Biochemical methane potential applied to solid wastes - review

T. M. Cabrita[1], M. T. Santos[1], A. M. Barreiros[1]

[1]ADEQ, Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, R. Conselheiro Emídio Navarro 1, 1959-007 Lisboa, Portugal

Presenting author email: tsantos@deq.isel.ipl.pt; Phone: +351 831 71 78

Abstract

Anaerobic digestion of solid organic waste has increase all over the world. In order to evaluate the biodegradability of different source wastes, Biochemical Methane Potential (BMP) test has been widely used. However, BMP test has several important factors, e.g. substrate, inoculum, experimental and operational conditions that influence the results. Notwithstanding the higher number of studies concerning the BMP from different solid wastes the methodologies used, results presentation and discussion with different units makes it difficult to compare values. In the present work an extend literature review was made concerning the BMP tests methodologies most applied and the conditional factors. Also, the organic solid substrates were analysed in terms of solid contents. Despite the significant effort done in the last 10 years the BMP methodologies applied to organic solid substrate vary significantly. This fact is reflected in the biogas production from the substrates anaerobic digested and in consequence, the results diverge.

Keywords: anaerobic digestion, Biochemical Methane Potential (BMP), solid wastes and review

1. Introduction

Anaerobic digestion (AD) is a widely applied technology to treat solid wastes and produce biogas. This process has been around for centuries but in the last decades, not only it has been seen as an answer to treat several types of organic waste but also as a source for biogas which is a contributor to achieve the targets of renewable energies [1]. The AD permits also the reduction of greenhouse gas emissions. In Europe, exist around of 120 full-scale plants to anaerobic digestion municipal solid wastes [2].

In Portugal the energy from biogas come from landfills, wastewater treatment plants and solid waste treatment plants representing only 1% of the total renewable energy sources. Biogas from Landfills represents 96% of total national production of renewable energy [3].

In order to increase the biogas production it is necessary to analyse wastes from several sources. Usually the analysis of the potential wastes for AD implies the determination of anaerobic biodegradability. The Biochemical methane potential (BMP) test is the most widely used technique to gauge the biodegradability of different substrates or mixture of substrates [4, 5] and is a valuable method to choose potential substrates to anaerobic digestion.

According to Angelidaki et al. [1] the papers referring BMP tests passed from 7 in 1991 to 70 in 2007. An extensive literature dealing with the BMP from to 2008 to 2015 demonstrated a growth from 100 to almost 500 publications showing the increasing interest in this field in the last few years. The BMP tests produce the ultimate amount of methane originated under anaerobic conditions of the substrates analysed. The ultimate methane potential is a key parameter to design and operate full-scale anaerobic digesters [1, 6].

Although the huge data generated from the literature the biodegradability comparison from different solid wastes is very problematic due to several factors such as different environmental conditions, methodologies applied and measuring equipment. Also, the results from BMP are presented in variable units [1].

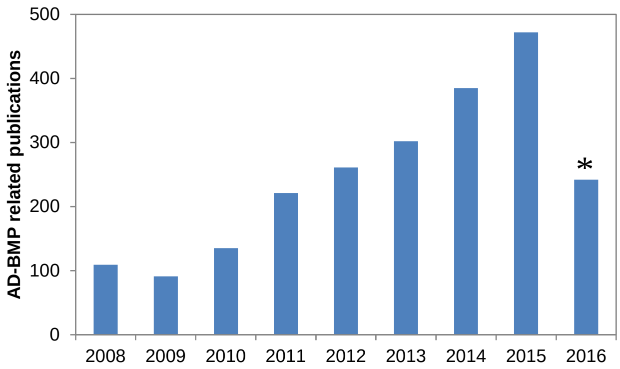
The main issue of the present review is to present and evaluate the BMP factors, methodologies, solid organic substrates and results.

2. BMP publications

The interest in BMP tests did not start now, even if more studies on subject are been published now more than ever. One of the first studies to determine the biodegradability of organics substrates was realized by Owen et al. [7], which laid the groundwork and blueprint for future studies.

According to Raposo et al. [6] the BMP tests has increased in the last years as reflected by the wide range of research papers.

The interest in BMP tests is also showed by the number of publications, which has visibly risen over the years, in particular after 2010 as seen in Fig. 1. This inquiry was made with the research engine from Online Knowledge Library (B-on) with peer-reviewed publications. In 2015, the BMP publications were near of 500. This number is expected to be greater in 2016 due to results for the first four months.



*Results up until the end of April 2016

Fig 1 – Number of publications with the keywords “anaerobic digestion” and “BMP”

3. BMP methods

Over the years several authors have contributed to the subject and changed the methods for the BMP tests in accordance with the knowledge of the time [1, 8].

Several studies were dedicated to the BMP methodology. Owen et al. [7] presents the most popular method for BMP in the last three decades. This methodology combined the Warburg respirometer with the serum bottles in order to overcome some limitations. The methodology consists in incubation (during 30 days) of inoculum, defined medium with nutrients, vitamins and substrate samples added to 250 mL serum bottles. The inoculum was used in a proportion of 20% by volume to defined media. The anaerobic conditions were initiated by flushing the bottles with the media at 0.5 L/min with a mixture of CO_2 and N_2 (30:70 volume ratio). The gas measurement was done with a sample collected with volumetric syringe and analysed by gas chromatography (GC).

Several authors used the Owen et al. [7] with some modifications concerning the reproducibility of BMP tests. For example, Chynoweth et al. [9] analysed the influence of three factors on BMP tests, inoculum source, inoculum/substrate ratio (I/S) and particle size. The results revealed that inoculum source could be from an active domestic sludge digester. The I/S ratio of 2 or greater and the particle size greater than the millimetre range should be used.

Owens & Chynoweth [10] modified the Owen et al. [7] methodology. The sample concentration was 2 g VS/L, the medium was prepared with different mineral concentrations and the inoculum was adapted with a fed of 1.6 g VS/L. The serum bottles had 275 mL with 100 mL of inoculum.

A study realized by Angelidaki and Ahring [11] referred the need to acclimate the inoculum to specific conditions like the ammonia concentrations.

Angelidaki and Ahring [12] used serum bottles of 117 mL, flushed with N_2:CO_2 (80:20) and added 20 mL of an adapted inoculum. This method was adapted and modified by Hansen et al. [8]. In this study, bottles of 2 L were used with 400 mL de inoculum and 100 mL of sample.

