A state of the art literature review on anaerobic digestion of food waste: influential operating parameters on methane yield

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Abstract

A thorough literature review was conducted to investigate the behavior of food waste in anaerobic digestion experiments. The main goal of this literature review was to study the effect of several operating parameters on methane yields and to develop a simplified regression equation to predict methane generation. Using a data prospection methodology, all the papers published within 2013-2015 that contained selected keywords were included in this study (a total of 613 papers). After screening, 167 papers were finally retrieved using the search engines and our methodology. From these papers, data from 231 experiments were recorded and evaluated. The parameters recorded in each paper were: operation mode (batch or continuous), temperature (mesophilic or thermophilic), moisture content (wet or dry), presence or absence of pretreatment, reactor scale (laboratory, bench, pilot, demonstration/full scale), presence or absence of co-substrates (co- or mono-digestion), organic loading rate (OLR), hydraulic retention time (HRT) and methane yield. The novelty of the work is that it employed various statistical tools to examine the effect of the above-mentioned factors on food waste methane generation. Most of the experiments were performed at mesophilic temperatures, at a wet system without substrate pretreatment. An equal number of papers described mono-digestion and co-digestion studies, and an equal number of papers described batch and continuous reactor experiments. The mean HRT for the continuous processes was 36.7 days. Statistical analysis indicated that the parameters that significantly affected methane yields were the "operation mode" and "pretreatment". A best reduced regression model was fitted to the methane yield data to describe the above effects. As a general conclusion, with this methodology, that involved the analysis of a large number of studies (with different conditions and set-ups, heterogeneous waste, etc), correlations between some typical operating parameters of anaerobic digestion and methane yields were not obvious.

Key words: Biogas; Anaerobic digestion; Food waste; Statistical analysis; Regression modelling

Highlights

- A data prospection methodology was applied to anaerobic digestion of food waste
- We used ANOVA and regression modelling to calculate influential parameters
- Operation mode (continuous, batch) and pretreatment affected methane yields
- The continuous mode runs resulted in higher methane yields than the batch mode runs
- The organic loading rate and the HRT did not correlate with methane yields

1. Introduction

Anaerobic digestion (AD) is an environmentally friendly process that can be implemented to face the challenge of managing the amounts of food waste (FW) that are being produced. Anaerobic digestion is a biological process running under the absence of oxygen and at redox potentials lower than -330 mV. During AD, microorganisms break down complex biodegradable organic matter to biogas, that mainly consists of methane (50 to 80%) and carbon dioxide (30 to 50% v/v). Consequently, biogas can be used as a valuable energy source with yields that range from 5.5 to 7 kWh m^{-3} of biogas.

As it has been reported by many authors, FW can be effectively degraded under anaerobic conditions (Campuzano and González-Martínez, 2016, Capson-Tojo et al., 2016). However, in the anaerobic digestion of FW, a low methane yield and a high incidence of process instability has been commonly reported, due to the increased generation and accumulation of volatile fatty acids (Zhang et al., 2014). Co-digestion (the simultaneous digestion of two or more substrates) and substrate pretreatment are the strategies that are mainly implemented to enhance biogas production, balance nutrients and control acidogenesis in the anaerobic digestion process (Esposito et al., 2011). Furthermore, FW composition and, consequently, its physicochemical characteristics, can be highly variable depending on the country, the type of food and the economic and cultural aspects (Capson-Tojo et al., 2016).

The implementation of anaerobic digestion to treat FW at full-scale has been steadily increasing. In Europe, more than 90% of the digestion capacity is provided by single-step digesters using wet or dry technologies (Cesaro and Belgiorno, 2014). Wet anaerobic digestion is the process in which waste is treated at less than 15-20% dry solids (DS) content (wb), whilst dry anaerobic digestion is the one operating at solids higher than 20% wb. When operating at the boundary of 20% DS, the process is usually called semi-dry anaerobic digestion (Hartmann and Ahring, 2006). Regarding dry processes, the main advantage is that higher organic loading rates (OLR) can be applied. However, mixing in dry digesters cannot usually achieve a good contact of waste and biomass. By 2010, dry anaerobic digestion installations for the treatment of organic Municipal Solid Waste (MSW) in Europe constituted 54% of the total capacity installed (De Baere and Mattheeuws, 2010). According to Hartmann and Ahring (2006), the highest biogas yields were obtained in thermophilic wet digestion processes, when processing the organic fraction of MSW (OFMSW) at organic loading rates below 6 kg VS m^{-3} d, while dry and semi-dry processes manifested a better performance at higher OLR.

Traditionally, mesophilic anaerobic processes (digestion temperature at around 37ºC) prevail over the thermophilic ones (digestion temperature at around 50-55ºC). It has been also reported that mesophilic processes are more stable, whilst operating and process failures have occured in thermophilic installations (De Baere and Mattheeuws, 2010). However, the thermophilic operation leads to a better hygienisation of the waste material (Ferrer et al., 2010; Kim et al., 2002) and to a higher methane yield that is sufficient to compensate for the energy consumption necessary to heat the digester.

At laboratory scale, digestion assays can be carried out in batch or continuous modes. Biochemical Methane Potential (BMP) tests (laboratory scale batch processes) have been widely used to estimate methane yields from various organic substrates (Angelidaki et al., 2009). Continuous operation is usually more labour and time-consuming than the batch operation; the latter, however, has been extensively used to determine the biogas potential of a substrate (Raposo et al., 2011).

Technical and scientific interest has been mainly directed towards the optimisation of the AD process by changing several parameters (Mata-Alvarez et al., 2000). For example, anaerobic process degradability can be improved by means of co-digestion. Mata-Alvarez et al. (2014) postulated that anaerobic co-digestion could be considered the most relevant topic within the anaerobic digestion field, since around 50% of the publications during 2010-2013 were on that topic. However, Mata-Alvarez et al. (2014) indicated that FW is not referenced as the main substrate in co-digestion and it is less studied than other substrates, such as manures or sewage sludge. On the other hand, several pretreatment methods (biological, mechanical or physicochemical) to increase the anaerobic biodegradability of FW have been widely studied (Cesaro and Belgiorno, 2014). Such pretreatment methods aim to accelerate the initial hydrolysis stage, which is traditionally the rate-limiting step in anaerobic processes dealing with high solid content. This limitation is caused by the presence of lignocellulosic and fatty fractions in various organic substrates. Finally, the dose of additives, inorganic and biological, to stimulate microbial activity and/or reduce the concentration of inhibitory agents has also been studied (Romero-Güiza et al., 2016). Apart from methane yields, the hydrogen production has been a recent research focus in the anaerobic digestion of organics (Capson-Tojo et al., 2016).

