurements at once and on time.

Last but not least, when we decreased the organic loading of the reactor following the observed problems, the biogas productivity gradually recovered without any external pH adjustment. This combined with the overall pH stability of the system highlighted one of the most important benefits of the specific type of bioreactor which is its robustness against sharp operational changes.

Overall, the PABR proves to be an effective high-rate anaerobic digestion system capable of anaerobically processing high organic-loaded feedstocks under low HRTs. Specifically, the PABR was effective in treating FORBI suspension under HRT of 5 d, which is 4 times less than the ones in conventional (i.e. CSTR) systems. Only after HRT approaches 2.5 d the system starts to show hydraulic malfunctions but even then, the system can easily recover by reducing its organic loading without any external adjustment.

## ACKNOWLEDGEMENTS

This work is produced under research project Horizon 2020, Grant Agreement No 688995. 'Moving towards Life Cycle Thinking by integrating Advanced Waste Management Systems' [WASTE4THINK].

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 15 February 2021; accepted in revised form 5 June 2021. Available online 17 June 2021