Although the several studies published concerning BMP Angelidaki and Sanders [13] referred a substantial uncertainty in the BMP determination because anaerobic biodegradation is a complex process with several groups of microorganisms. This study also suggested to present the results from BMP tests with different units in accordance to the substrate stat or characterization, e.g. L CH_4/kg-waste, L CH_4/L-waste, L CH_4/kg-VS added or L CH_4/ kg-COD added. The methane production was corrected for standard conditions of pressure (1 atm) and temperature (0 ºC) (STP).

Some guidelines and advices concerning the several factors affecting the BMP tests, in order to gain comparable results especially for solid organic substrates, were proposed by Angelidaki et al. [1]. This study referred substrate, inoculum source, inoculum activity, medium blank and controls, replicates, mixing, data collection, bottles volume (0.1 to 2 L), interpretation and reporting conditions.

Some other methods to estimate biodegradability have been used like technical guideline VDI 4630 [14] and ISO guideline 11734 [15].

Even today, several studies continue to apply the Owen et al. [9] methodology modified essentially in volume reactor, Inoculum source and concentration [16]. Also the Angelidaki and Sanders [13] methodology continue to be used [17].

4. Factors affecting BMP tests

BMP is influenced by several factors including, temperature, mixing rate, ratio between different substrates, C/N ratio of the substrates, inoculum and substrate ratio (I/S), substrate pretreatment utilized, headspace pressure, particle size of substrate [1], substrate source, methane production, reactor volume, pH, inoculum source, measurement of biogas and tests duration [6, 16-21].

Before starting the BMP tests, it is essential to characterize the substrate and the inoculum. The substrate can be characterised with t following parameters: TS, VS, component composition (e.g. fats, proteins, carbohydrates and lignin), elemental composition (C, O, H, N and S) and COD. For BMP tests it is also important the initial concentration or the reactor load. A small load produce very low biogas quantities, therefore the metabolic activity of microorganisms is low. If the load is too high more volatile fatty acids form which can cause anaerobic digestion inhibition.

Normally in anaerobic digestion of particulate substrates, the hydrolysis step is the rate-limiting step. Therefore, the surface area and particle size are two important parameters. Although the relationship between these parameters is not fully investigated, Raposo et al. [6] suggested a particle size $\leq$ 10 mm.

The inoculum greatly influences the BMP test. Usually it depends of several factors: source, concentration, activity, pre-incubation, acclimation and storage. The inoculum characterization is made by VS or VSS. Although the inoculum source is not uniform, it can be used digested sludge from municipal wastewater, soil extracts, industrial treatment plants, rumen and animal manure. In general, sludge from WWTP is a valid source in terms of activity and diversity of microorganisms. In terms of inoculum concentrations it should be sufficient for a sort lag phase and BMP test. From literature, several different concentrations were reported. Inoculum concentrations of 2.1 g VS/L was presented by El-Mashad and Zhang [22] and Rincón et al. [23] presents a different value of VS = 21 g/L. The VDI 4630 [14] indicates a range of 15 to 20 gVS/L. Angelidaki et al. [1] suggested to use a fresh sludge if possible.

The experimental conditions for BMP tests are presented in Fig 2 [6, 18]. As it can be observed there are several methods to measure the biogas produced during the incubation time of BMP tests. These methods have different accuracy and precision. The operational conditions are divided in physical, chemical and I/S ratio. The chemical conditions involve the mineral medium with several nutrients and vitamins for anaerobic microorganisms. Nevertheless, some studies do not use this medium [24-26], because in industrial scale with anaerobic treatment of organic solids wastes it is difficult the same application due to the costs involved.

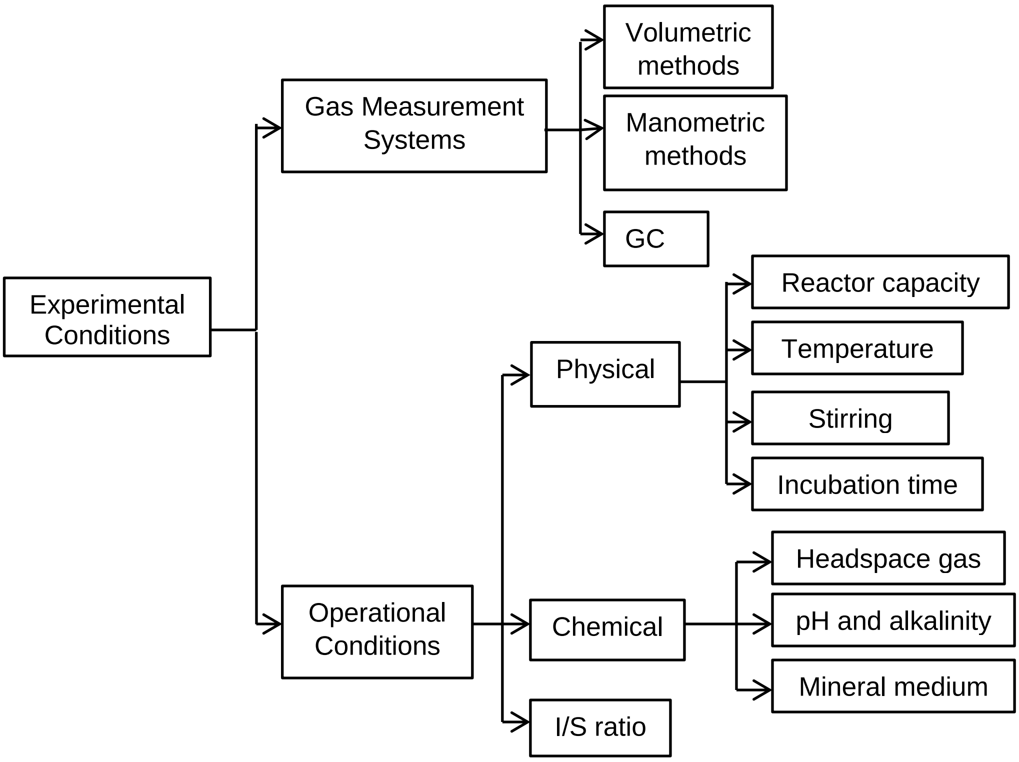


Fig 2 - Scheme of the experimental conditions for BMP tests adapted from [6, 18]

5. BMP applied to solid substrates

The BMP tests have been widely used for more than three decades to estimate methane yield and biodegradability of different solid wastes [7, 17, 20, 24, 27- 30].

Solid organic substrates can be obtained from a variety of sources. In 1997 Gunaseelan [27] presented a review with some substrates sources submitted to BMP, such as food packing, paper, OFMSW from hand and mechanically sorted and yard wastes. This work referred also a significant number of other substrates submitted to anaerobic digestion. The substrates with high yields of methane were OFMSW, fruits and vegetables, grass, woody biomass terrestrial weed and marine and freshwater biomass.