The main goal of this work was to study the behaviour of FW during anaerobic digestion by developing a best reduced simplified regression model that can predict methane yields. Eventually, the aim was to find the most important operating parameters that affect methane yields using extensive literature information. To do this, an initial collection of 613 scientific articles between years 2013 and 2015 was made using appropriate search engines and keywords. After further screening, 167 articles were finally considered relevant and used in this study. Various parameters were then recorded from the experiments described in each paper, such as the temperature, the operation mode (batch or discontinuous), the implementation of pretreatment, the use of co-substrates, the moisture content (wet, dry), etc. After grouping the experiments to the aforementioned parameters, the regression model that was developed included categorical and continuous independent variables and the methane yield as the statistical response. To the knowledge of the authors, this is the first time that such a statistical analysis is performed to investigate FW methane yields using a large amount of literature data.

2. Methodology

2.1 Data prospection

The selection of articles was done through a search at the Web of Science between years 2013 and 2015. The keywords used in the search were: "food waste", "organic fraction of municipal solid waste", "OFMSW", "biowaste" or "kitchen waste", combined with "biogas" or "anaerobic digestion" and synonymous or relevant words (e.g. anaerobic process, methane, biomethane, etc.). As a result of the search, 613 articles were initially retrieved. A further screening eliminated some articles that dealt with other topics, such as landfilling, or ones that targeted to the generation of by-products other than biogas (e.g. bio-hydrogen, lactic acid, biodiesel, volatile fatty acids, etc.). Eventually, 167 articles were considered for detailed analysis. These articles described 231 experiments, since, in some case, one publication included more than one experiments (refer to Supplementary Material for the complete list of the 167 articles used in this study). The experiments were categorised according to different process parameters and characteristics, namely: i) Operation mode: Batch or Continuous, ii) moisture content (dry: moisture <80% wb), wet: moisture > 80% wb), iii) Temperature: Mesophilic (35°C± 5°C) or Thermophilic (50°C± 5°C), iv) type of digestion: Monodigestion (digestion of FW without any other co-substrates) or Co-digestion (use of co-substrates), v) Use of pretreatment or not, vi) Reactor scale: Laboratory (up to 5 L), Bench (5 to 25 L), Pilot (25 to 250 L) and Demonstration/Full-scale (> 250 L).

Moreover, several additional process parameters were recorded. The FW used in most of the experiments were either source separated waste, obtained from full scale OFMSW treatment plants, canteens or restaurants, or simulated FW.

2.2 Normality tests and analyses of variance (ANOVA)

The check of the normality of the data was initially performed to justify the use of ANOVA in the subsequent statistical analyses. The normality of the methane yields per category was done using the Anderson-Darling test. The aforementioned test is appropriate to test normality for relatively large samples sizes (n) (i.e. larger than 10), as was the case here, as opposed to the Shapiro-Wilk test which is more appropriate for relatively small samples sizes (i.e. less than 10). During normality check, the skewness and kurtosis coefficients were also calculated per category. The normality test results are included in Table 1. After ensuring normality of data, an ANOVA was performed to compare and group multiple means by applying the Tukey's pairwise comparison test (at $p < 0.05$).

2.3 Regression modelling

Modelling was done using the methane yield (in L CH_4/kg VS) as a response (dependent variable), six categorical variables and two continuous variables as predictors (independent variables). The coding of each of the categorical variables, as used later one, is included below:

i) Operation mode: Continuous (CN), Batch (BA).
ii) Temperature: Mesophilic (M), Thermophilic (T).
iii) Moisture: Wet system (W), Dry system (D).
iv) Pretreatment of the main substrate: Yes (Y), No (N).
v) Use of co-substrates: Mono-digestion (M), Co-digestion (C).
vi) Reactor scale: Laboratory (L), Bench (B), Pilot (P), Demonstration/Full-scale (D).

The first five categorical variables comprised of 2 categories, whilst only the "reactor scale" variable comprised of 4 categories. The organic loading rate (OLR) and the hydraulic residence time (HRT) were included in the model as continuous variables.

Using the above parametric analysis structure, an Analysis of Variance (ANOVA) was performed by developing a General Linear Model, which is a factorial regression model. After developing the initial full model, that included all 8 aforementioned terms, we then sequentially removed terms, one by one, to reach the best reduced model (BRM), following the procedure suggested by Berthouex and Brown (2002). That is, after removing the statistically insignificant terms (the ones with $p > 0.05$), we final calculated the simplest model with statistically significant terms. The initial full regression model had the form of Equation (1).

$$\text{Methane yield} = \text{Constant} + A_1 \times \text{OperationModeCN} + A_2 \times \text{OperationModeBA} + B_1 \times \text{TemperatureM} + B_2 \times \text{TemperatureT} + C_1 \times \text{MoistureW} + C_2 \times \text{MoistureD} + D_1 \times \text{PretreatmentN} + D_2 \times \text{PretreatmentY} + E_1 \times \text{CoSubstrateM} + E_2 \times \text{CoSubstrateC} + F_1 \times \text{ExpScaleL} + F_2 \times \text{ExpScaleB} + F_3 \times \text{ExpScaleP} + F_4 \times \text{ExpScaleD} + \text{G} \times \text{HRT} + \text{H} \times \text{OLR} \qquad \text{(equation 1)}$$

where:

Methane yield in L CH_4/kg VS;

Constant: a constant in the same units as the methane yield;

A_1, A_2, B_1, B_2, C_1, C_2, D_1, D_2, E_1, E_2, F_1,F_2,F_3,F_4, G, H: model coefficients.

All the categorical variables take the values of either 0 or 1. For example, for a continuous system, OperationModeBA would equal 0 and OperationModeCN would equal 1.

All aforementioned statistical analysis was done with Minitab® v17.