BMP tests have been applied to various types of wastes by several authors [7, 10, 29, 31- 38].

An extensive literature review was made in order to present the organic solid substrates analysed by BMP since 2011 to 2016 (Table 1). According to the results presented in Table 1 around 70 different substrates were submitted to BMP tests. The results of solids contents were expressed in different units such as g/L, g/kg, %, mg/L and some expressed the values in wet bases, which makes difficult to compare the substrates. For example, the total solids (TS) contents of the substrates represented in percentage vary significantly from 0.7 to 100% of TS. In the g/kg units the TS is in the range of 47.3 to 991 g/kg and in the g/L varies from 3.97 to 331.33 g/L. Concerning the volatile solids (VS) contents the values are presented in different bases, e.g. related with TS, dry mass and wet weight.

Table 1 - Type and solids contents of substrates analysed by BMP

Substrate	**TS**	**VS**	**Reference**
Aerobic granular sludge	29.6-106.1 g/L	27.3-60.1 g/L	[39]
Agro-food industry organic waste	72.1-209 g/kg	51.5-200.3 g/kg	[40]
Bambo waste	93.3–94.5 %	77.3–90.0 %	[41]
Banana waste	9.70-17.90 % (fresh mass)	83.35-92.98 % (dry mass)	[42]
Biological sludge from WWTP	71.2 g/kg	54.9 g/kg	[43]
Blue algae	4.13 ± 0.18 %	86.68 ± 1.47 % TS	[44]
Bread waste	67.4 %	65.5 %	[45]
Brewery grain waste	24.2 %	23.0 %	[45]
Cattle manure	3.8-9.3 %	2.8-7.4 % (of wet weight)	[46]
Chicken feather waste	100 ± 0.5 %	99 ± 1.4 %	[47]
Cocoa shell	89.9 ± 1.1 %	82.3 ± 1.2 %	[19]
Commercial food waste	7.7-92.7 %TS/FM	90.6-100 %VS/TS	[48]
Cow manure	3.97 ± 0.09 g/L	1.73 ± 0.09 g/L	[49]
Cow manure from slaughterhouse	221.6 g/kg	208.5 g/kg	[43]
Cow slurry	78 g/kg	782 g/kg TS	[50]
Dairy manure	13.6 ± 0.4 %	11.9 ± 0.4 %	[19]
Dairy manure	10.2 %TS/FM	83.6 %VS/TS	[48]
Dairy manure	124.0 g/kg	102.1 g/kg	[24]
Excess sludge (Dewatered sludge)	97,900±525 mg/L	37,200±250 mg/L	[51]
Fish waste	31.4-38.5 %	27.63-36.19 %	[45]
Food residues	71.4-991.0 g/kg	59.8-988.8 g/kg	[24]
Food waste	24.1 wt.%	88.2% dry weight (dw)	[52]
Food waste	20.05 %	19.21 %	[5]
Food waste	29.4 %	95.3 % DS	[53]
Food waste	48,400 ± 2,700 mg/L	27,900 ± 1,300 mg/L	[54]
Fruit and vegetable waste	23.83±0.13 %	91.67±0.12 % of TS	[55]
Grain mill residues	874-912 g/kg	896-940 g/kg TS	[50]
Grass silage	292.7 ± 3.4 g/kg	268.4 ± 2.8 g/kg	[56]
Grease waste from a DAF tank from WWTP	505.2 g/kg	468.2 g/kg	[43]
High solid waste	16.7 ± 0.5 %, w/w	70.5 ± 0.1 VS/TS	[57]
Invasive aquatic plants	51.8-148.8 g/kg	37.7-74.2 g/kg	[24]
Livestock residues on-farm	42-45 wt%, wet basis	31-35 wt%, wet basis	[58]
Low-organic waste of landfills	18-90 %, kg/kg waste, ww	7-70 %, kg/kg waste, ww	[59]
Meat-processing wastes	65-88 %	65-86 %	[60]
Municipal solid waste	351.4 g/kg	246.0 g/kg	[43]
Municipal solid waste	0.97 (0.02) % Raw matter	0.74 (0.09) % Raw matter	[61]
OFMSW	109.9 g/kg	105.1 g/kg	[43]
Olive oil waste (olive pomace)	331.33 ± 6.81 g/L	305.60 ± 6.18 g/L	[21]
Organic fraction of municipal solid waste	23.3 ± 0.34 %	20.2 ± 0.26 %	[20]
Organic fraction of municipal solid waste	461 g/kg	386 g/kg	[62]

Substrate	**TS**	**VS**	**Reference**
Paragrass	29.37 ± 0.27 % (wet weight)	25.80 ± 0.22 % (wet weight)	[63]
Pharmaceutical sludge	3.1 %	94.7 %	[64]
Pig slurry	69.9 g/kg	794 g/kg TS	[50]
Poultry litter	77 ± 1.3 %	70 ± 1.5 %	[47]
Primary sludge from a municipal WWTP	26,300 ± 260 mg/L	20,000 ± 250 mg/L	[54]
Pulp and paper industry WWTP biosludge	1.1-1.5 %	0.7-1.0 %	[65]
Raw straw (mainly straw of maize, sorgos and wheat)	na	na	[5]
Refinery waste sludge	0.4-16.9 %	74-85 %	[66]
Rice straw	92.59 %	70.37 %	[26]
Rice straw	92.6 ± 0.31 %	70.4 ± 0.22 %	[20]
Secondary sewage sludge from WWTP	19.05 ± 1.21 g/L	13.99 ± 1.05 g/L	[67]
Separated dairy manure	41.1 ± 0.06 g/L	32.4 ± 0.1 g/L	[68]
Slurry from dairy farm	87.5 ± 2.1 g/kg	66.9 ± 1.8 g/kg	[56]
Slurry from the pretreatment of SSOFMSW	9.0-19.5 %	84.6-92.3 %	[25]
Solid fish waste	25-37 %	0.737-0.851 g VS/g dry waste	[69]
Solid fraction of dairy manure	25.8 ± 0.3 %	23.3 ± 0.4 %	[70]
Solid fraction of pig manure	166.4 ± 0.2 g/kg	138.6 ± 0.2 g/kg	[71]
Solid slaughterhouse wastes	27.9-65.2 %	95.2-98.6 %	[30]
Solid waste produced in RAS	11.65 ± 1.15 g TS/ L	7.57 ± 0.87 g TVS/ L	[72]
Source-separated organic household waste	28-52 %	76-94 % TS	[73]
Source-separated organic household waste	24-86 % ww	81-94 % TS	[74]
Spent grain from brewery industry	243.6 g/kg	233.4 g/kg	[43]
Sunflower soil cake	93.0 (±0.1)%	93.0 (±0.1)% (dry basis)	[75]
Swine manure	23.58 ± 1.06 %	89.86 ± 2.15 % TS	[44]
Thickened sludge	30,300 ± 215.6 mg/L	20,050 ± 145.0 mg/L	[17]
Thickened waste activated sludge	14.18 %	6.72 %	[26]
Thickened waste activated sludge	14.2 ± 0.16 %	6.7 ± 0.09 %	[20]
Two-phase olive mill solid waste	265.0 ± 2.6 g/kg	228.4 ± 2.3 g/kg	[23]
Two-phase olive mill solid waste	265±3 g/kg	228±2 g/kg	[76]
Unseparated dairy manure	73.6 ± 2.0 g/L	64.8 ± 1.9 g/L	[68]
Waste activated sludge	47.3 ± 0.4 g/kg	40.5 ± 0.1 g/kg	[77]
waste coffee grounds	40.6 ± 0.3 %	40.0 ± 0.3 %	[19]
Wastes from a pig slaughterhouse	180.0-297.5 g/kg	170.2-256.4 g/kg	[78]
Wastes of an ice-cream processing plant	9.10 ± 0.36 g/L	9.27 ± 0.53 g/L	[49]
Wastes of manufacturing Chicken fat for marinades	289 ± 5 g/L	275 ± 4 g/L	[49]
Wastes of manufacturing Cranberry sauce	224 ± 6 g/L	225 ± 6 g/L	[49]

Substrate	TS	VS	Reference
Wastes of Meatball fat from frozen food processing	144 ± 24 g/L	135 ± 23 g/L	[49]
Water hyacinth	8.24±0.36 %	76.54± 0.30 % of TS	[55]
Wheat straw	na	0.93±0.003 gOM/gDM	[16]
Wheat straw	895-924 g/kg	821-846 g/kg	[79]
Wheat straw	922 ± 2 g TS/kg	92 % VS/TS	[80]
Wheat straw	94.0 %	86.8 % (of wet weight)	[45]

na: not available

6. BMP conditions and results

The evolution of BMP experimental conditions of organic solid substrates, since 2011 to 2016: inoculum and substrate sources, reactor volume, headspace, I/S ratio, temperature, incubation time and measurement of biogas are presented in Table 2. The results of BMP tests, expressed in biogas production, are presented in the last column of Table 2.

The organic solid substrates were submitted to several pretreatments, with the most used being thermal at different temperatures and chemical with base (NaOH).

The inoculum source most used is sludge from wastewater treatment plant (WWTP). The reactor volume varies from 60 [66] to 3,000 mL (effective volume) [51] with different working volumes even for similar reactor volume. The temperature incubation for BMP usually is mesophilic range. Related to I/S ratio an enormous range is presented, nevertheless the I/S of 2 is the most used. Concerning the incubation time the range varies from 7 [75] to 216 days [68]. According to Raposo et al. [6] a higher range from 7 to 365 days were used.

The biogas production measurement consist in three main methods for volume determination: pressure transducer and volume displacement and syringe. Methane contents typically are determined by GC. Usually the methane results are presented in standard conditions for pressure and temperature (1 atm and 0 ºC). In the literature review, it was found a study with a different temperature of 20ºC [72].

The results of BMP tests of solid organic substrates found in literature were also very discrepant and difficult to compare, mainly because of different units used and the experimental conditions applied. Similar conclusions were related by Angelidaki et al. [1] and Raposo et al. [6].

Table 2 - BMP experimental conditions of organic solid substrates and results

Author	Substrate source	Inoculum source	Pretreatment	Reactor (mL)	Headspace (mL)	I/S	T (°C)	Incubation time (d)	Measurement of biogas	Biogas Production
[24]	Raw manures; Food residues; Invasive aquatic plants; Others (switchgrass, corn silage, corn leachate, mouthwash, suspended FOG and settled FOG)	Farm-based completely mixed ADig	na	250	na	na	35	40	Pressure transducers	106.5-648.5 mL CH_4/g VS_{added}
[50]	AS, FIW and CIR	Anaerobic reactor of a WWTP	na	575	375*	150 mL/0.3 g TS	36	48-72	Pressure transducer and GC	AS: 238-319 L CH_4./kgVS_{added}; FIW: 335-714 L CH_4./kgVS_{added}; CIW: 272-384 L CH_4./kgVS_{added}
[61]	MSW, “raw” wastes (papers, vegetables and a waste built by mixing some of the simple wastes) and lignocellulosic green wastes	Active anaerobic sludge	na	600	na	0.5	35	35	Every 2 days with Micro-GC	MSW: 87-355 mL CH_4./g VS; Raw samples: 20-400 mL CH_4./g VS
[81]	Thickened sludge samples were collected from different WWTPs	Digested sludge from the fullscale digester-WWTP	na	1,000	na	100 g/500 g	MC	21	Displacement of the liquid in the cylinders. GC-TCD	25-456.3 mL CH_4/g ODM
[39]	Aerobic GS		Thermal (60-210 °C)	570	170*	1 g VS/VS	35	26	Pressure transducer and GC	169-404 mL-CH_4/g-VS_{fed}
[40]	Wastes from agro-food industries (dairy, cider production, cattle farming)	Anaerobic sludge from a municipal WWTP	na	2,000	1,400*	0.67, 1, 1.33, 2 and 4.00 VS	35	55	Manually by a pressure transmitter and GC-TCD	202-549 mL STP CH_4·/gVS waste