3. Results and Discussion

3.1. General observations and descriptive statistics

Based on the total number of articles studied (167), the affiliation of the first author was from the People's Republic of China in 39% of the retrieved papers. Italy, United Kingdom, Spain and United States followed China as the countries with most publications (institutions based on the affiliation of the first author) with 9%, 7%, 5% and 5% appearance, respectively. It is interesting to note that, while the number of publications increased in China, Italy and the United States throughout the studied period (2013 to 2015), the number of publications decreased for Spain and the United Kingdom. The leading publication rate of Chinese Institutions agrees with the development of the biogas industry in this country that is promoted by the Chinese Government

(Wang et al., 2016). On the other hand, Germany, a country where anaerobic digestion is highly promoted with a large number of full-scale anaerobic digestion (Edwards et al., 2015, World Bioenergy Association, 2016), is not among the countries with the highest number of publications on anaerobic digestion of FW during the period studied (2013 to 2015). Most of the articles have been published in journals “Bioresource Technology” and “Waste Management” (29% and 14%, respectively). Then followed the journals “Applied Energy”, “Chemical Engineering Journal”, “Environmental Technology”, “Journal of Environmental Management” and “Waste Management & Research”; each of the above 5 journals accounted for 4% of the total publications.

As it can be observed in Table 1, most of the experiments were performed at mesophilic temperatures (88%). In addition, the wet system experiments were prevalent (89%) compared to dry systems. Most experiments (82%) were done without pretreatment of FW. An approximately equal number of papers described mono-digestion and co-digestion studies, whilst an equal number of papers employed batch and continuous mode experiments. As reported by Mata-Alvarez et al. (2014) regarding anaerobic digestion in general, co-digestion is also seen as a main research area in the anaerobic digestion of FW. Most studies dealt with one stage processes (83%). There were also few studies performed at demonstration scale (6.6%), which, perhaps, reflects a possible gap between academic research centres and the real world.

It is noted here that the average values included in Table 1 are difficult to interpret. A batch experiment could be performed in any type of temperature, or both types of moisture (wet, dry), with or without pretreatment, etc. Therefore, to explain solely a mean value would be rather misleading; however, those mean values are included in Table 1 as a first indication of the range of methane yields encountered in this work. The statistical analysis that follows clarifies the differences among means per category.

The Anderson Darling normality test reveals the groups of data that were distributed normally. In this work, the normality condition applied to all data groups that have significance level (α) values higher than 0.01.

Table 1. Descriptive statistics from 231 experiments with the corresponding methane yields

			Average CH_4 yield reported in L CH_4/kg VS			
Parameter		% of experiments	Mean ± stdev.	Skewness*	Kurtosis*	Anderson Darling normality test (p-value)**
Operation (mode)	Batch	48.1	348±165	0.5	1.2	0.347
	Continuous	51.9	402±130	0.6	2.7	<0.005
Temperature	Mesophilic	88.3	380±149	0.4	2.0	<0.005
	Thermophilic	11.7	349±159	0.15	-0.6	0.308
Experimental scale	Laboratory	64.9	370±164	0.6	1.7	0.026
	Bench	16.6	406±100	-0.12	1.4	0.060
	Pilot	1.18	369±144	-0.22	0.17	0.854
	Demonstration	6.6	371±123	-1.0	0.26	0.077
Pretreatment	No pretreatment	82.1	369±142	-0.01	0.99	<0.005
	Pretreatment	17.9	409±180	1.1	2.2	0.050
Moisture	Dry	11.3	342±111	0.13	-0.16	0.622
	Wet	88.7	380±153	0.4	1.7	<0.005
Co-digestion	Mono-digestion	50.9	395±132	0.44	2.7	<0.005
	Co-digestion	49.1	356±163	0.49	1.4	0.152

*: the normality of the data increases as these values approach 0; **: p>0.01 indicate normally distributed data.

Nineteen percent (19%) of the experiments involved batch co-digestion processes performed at a mesophilic temperature under wet conditions without pretreatment. Another 19% were continuous mono-digestion processes performed at a mesophilic range under wet conditions without substrate pretreatment. Table 2 details the different process characteristics of the selected anaerobic digestion processes.

Table 2 reveals that more research efforts should be focused on dry anaerobic digestion and thermophilic processes to improve the knowledge of anaerobic digestion of FW under those conditions. The relatively small number of published papers on thermophilic processes contradicts the large number of full scale thermophilic anaerobic digestion plants treating MSW, at least in Europe, where 50% of the total installed capacity of thermophilic digesters worldwide exists (Cesaro and Belgiorno, 2014). The same conclusions can be drawn on dry anaerobic digestion since, as reported by De Baere and Mattheeuws (2010), full scale dry anaerobic digesters for the treatment of MSW in Europe provide 54% of the total capacity installed. On the other hand, in the studied period, mainly wet anaerobic processes (87%) were found in the publications studied.

Continuous processes were mostly performed at a HRT in the range of 10-30 days (Figure 1a); however, the mean value was 36.7 days since there were a couple of continuous mode experiments that had been performed at very high HRTs (i.e. 160, 175 days) under dry conditions. For wet processes, mean HRT was 32 days. For batch processes, the most highly used experimental time was in the range of 20 to 40 days, with a mean value of 39 days (Figure 1b). Another important parameter for batch experiments was the inoculum to substrate ratio (ISR). This information could be retrieved from 74 experiments pointing that 50% of them used an ISR higher than 2, which is suggested as a non-inhibitory ratio (Raposo et al., 2011). On the other hand, 18% of the experiments reported an ISR lower than 1.

Table 2. Grouping of process characteristics in the 231 experiments.

Operation mode	Co- or mono-digestion	Temperature	Moisture content	Presence of pretreatment	Percentage (%)
Continuous	Mono-digestion	Mesophilic	Dry	Pretreatment	0.4
				No pretreatment	1.7
			Wet	Pretreatment	2.6
				No pretreatment	18.6
		Thermophilic	Dry	Pretreatment	0
				No pretreatment	1.3
			Wet	Pretreatment	0.4
				No pretreatment	3.0
	Co-digestion	Mesophilic	Dry	Pretreatment	0.0
				No pretreatment	4.8
			Wet	Pretreatment	0.9
				No pretreatment	14.7
		Thermophilic	Dry	Pretreatment	0.0
				No pretreatment	0.0
			Wet	Pretreatment	2.2
				No pretreatment	2.2
Batch	Mono-digestion	Mesophilic	Dry	Pretreatment	0.0
				No pretreatment	2.2
			Wet	Pretreatment	6.9
				No pretreatment	10.8
		Thermophilic	Dry	Pretreatment	0.0