Author	Substrate source	Inoculum source	Pretreatment	Reactor (mL)	Headspace (mL)	I/S	T (°C)	Incubation time (d)	Measurement of biogas	Biogas Production
[54]	OFMSW and primary sludge of WWPT	1 - primary MC ADig at a WWTP; 2 - MC ADig treating SSO , 3 - MC ADig treating primary and secondary wastewater	na	260*	60	0.25, 0.5, 1, 2 and 4 mass VSS/mass COD	37	App. 28	At the end of the test using appropriately sized glass syringes in the 5–100 mL range. GC-TCD	primary sludge: 221-283 mL CH_4/g VSSsub; FW: 440-1400 mL CH_4/g VSSsub
[82]	Herbaceous plants that do not have a persistent woody stem and nonherbaceous material such as hedge and tree trimmings	Biogas plant 37ºC fed with 80% animal slurry and about 20% organic industrial waste	na	1,000 (EV)	na	3:1 TS	37	App. 60	VDI and GC-TCD	104-388.9 CH_4 N L /kg VS
[75]	Sunflower oil cake sample from a sunflower oil factory	GS taken from an industrial ADig 35 ^{0}C	Chemical and TC (75 ^{0}C)	250 (EV)	na	2 VS/2.5 COD	35	Between 7 and 10	Volume displacement (gas flushed through a 2 N NaOH solution)	0-273 mL CH_4 /gCOD$_{added}$
[47]	Chicken feather waste and poultry litter from poultry industry	Anaerobic suspend sludge - municipal ADig. Anaerobic GS - brewery industry	TC (20-90 ^{0}C)	50 (EV)	na	0.66, 0.71, 0.76 and 1.32 g VS/ g VS	37 and 65 (BA)	80	GC-FID	45-123 L CH_4 /kg VS$_{added}$
[69]	Solid fish waste - tuna, sardine, mackerel and needle fish	Suspended sludge - urban WWTP. GS - brewery industry	na	na	na	0.15–0.18, 0.30–0.36 and 0.77–0.91 g VS/g VS; 0.4, 0.77 and 1.25 g VS/g VS; 0,71 and 0.83 g VS/g VS	37	60-80	Pressure transducer. GC-FID	0.04-0.35 L CH_4/g VS$_{added}$; Co-digestion (tuna:gorse): 0.16-0.21 L CH_4/g VS$_{added}$

Author	Substrate source	Inoculum source	Pretreatment	Reactor (mL)	Headspace (mL)	I/S	T (°C)	Incubation time (d)	Measurement of biogas	Biogas Production
[17]	Thickened primary and secondary sludge was obtained from a municipal activated sludge facility	Anaerobic GS was obtained from an UASB treating industrial waste	na	250	100*	1/1, 1/3 and 1/8	35	21	The syringe method. GC-TCD	21.93-76.27 mL CH_4/g VS_{added}
[60]	Two wastes from a meat-processing plant: (i) greaves and (ii) rinds	GS from a brewery WWTP	NaOH, NaOH+T, NaOH+AC, T, Enzyme and AC+enzyme (25-121 °C)	160	80	4 g VS g^{-1} $COD_{soluble+colloidal}$ and 1.3–3.3 g VS g^{-1} COD_{total}; untreated: 4 g VS g^{-1} COD_{total}	37	50-110	GC	305-919 LCH_4 STP /kgVS of the original waste
[46]	Dry (non-treated) and steam-exploded wheat straw. CM from a farm	biogas plant at MC with SSMHW and grass silage	na	1,120	420*	2 VS	na	25 and 60	GC	0.15-0.33 N L CH_4/g VS
[51]	Dewatered sludge from a WWTP	digested sludge from MC ADig-WWTP	Mild thermal (50-120 ^{0}C)	3000 (EV)	na	0,0014, 0.0015, 0.0016, 0.0078, 0.013, 0.016 and 0.022 gSS/mg COD	na	30	Water displacement method	67.7-144.7 $mLCH_4$/g VS_{added} (for 20 d and without the untreated)
[56]	Grass silage; Fresh slurry - dairy farm	2 digesters (FW and mix of poultry/CM	na	500	100	2:1	37	30	Water displacement method	239-400 L CH_4 /kg VS

Author	Substrate source	Inoculum source	Pretreatment	Reactor (mL)	Headspace (mL)	I/S	T (°C)	Incubation time (d)	Measurement of biogas	Biogas Production
[44]	Algal biomass - mixture of algae bloom and lake water. Swine manure	Swine manure. GS	na	500	100	0.5, 1.0, 2.0 and 3.0 VS	35	22	Passed through an alkali solution then transported to the gas flow meter. GC-TCD	blue algae/swine manure: 48.2-212.7 mL CH_4 /g VS; blue algae inoculated with GS: 32.8-73.5 mL CH_4 /g VS
[78]	Wastes from a pig slaughterhouse	Inoculum was collected from a farm-scale biogas plant that digests piggery slurry	na	160	100	0.67, 1, 2 and 10 VS	38	76	Periodically by displacement of an acidified brine solution in a burette. GC-TCD	0.357-1.076 N m^3/kg-VS_{added}
[41]	Bamboo waste from a chopstick production factory	Anaerobic sludge collected from a MC ADig feed with dewatered sewage sludge from a local WWTP	Acid, alkaline, enzyme and alkaline aided enzyme	na	na	2	37	30-33	na	25-303.3 mL CH_4/g VS
[43]	Biological sludge thickened - WWTP; OFMSW - synthetic mixture of foods; MSW sorted from WWTP; grease waste from DAF - WWTP; spent grain from brewery industry; CM from slaughterhouse	WWTP mesophilic digested sludge	Thermal hydrolysis (120-170 ^{0}C)	300	na	1:1 VS	35	App. 40	Periodical monitoring analyses of biogas production by pressure meter. GC	184-524 $mLCH_4/gVS_{in}$

Author	Substrate source	Inoculum source	Pretreatment	Reactor (mL)	Headspace (mL)	I/S	T (°C)	Incubation time (d)	Measurement of biogas	Biogas Production
[79]	Pig slurry	Anaerobic inoculum from a pilot sludge digester treating activated sludge	Thermal steam explosion (120-180 ^{0}C)	300	190*	2 gVS/VS	35.1	App. 40	Manually by a pressure transmitter. GC-TCD	159-329 mL CH_4/gVS$_{fed}$
[5]	FW and straw shredded to a small size	Anaerobic GS - UASB reactor treating starch processing waste water at 35 ^{0}C	na	1,000	400*	0.014 g VS /12 g VS	35	8	Water dislocation method and GC-TCD	0.157-0.392 m^3CH_4/kg VS
[72]	Solid waste produced in RAS	Digested CM	na	540	340*	4, 8 and 16 g/g*	35	24	GC	359 ± 29 mL CH_4/gTVS
[63]	Variety of paragrass samples	Mesophilic anaerobic sludge from a domestic WWTP. A portion of the sludge was acclimated to fibrous substrates in raw palm oil mill effluent	na	100	40*	1 g VS/g VS	32-35	80	Periodically with needle syringes and GC-TCD	277 and 316 mL STP/g VS
[57]	Dewatered/high solid sludge from a municipal WWTP	Pre-incubation at 35 ^{0}C in a water bath for 2 d	Thermal hydrolysis (60-90 ^{0}C and 120-180 ^{0}C)	500	na	2/1 VS	37	28	GC-TCD	0.94 -1.07 L biogas/g VS removed