				No pretreatment	0.4
			Wet	Pretreatment	0.4
				No pretreatment	1.7
	Co-digestion	Mesophilic	Dry	Pretreatment	0.4
				No pretreatment	1.3
			Wet	Pretreatment	3.9
				No pretreatment	19.0
		Thermophilic	Dry	Pretreatment	0.0
				No pretreatment	0.0
			Wet	Pretreatment	0.4
				No pretreatment	0.0

For precise definition of some categories, see section 2.1

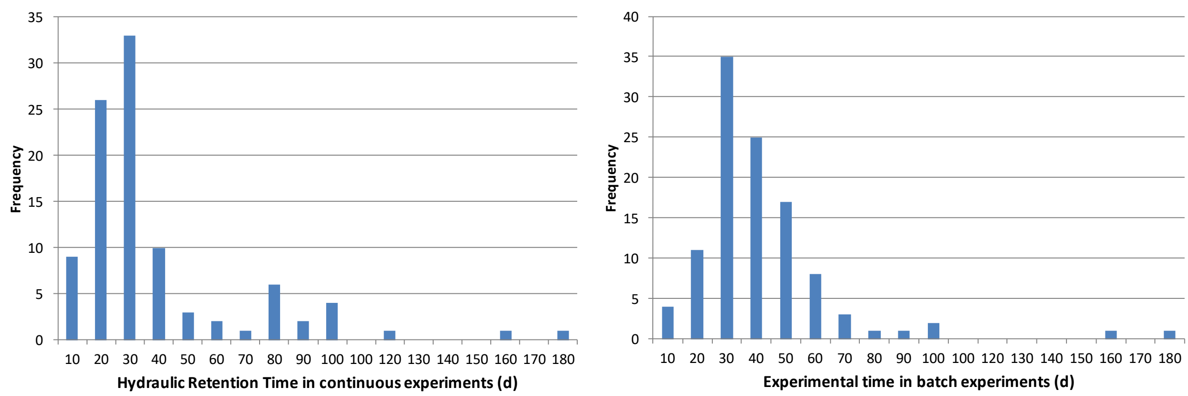


Figure 1. Frequency distribution (number of experiments) of Hydraulic Retention Time in continuous processes (left) and experimental time in the batch experiments (right).

As revealed in Table 1, some type of pretreatment was used in 18% of the experiments. Mainly thermal pretreatment and mechanical pretreatment (grinding or ultrasound) were used (37% and 24% respectively of the total pretreatments), followed by hydrolysis and chemical pretreatment (18% and 12% respectively) and, finally, thermochemical and thermomechanical pretreatment (6% and 3% respectively). In addition, 49% of the experiments analysed included co-digestion. As shown in Table 3, the most widely used co-substrates were manure (32.2%) and wastewater sludge (26.7%).

Table 3. Types of co-substrates used for the co-digestion of food waste (percentages based on 231 experiments).

Co-substrate	**%**
Manure	32.2
Wastewater sludge	26.7
Lignocellulosic wastes	14.4
Animal wastes	4.4
Green waste	4.4
Cheese Industry Waste	3.3
Fruit waste	3.3
Paper waste	3.3
Wastewater	3.3
Landfill leachate	2.2
Glycerine	1.1
Fat, oil and grease	1.1

3.2 Descriptive statistics and correlations for methane yields

A graphical depiction of the data was performed using comparative boxplots that represent the range of values and can allow a visual comparison of the different parameters.

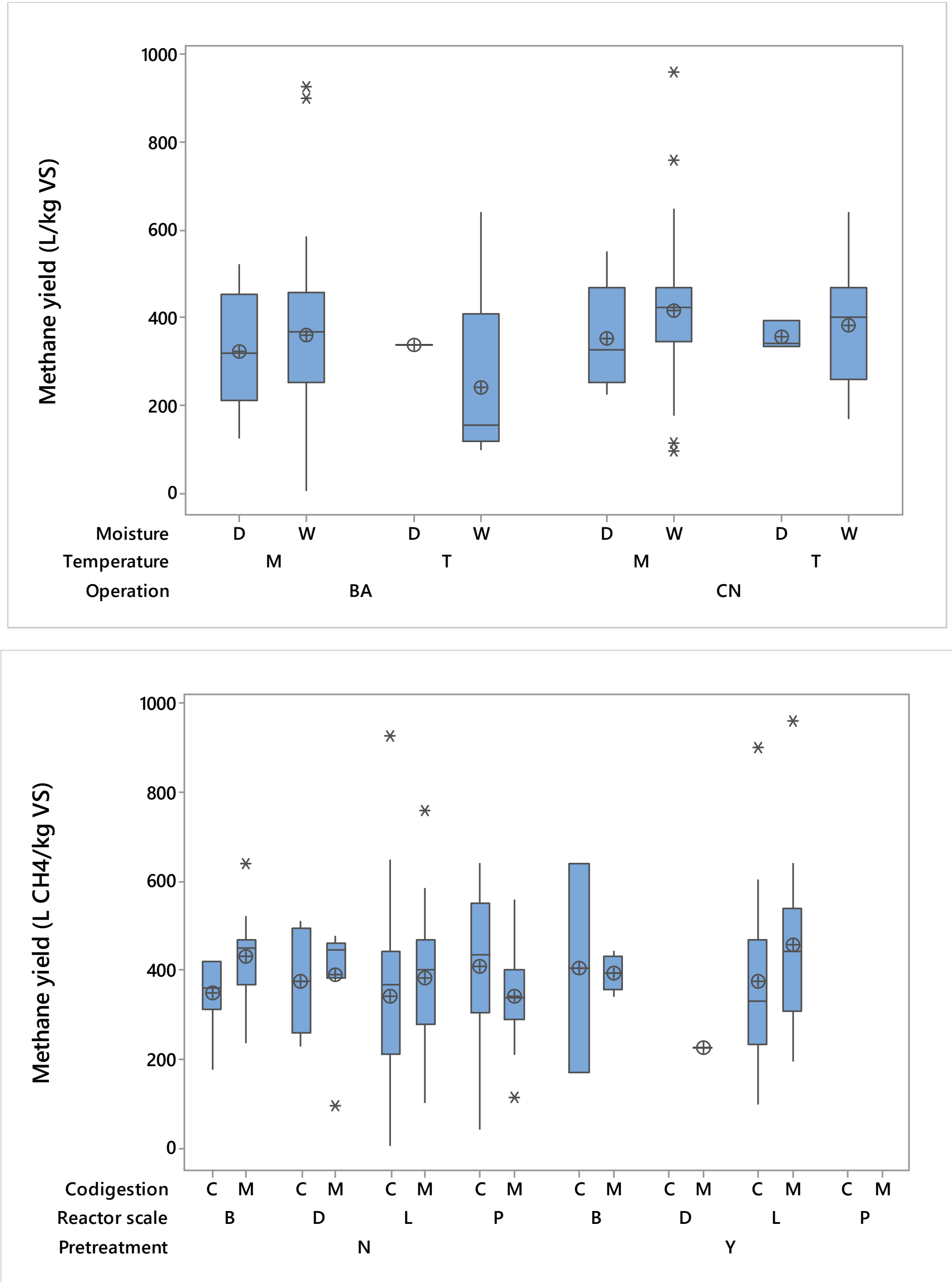
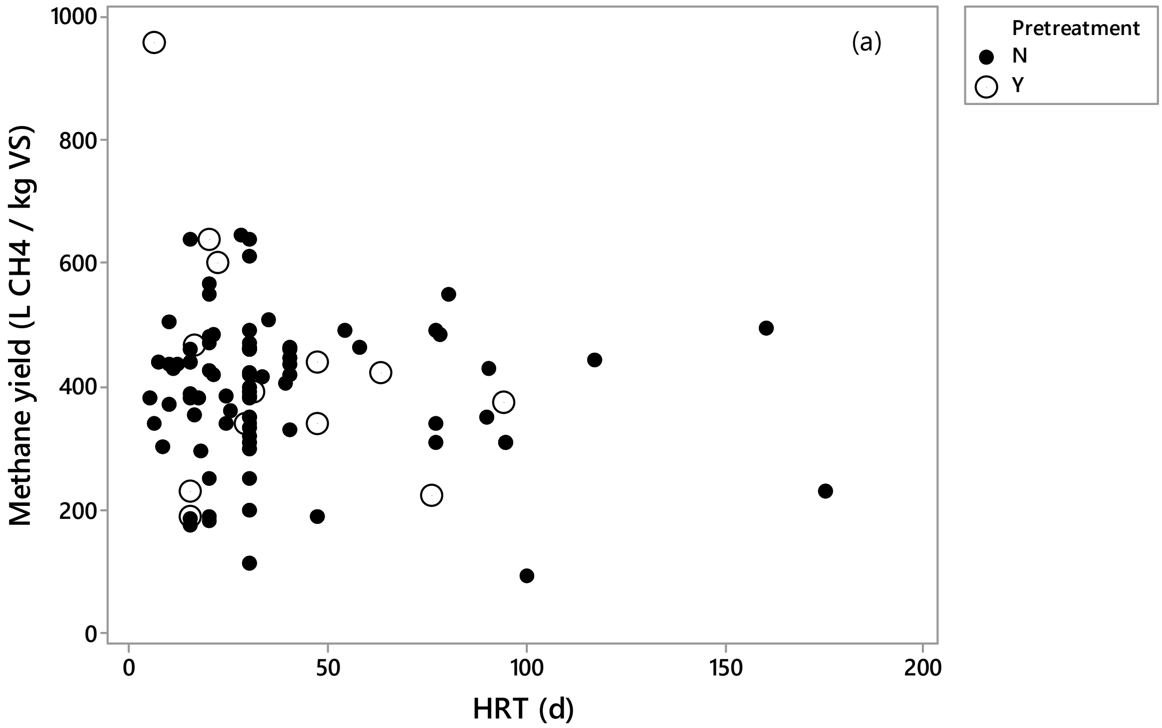


Figure 2. Effect of 6 categorical variables on methane yields (Moisture: D=Dry, W=Wet; Temperature: M=Mesophilic, T=Thermophilic; Operation mode: BA=Batch, CN=Continuous; Codigestion: M=Mono-digestion, C=Co-digestion; Reactor scale: L=Laboratory, B=Batch, P=Pilot, D=Demonstration; Pretreatment: N: No pretreatment, Y: Some type of pretreatment). Circled symbols within a box are the mean values.

The average methane content in biogas was 60.7% ± 7.5% (v/v). No significant differences were observed in the methane content between batch and continuous mode experiments at either mesophilic or thermophilic temperatures. This value is in accordance with the typical methane content from food waste anaerobic digestion as observed by other authors (Archer et al., 2005; Braber, 1995).

According to Figure 2, methane yields show a variable distribution depending on the process characteristics of the experiments evaluated. On the other hand, Figure 3 shows the correlation between methane yields and HRT (Figure 3a) and OLR (Figure 3b). Data are categorised according to the presence or absence of pretreatment. Since there were no available data for the HRT and OLR for all experiments (no such values existed for the batch experiments), Figure 3 was constructed based on a total sample size of n=104 (for the ORL correlation) and n=103 (for the HRT correlation).