Author	Substrate source	Inoculum source	Pretreatment	Reactor (mL)	Headspace (mL)	I/S	T (°C)	Incubation time (d)	Measurement of biogas	Biogas Production
[67]	Secondary sewage sludge - WWTP	Anaerobically digested sludge – MC ADig fed with mixed sludge from the local WWTP	Thermal hydrolysis and advanced thermal hydrolysis (H_2O_2) (90-170 ^{0}C)	160	60	2	35	28	Periodically with a manual pressure transmitter and GC-TCD	227-327 $mLCH_4/gVS_{fed}$
[25]	Composite slurry samples	Digestate collected from an ADig treating SSOFMSW, manure and industrial waste	na	1,000	700*	2/1 VS	37	35	With gas tight syringe and GC-TCD	445-568 m^3 N CH_4/ton VS introduced
[65]	WWTP that treats pulp and paper industry wastewater	MC digested municipal sewage sludge WWTP and digestate from a CSTR	Thermal (80-134 ^{0}C)	120	60	2 VS/VS	35	35	Water displacement and GC-FID	between 40 and 160 N L CH_4 /kg VS
[68]	unseparated manure and separated manure	MC digester treating the separated CM	na	250	120	1 VS unseparated manure; 2 VS separated manure	14 and 24	216	Every week with a graduated, gas-tight, wet-tipped 50 mL glass syringe. GC-FID	107-479 $mLCH_4$/g VS_{added}
[64]	Pharmaceutical sludge from a pharmaceutical factory	Inoculum sludge - digester from fecal sludge	na	1,000	na	0, 0.65, 2.58 and 10.32 TS	37	App. 55	Water displacement and Biogas Analyser (daily)	6.98-499.46 mL biogas / g TS pharmaceutical sludge
[70]	SF of CM. Raw manure slurry was separated into SF and LF	screened LF of CM digested at 50 ^{0}C	na	500	na	1 VS	35 for manure and LF. 50 for SF.	80	Pressure measurement and GC-TCD	298 (manure), 343 (LF) and 265 (SF) L CH_4 /kgVS

Author	Substrate source	Inoculum source	Pretreatment	Reactor (mL)	Headspace (mL)	I/S	T (°C)	Incubation time (d)	Measurement of biogas	Biogas Production
[21]	Olive pomace	CM	NaOH, Salts, US, US+salts	250	na	na	30	App. 60	Water dislocation method and GC	2-193 L CH_4 /$kgVS_0$
[48]	Commercial FW. CM slurry	Post solid separated effluent – ADig MC that codigested CM with assorted FW	na	500	Ranging from 100 to 200*	2 gVS/gVS	37	33	Continuously using the AMPTS II (Bioprocess Control) and GC-TCD	165-496 mL CH_4/g VS_{added}
[42]	Hay (control and standard substrate), peel, stalk, flesh and unpeeled banana	prepared as described previously (Bolduan et al., 2011; Brulé, 2014)	na	2,000	na	0.7 VS	37	35	Volumetric method and with a methane analyser equipped with an infrared sensor	0.256-0.367 m^3 CH_4/kg VS
[74]	Source-separated organic household waste	Collected from a WWTP	na	1,000	Adjusted to 70%	2 VS	37	45	GC-FID	202-572 mL CH_4/g $VS_{subtrate}$
[26]	TWAS from wastewater treatment plant. RS	WWTP	Thermal and thermo-NaOH for TWAS (70-90 ^{0}C). NaOH and H_2O_2 for RS	250	70	0.5 TS	37	50	Water displacement method and GC-TCD	184.63-401.89 mLbiogas/gVS_{added}
[52]	FW from a canteen	Anaerobic sludge - up-flow ADig of a paper mill	Storage as a pretreatment. FW separately stored for 0-12 d	1,000	na	2:1 VS	35	21/60	Flowed through 3 mol/L NaOH, and principle of water-displacement	311-571 mL CH_4/g-VS_{added}; 285-696 mL CH_4/g-VS_{added}

Author	Substrate source	Inoculum source	Pretreatment	Reactor (mL)	Headspace (mL)	I/S	T (°C)	Incubation time (d)	Measurement of biogas	Biogas Production
[76]	Two-phase OMSW or alperujo	Full-scale MC ADig treating brewery wastewater	Steam-explosion (200 ^{0}C). Afterwards a LF and a SF obtained	250 (EF)	na	2 VS	35	23	Liquid displacement passing the biogas through a 3N NaOH	(LF) 589±42 mL CH_4/g VS_{added}; (SF) 263±1 mL CH_4/g VS_{added}; (Untreated) 366±4 mL CH_4/g VS_{added}
[23]	The two-phase OMSW used was collected from the Experimental Olive Oil Factory	Industrial ADig treating brewery wastewater 35 ^{0}C	Thermal (100-180 ^{0}C)	250 (EF)	na	2 VS	35	Period of c.a. 20	Liquid displacement passing the biogas through a 3N NaOH	373-392 mL CH_4/g VS_{added}
[55]	WH was harvested. FVW was collected from typical market	Mesophilic anaerobic sewage sludge - UASB treating domestic wastewater	na	500	100	na	37	60	Liquid displacement and GC-TCD	0.114 m^3 biogas/kg VS_{added} (WH); 0.141 m^3 biogas /kgVS_{added} (WH+FVW)
[66]	DAF sludge and WAS collected from a large refinery	MC ADig at a municipal WWTP	Ozonation in a bubble column setup	60	na	DAF sludge 2-10 gVS/gVS_{DAF}; Treated DAF sludge 20–100 gVS/gVS_{DAF}; 5 gVS/gVS_{WAS}	MC	30-50	na	80-160 L_{biogas}/ kgCOD_{added}
[30]	Selected solid waste fractions from cattle, pig and chicken slaughtering facilities	Granular mesophilic inoculum sourced from a MC UASB reactor treating dairy processing waste	Pasteurisation	1,000	100	2 VS	36-39	30-50	Directly through positive liquid displacement after the biogas produced passed through an alkaline solution	465.34-515.47 mLCH_4/gVS (UP); 501.13-650.92 mLCH_4/gVS (P)

*Calculated values

AC – Autoclaving; AD – Anaerobic Digestion; ADig – Anaerobic digester; AS – Agricultural substrates; BA – Bioaugmentation; CIR – Cereal industry residues; CM – Cattle manure; DAF – dissolved air flotation unit; EV – Effective volume; FIW – Food industry wastes ; FOG – Fat, oil and grease; FVW – Fruit and vegetable waste; FW – Food waste; GS – Granular sludge; LF – Liquid fraction; MC – Mesophilic conditions; MSW – Municipal solid waste; ODM – Organic dry matter; OFMSW – Organic fraction municipal solid waste; OMSW – Olive mill solid waste; P – Pasteurised; RAS – Recirculating aquaculture systems; RS – Rice straw; SF – Solid fraction; SSMHW – Source-sorted municipal household waste; SSO – source separated organics; SSOFMSW – Source sorted organic fraction municipal solid waste; STP – Standard temperature and pressure; T – Temperature; TC – Thermochemical; TWAS – Thickened waste activated sludge; UASB - Up-flow Anaerobic Sludge Blanket; UP – Unpasteurised; US – Ultrasonic; WWTP – Water waste treatment plant

7. Conclusions

The BMP tests continue to be widely used to analyse the potential organic solid wastes for anaerobic digestion. Despite several attempts made in recent years to normalise the BMP tests the variability of the substrate sources and its characteristics and the available resources imply adaptation of several operational conditions tests.

BMP results, namely the biogas or methane production should be presented in comparable units.

Nevertheless the huge number of publications since 2011 to 2016, it is important to continue the investigation concerning the potential substrates for anaerobic digestion due to the waste management and energy resource applications.

References

[1] Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J. L., Guwy, A. J., Kalyuzhnyi, S., Jenicek, P., van Lier, J. B.: Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water Sci. Technol. (2009). doi: 10.2166/wst.2009.040

[2] De Baere, L.: Will Anaerobic Digestion of Solid Waste Survive in the Future? Water Sci Technol (2006). DOI: 10.2166/wst.2006.249

[3] APA, Relatório Ambiental Final, PERSU 2020. http://www.apambiente.pt/_zdata/AAE/PERSU%202020_RA_preliminar_25_08_14.pdf (2014). Accessed 13 April 2016

[4] Kafle, G. K., Chen, L.: Comparison on batch anaerobic digestion of five different livestock manures and prediction of biochemical methane potential (BMP) using different statistical models. Waste Manage. 48, 492-502 (2016). http://dx.doi.org/10.1016/j.wasman.2015.10.021

[5] Yong, Z., Dong, Y., Zhang, X., Tan, T.: Anaerobic co-digestion of food waste and straw for biogas production. Renew. Energ. (2015). http://dx.doi.org/10.1016/j.renene.2015.01.033

[6] Raposo, F., De la Rubia, M. A., Fernández-Cegrí, V., Borja, R.: Anaerobic digestion of solid organic substrates in batch mode: An overview relating to methane yields and experimental procedures. Renew. Sust. Energ. Rev. (2011). doi: 10.1016/j.rser.2011.09.008

[7] Owen, W. F., Stuckey, D. C., Healy Jr., J. B., Young, L. I., McCarty, P. L.: Bioassay for monitoring biochemical methane potential and anaerobic toxicity. Water Res. 13, 485–492 (1979)

[8] Hansen, T. L., Schmidt, J. L., Angelidaki, I., Marca, E., Jansen, J.l.C., Mosbæk, H., Christensen, T. H.: Method for determination of methane potentials of solid organic waste. Waste Manage. (2004). doi: 10.1016/j.wasman.2003.09.009

[9] Chynoweth, D. P., Turick, C. E., Owens, J. M., Jerger, D. E., Peck, M. W.: Biochemical methane potential of biomass and waste feedstocks. Biomass Bioenerg. 51 (1), 95–111 (1993)

[10] Owens, J. M., Chynoweth, D. P.: Biochemical methane potential of municipal solid waste (MSW) components. Water Sci. Technol. 27 (2), 1–14 (1993)

[11] Angelidaki, I., Ahring, B. K: Thermophilic anaerobic digestion of livestock waste: the effect of ammonia. Appl. Microbiol. Biotechnol. 38, 560-564 (1993)

[12] Angelidaki, I., Ahring, B. K.: Codigestion of olive oil mill wastewaters with manure, household waste or sewage sludge. Biodegradation 8, 221–226 (1997)

[13] Angelidaki, I., Saunders, W.: Assessment of the anaerobic biodegradability of macropollutants. Environ. Sci. Technol. 3, 117–129 (2004)

[14] VDI 4630. Fermentation of organic materials. Characterisation of the substrates, sampling, collection of material data, fermentation tests. VDIHandbuch Energietechnik; 2006

[15] ISO 11734. Evaluation of the "ultimate" anaerobic biodegradability of organic compounds in digested sludge – method by measurement of biogas production; 1995

[16] Dumas, C., Damasceno, G. S. G., Barakat, A., Carrère, H., Steyer, J. P., Rouau, X.: Effects of grinding processes on anaerobic digestion of wheat straw. Ind. Crop. Prod. (2015). http://dx.doi.org/10.1016/j.indcrop.2015.03.043

[17] Lim, S. J., Fox, P.: Biochemical Methane Potential (BMP) Test for Thickened Sludge Using Anaerobic Granular Sludge at Different Inoculum/Substrate Ratios. Biotechnol. Bioproc. E. (2013). doi: 10.1007/s12257-012-0465-8

[18] Raposo, F., Fernández-Cegrí, V., De la Rubia, M. A., Borja, R., Béline, F., Cavinato, C., Demirer, G., Fernández, B., Fernández-Polanco, M., Frigon, J. C., Ganesh, R., Kaparaju, P., Koubova, J., Méndez, R., Menin, G., Peene, A., Scherer, P., Torrijos, M., Uellendahl, H., Wierinck, I., de Wilde, V.: Biochemicalmethane potential (BMP) of solid organic substrates: evaluation of anaerobic biodegradability using data from an international interlaboratory study. J. Chem. Technol. Biotechnol. (2011). doi: 10.1002/jctb.2622

[19] Valero, D., Montes, J. A., Rico, J. L., Rico, C.:_Influence of headspace pressure on methane production in Biochemical Methane Potential (BMP) tests. Waste Manage. (2016). http://dx.doi.org/10.1016/j.wasman.2015.11.012

[20] Abudi, Z. N., Hu, Z., Xiao, B., Rajaa, N., Liu, C., Guo, D.: Batch anaerobic co-digestion of OFMSW (organic fraction of municipal solid waste), TWAS (thickened waste activated sludge) and RS (rice straw): Influence of TWAS and RS pretreatment and mixing ratio. Energy (2016). http://dx.doi.org/10.1016/j.energy.2016.03.141

[21] Ruggeri, B., Battista, F., Bernardi, M., Fino, D. & Mancini, G.: The selection of pretreatment options for anaerobic digestion (AD): A case study in olive oil waste production. Chem. Eng. J. (2015). http://dx.doi.org/10.1016/j.cej.2014.08.035

[22] El-Mashad, H. M., Zhang, R.: Biogas production from co-digestion of dairy manure and food waste. Bioresour. Technol. (2010). doi:10.1016/j.biortech.2010.01.027