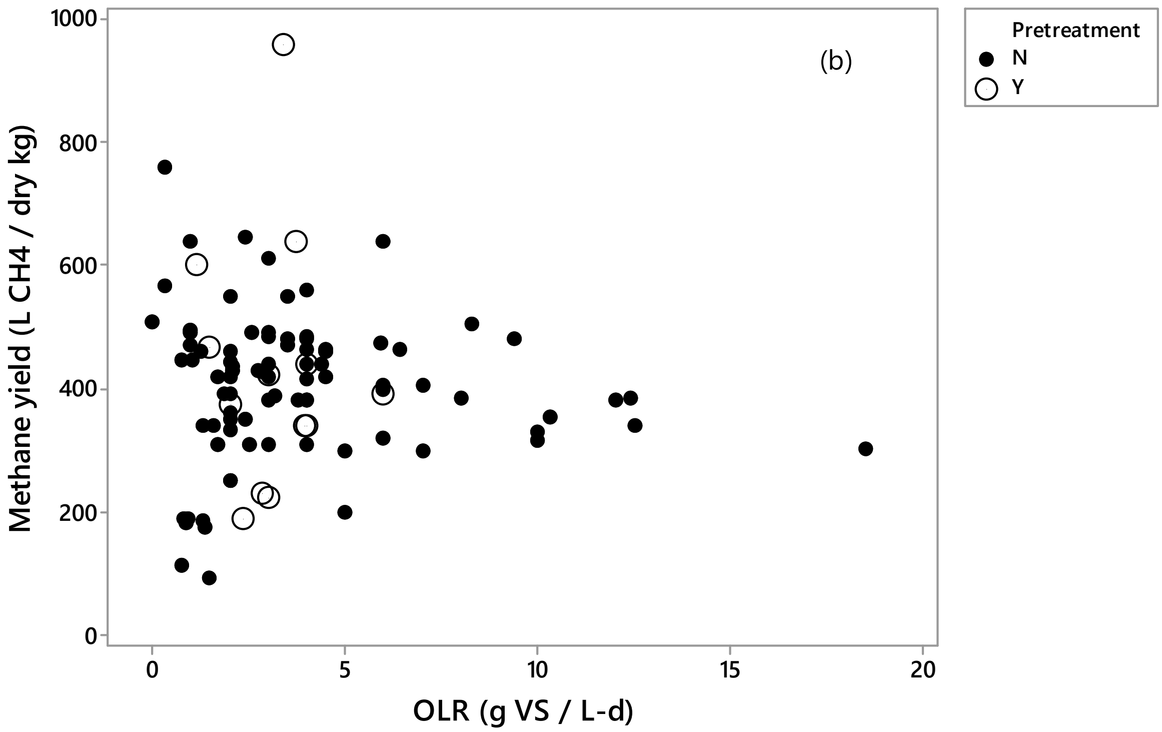


Figure 3. a) Correlation of methane yield with Hydraulic Retention Time (HRT) and b) Organic Loading Rate (OLR); N: absence of any pretreatment; Y: presence of pretreatment.

As revealed in Figure 3a, no correlation exists between methane yield and HRT. In a similar manner to Figure 3a, Figure 3b also indicates that no correlation exists between methane yield and OLR (for the continuous mode experiments). The lack of correlation was proved by the lack of significance of the resulting Pearson linear coefficients between the methane yields and OLR or HRT, and is also confirmed by the regression equation of section 3.3 that follows. Figure 3 shows that the highest HRTs and OLRs had been achieved in the experiments without pretreatment. The statistics in section 3.3 permit a better interpretation of the effect of the various parameters on methane yields and confirm the lack of correlation with HRT and OLR.

3.3 ANOVA and regression modelling results

After fitting a General Linear Model (GLM) with all 8 parameters, the resulting ANOVA revealed that 6 of the parameters were statistically insignificant (had p-values higher than 0.05) and 2 parameters were statistically significant ($p<0.05$). The ANOVA results are included in Table 4. Table 4 indicates that the "operation" and "pretreatment" parameters were the only statistically significant parameters that influence methane yields.

Table 4. ANOVA analysis of the final best reduced model (DF: degrees of freedom; AdjSS: Adjusted sum of squares; AdjMS: Adjusted mean of sum of squares)

Source	**DF**	**AdjSS**	**AdjMS**	**F-Value**	**p-value**
Operation	1	186843	186843	8.62	0.004
Pretreatment	1	87116	87116	4.02	0.046
Error	211	4571731	21667		
Lack-of-Fit	1	30310	30310	1.40	0.238
Pure Error	210	4541422	21626		
Total	213	4810646			

As revealed in Table 4, the "pretreatment" parameter is marginally affecting methane yields, since it obtains a p-value only slightly lower than 0.05. It was therefore decided to maintain this parameter in the model. The "operation" parameter is clearly the one that affects methane yields (with $p < 0.005$) the most. The Tukey's pairwise comparison test revealed the following grouping of the experiments.

Table 5. Grouping of parameters according to the Tukey's pairwise comparison test.

	N	Mean methane yield (L CH_4/kg VS)	Grouping
Operation			
Continuous	111	421	A
Batch	103	362	B
Pretreatment			
Yes	40	418	A
No	174	365	B

Means that do not share the same letter are significantly different. The pairwise comparison was made within each group solely (i.e. continuous vs batch, presence of pretreatment vs absence of pretreatment).

The different letters in the groups of Table 5 reveal that a) different operation modes result in statistically different methane yields, and b) the presence of pretreatment statistically affects methane yields. The mean values for the experimental studies of the different groups are included in the table. For example, the mean methane yield from all studies that involved experiments performed under continuous mode was 421 L CH_4/kg VS, which was statistically higher than the mean value of the batch mode experiments, namely 362 L CH_4/kg VS. In a similar manner, all pretreated substrates resulted in an average methane yield equal to 418 L CH_4/kg VS, which was statistically higher than that of untreated substrates.

A multiple regression model (equation 2) was finally fitted to the data following the structure of equation (1). The regression model included only the two aforementioned statistically significant parameters. The regression model aids to better understand how these two parameters affect methane yields. Using those two parameters, the final best reduced regression model becomes:

$$Methane\ yield\ \left(\frac{L}{kg\ VS}\right) = 391.5\ (12.9) - 30.0\ (10.2) \times\ OperationModeBA + +30\ (10.2) \times\ OperationModeCN - 26.2\ (13.1) \times\ PretreatmentN + 26.2\ (13.1) \times PretreatmentY \qquad \text{(equation 2)}$$

where the definition of the parameters is given in equation (1). Values in parentheses are the standard errors of the corresponding coefficients. All terms are statistically significant at $p<0.05$.

To our knowledge this is the first time that a simple and statistically validated equation is presented to predict methane yields from FW through anaerobic digestion. Specifically, the above equation reveals the following:

i. The operation mode affects methane yield slightly more than pretreatment, since the operation mode coefficient (30.0) is higher than the coefficient of the pretreatment parameter (26.2).
ii. The continuous operation system results in statistically higher methane yields compared to batch systems;
iii. The pretreated food wastes produce statistically higher methane amounts than the untreated ones, since the coefficient of the pretreatment parameter (PretreatmentY) is positive.
iv. Moisture mode, temperature, reactor scale and digestion mode (mono or co-) do not significantly affect methane yields and, thus, do not appear in the regression equation.
v. An average methane yield derived from food waste studied in batch mode reactors without any pretreatment is 335 L CH_4/kg VS.
vi. Parameters such HRT or OLR, that one would expect that they would normally influence methane yields in continuous systems, do not have a statistically significant effect, based on the set of data used in this study.

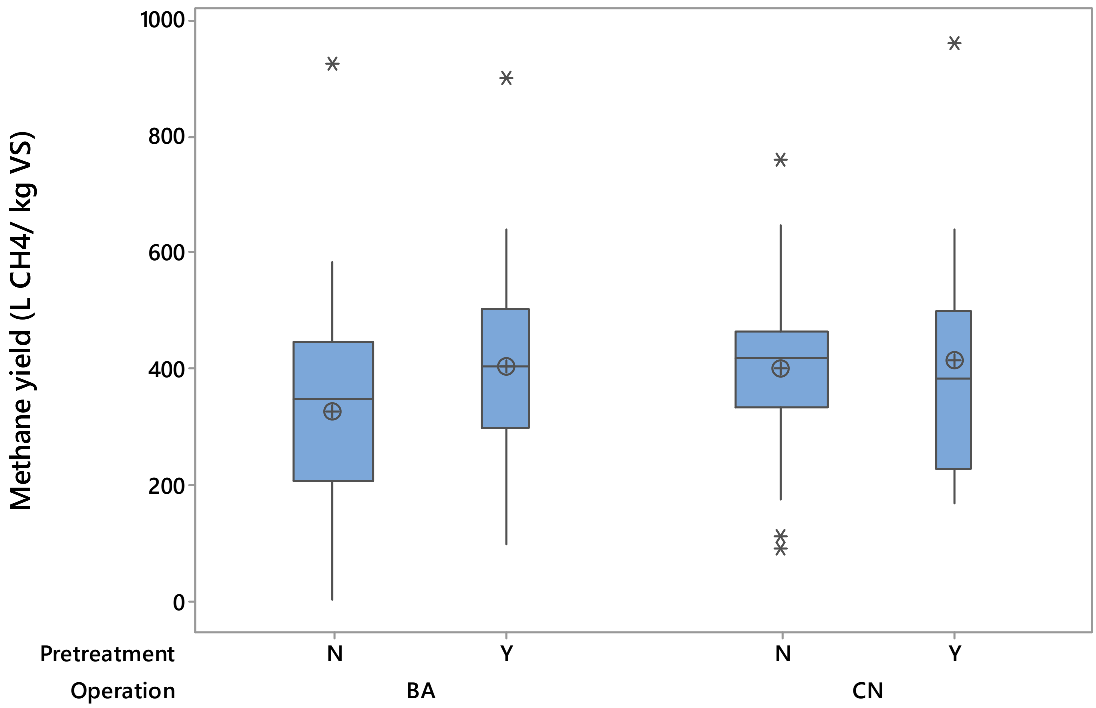


Figure 4. Effect of pretreatment and operation mode on methane yields. Dots show mean values whilst horizontal lines within the box are the medians (boxes are proportional to sample size). BA: Batch, CN: Continuous, Pretreatment: N (no pretreatment), Y (with some type of pretreatment).

Figure 4 is a graphical illustration of the statistical analysis and shows only the significant parameters. Figure 4 confirms that findings of equation 2, which are in agreement with several research results that demonstrate that pretreatment (e.g. chemical, thermal, microwave) can enhance methane generation during anaerobiosis. In lignocellulosic substrates, pretreatment usually achieves the breakdown of lignin and hemi-cellulose that commonly sheath cellulose, making the latter more readily available to microbial attack (Montgomery and Bochmann, 2014).

The lack of significant effect of the other parameters (moisture content, temperature, presence of co-substrates, OLR, HRT) onto methane generation might not have been expected. However, we need to emphasize that the results presented here are not based on a controlled experiment with the same setup and with a particular experimental design. They are based on the collection of information from several variable experiments performed around that world. Even if some experiments were grouped under the same category, a variability among them would be expected (i.e. there are different types of pretreatment, moisture contents may vary even within the wet or dry modes, different co-substrates used in the process). As a result, the mean values per group had a large variance, which would inevitably lead to statistically similar means and the calculation of lack of influence for those parameters onto methane yields. Apparently, this was not true for pretreatment and the operation mode, which most strongly influenced methane yields, being the most important operating parameters during anaerobic digestion of FW.

Another potential explanation for the lack of correlation between yields and OLR and HRT is due to an upper limit that exists for this yield, regardless of high HRTs or high OLRs. Thus, these correlations can be found in specific individual studies, but apparently are more difficult to calculate when comparing a large number of experiments performed under different conditions, different FW compositions and experimental setups.

In consequence, when analysing a large number of independent papers, it is not obvious to find correlation between the typical parameters of the anaerobic digestion process, especially when a large number of technologies are considered and a highly heterogeneous material (FW) is being used. In this sense, it is important to highlight that FW can present important differences as the composition can be different from country to country (Capson-Tojo et al., 2016).

3.4 Effect of food origin parameters on methane yields

An attempt was made to investigate the potential influence of FW origin on methane yields. As earlier mentioned, on all papers used in this work, the term food or kitchen waste was used, without any precise information in the composition by weight of the individual components (except in some cases that a reference to the major components of food wastes was done). However, there is a reasonable likelihood that food waste generated in some countries or continents is different than others due to cultural differentiations (e.g. a larger amount of rice might be contained in FW from Asian countries compared to that in Europe or North America). To further investigate the potential effect of FW composition on methane yields, we grouped the countries to 4 continents, namely Asia, Europe, America and Africa. The number of experiments performed in each continent was: Asia (123), Europe (86), America (19) and Africa (3). The larger amount of research work was conducted in Asian countries, closely followed by European countries. In America, 18 experiments were conducted in the USA and Canada and only one in Brazil during years 2013-2015. An ANOVA performed on the methane yields per continent showed that only the mean of the methane yields from Africa was statistically different than the other 3 means (Figure 5).

Although it can be inferred that FW composition affects methane yields, Figure 5 indicates that there are no differences among methane yields from different continents, except in the case of Africa. However, the sample size from Africa was relatively low (n=3) to render the statistical difference of this continent explainable. Therefore, Figure 5 reveals that the potential food waste composition differences assumed to exist earlier among the 4 continents do not seem to affect the corresponding methane yields.

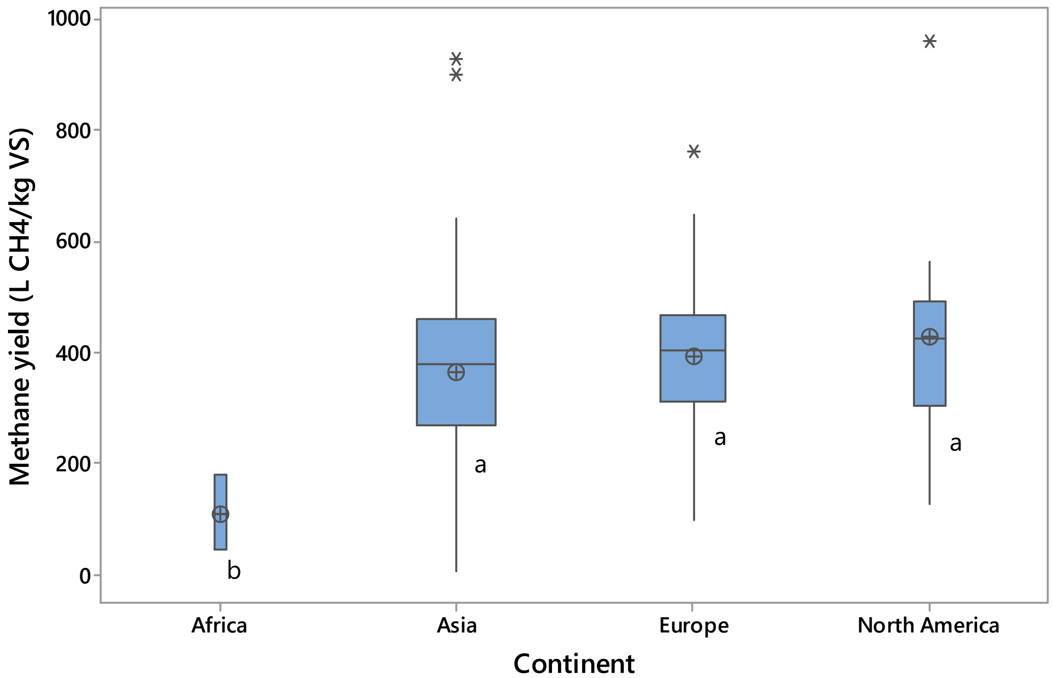


Figure 5. Methane yields distribution depending on the origin of food wastes (different letters indicate statistically different means at $p<0.05$). Box size is proportional to sample size (n).

Figure 6 further attempts to evaluate the effect of FW origin on methane yields and their dependence on HRT and OLR (for the continuous mode experiments only). It is clearly shown that there is no effect of the HRT or OLR on the methane yields, even within continents.

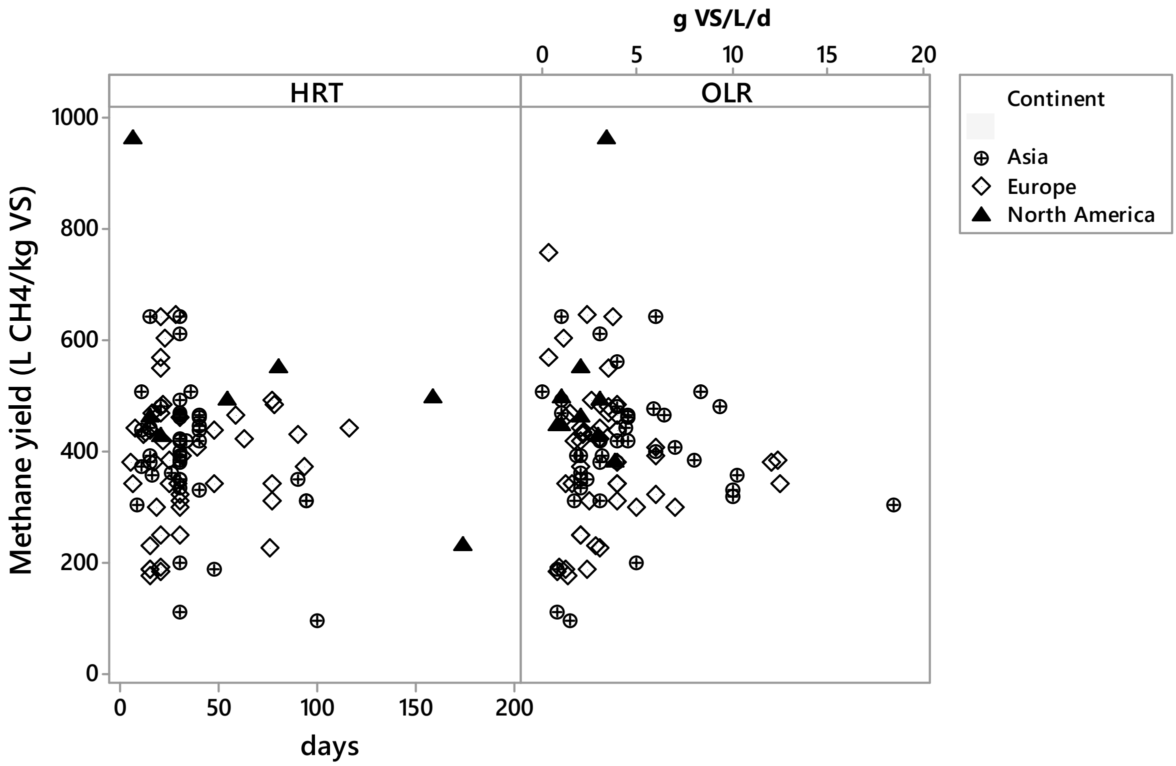


Figure 6. Methane yields per Hydraulic Retention Time (HRT in d) and Organic Loading Rate (OLR in g VS/L d), for the continuous mode experiments only. There were no continuous experiments recorded from Africa.

This finding was also supported by a multiple regression analysis performed per continent, during which neither the OLR nor the HRT proved to be statistically significant coefficients in the resulting linear models, as was true for the whole data (see section 3.3). An explanation for this lack of correlation was provided in section 3.3.

4. Conclusions

After the evaluation and statistical analysis of data from 231 experiments obtained from 167 articles that dealt with the anaerobic digestion of FW, the conclusions of this work are:

- The methane yields were statistically significantly affected by the operation mode (batch, continuous) and the pretreatment. Specifically, the continuous mode and the pretreated food waste would result in significantly higher methane yields than the batch operation modes with raw (untreated) food waste, respectively.

- Several parameters that were expected to affect methane yield (i.e. temperature, co-digestion, moisture content, experimental scale, HRT, OLR) did not statistically significantly affect it. This might be explained by the large variability of the mean values within each grouped category.
- The average methane yields from the FW of the different continents were statistically similar which can be also explained by the large variability of the mean values of the experiments from different researchers.

Further research can focus on the influence of parameters on the methane yields of other extensively used substrates, such as sewage sludge or animal manures.

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