[23] Rincón, B., Bujalance, L., Fermoso, F. G., Martín, A., Borja, R.: Biochemical methane potential of two-phase olive mill solid waste: Influence of thermal pretreatment on the process kinetics. Bioresour. Technol. (2013). http://dx.doi.org/10.1016/j.biortech.2013.04.090

[24] Labatut, R. A., Angenent, L. T., Scott, N. R.: Biochemical methane potential and biodegradability of complex organic substrates. Bioresour. Technol. (2011). doi: 10.1016/j.biortech.2010.10.035[24]

[25] Carlsson, M., Holmström, D., Bohn, I., Bisaillon, M., Morgan-Sagastume, F., Lagerkvist, A.: Impact of physical pre-treatment of source-sorted organic fraction of municipal solid waste on greenhouse-gas emissions and the economy in a Swedish anaerobic digestion system. Waste Manage. (2015). http://dx.doi.org/10.1016/j.wasman.2015.01.010

[26] Abudi, Z. N., Hu, Z., Xiao, B., Abood, A. R., Rajaa, N., Laghari, M.: Effects of pretreatments on thickened waste activated sludge and rice straw co-digestion: Experimental and modeling study. J. Environ. Manage. (2016). http://dx.doi.org/10.1016/j.jenvman.2016.04.028

[27] Gunaseelan, V. N.: Anaerobic digestion of biomass for methane production: a review. Biomass Bioenerg. 13 (1–2), 83–114 (1997)

[28] Lin, J.-G., Ma, Y.-S., Chao, A. C., Huang, C.-L.: BMP test on chemically pretreated sludge. Bioresour. Technol. 68, 187-192 (1999)

[29] Gunaseelan, V. N.: Biochemical methane potential of fruits and vegetable solid waste feedstocks. Biomass Bioenerg. (2004). doi:10.1016/j.biombioe.2003.08.006

[30] Ware, A., Power, N.: What is the effect of mandatory pasteurisation on the biogas transformation of solid slaughterhouse wastes? Waste Manage. (2016). http://dx.doi.org/10.1016/j.wasman.2015.10.013

[31] Bilgili, M. S., Demir, A., Varank, G.: Evaluation and modeling of biochemical methane potential (BMP) of landfilled solid waste: A pilot scale study. Bioresour. Technol. (2009). doi: 10.1016/j.biortech.2009.05.012

[32] Fernández, A., Sánchez, A., Font, X.: Anaerobic co-digestion of a simulated organic fraction of municipal solid wastes and fats of animal and vegetable origin. Biochem. Eng. J. (2005). doi:10.1016/j.bej.2005.02.018

[33] Raposo, F., Banks, C. J., Siegert, I., Heaven, S., Borja, R.: Influence of inoculum to substrate ratio on the biochemical methane potential of maize in batch tests. Process Biochem. (2006). doi:10.1016/j.procbio.2006.01.012

[34] Davidsson, Å., Gruvberger, C., Christensen, T. H., Hansen, T. L., Jansen, J.l.C.: Methane yield in source sorted organic fraction of municipal solid waste. Waste Manage. (2007). doi: 10.1016/j.wasman.2006.02.013

[35] Gunaseelan, V. N.: Regression models of ultimate methane yields of fruits and vegetable solid wastes, sorghum and napiergrass on chemical composition. Bioresour. Technol. (2007). doi:10.1016/j.biortech.2006.05.014;

[36] Santos, M. T., Contribuição para o estudo da digestão anaeróbia de resíduos orgânicos, PhD Thesis, FCT-Universidade Nova de Lisboa, (2010). http://run.unl.pt/bitstream/10362/5085/1/Santos_2010.pdf

[37] Neves, L., Gonçalo, E., Oliveira, R., Alves, M. M.: Influence of composition on the biomethanation potential of restaurant waste at mesophilic temperatures. Waste Manage. (2008). doi:10.1016/j.wasman.2007.03.031

[38] Zhu, B., Gikas, P., Zhang, R., Lord, J., Jenkins, B., Li, X.: Characteristics and biogas production potential of municipal solid wastes pretreated with a rotary drum reactor. Bioresour. Technol. (2009). doi: 10.1016/j.biortech.2008.08.024

[39] Val del Río, A., Morales, N., Isanta, E., Mosquera-Corral, A., Campos, J. L., Steyer, J. P., Carrère, H.: Thermal pre-treatment of aerobic granular sludge: Impact on anaerobic biodegradability. Water Res. (2011). doi: 10.1016/j.watres.2011.08.050

[40] Nieto, P. P., Hidalgo, D., Irusta, R., Kraut, D.: Biochemical methane potential (BMP) of agro-food wastes from the Cider Region (Spain). Water Sci. Technol. (2012). doi: 10.2166/wst.2012.372

[41] Shen, S., Nges, I. A., Yun, J., Liu, J.: Pre-treatments for enhanced biochemical methane potential of bamboo waste. Chem. Eng. J. (2014). http://dx.doi.org/10.1016/j.cej.2013.11.075

[42] Khan, M.T., Brulé, M., Maurer, C., Argyropoulos, D., Müller, J., Oechsner, H.: Batch anaerobic digestion of banana waste - energy potential and modelling of methane production kinetics. Agric. Eng. Int.: CIGR Journal, 18(1), 110–128 (2016)

[43] Cano, R., Nielfa, A., Fdz-Polanco, M.: Thermal hydrolysis integration in the anaerobic digestion process of different solid wastes: Energy and economic feasibility study. Bioresour. Technol. (2014). http://dx.doi.org/10.1016/j.biortech.2014.02.007

[44] Miao, H., Wang, S., Zhao, M., Huang, Z., Ren, H., Yan, Q., Ruan, W.: Codigestion of Taihu blue algae with swine manure for biogas production. Energ. Convers. Manage. (2014). http://dx.doi.org/10.1016/j.enconman.2013.10.025

[45] Kafle, G. K., Kim, S. H., Sung, K. I.: Ensiling of fish industry waste for biogas production: A lab scale evaluation of biochemical methane potential (BMP) and kinetics. Bioresour. Technol. (2013). http://dx.doi.org/10.1016/j.biortech.2012.09.032

[46] Risberg, K., Sun, L., Levén, L., Horn, S. J., Schnürer, A.: Biogas production from wheat straw and manure – Impact of pretreatment and process operating parameters. Bioresour. Technol. (2013). http://dx.doi.org/10.1016/j.biortech.2013.09.054

[47] Costa, J. C., Barbosa, S. G., Sousa, D. Z.: Effects of pre-treatment and bioaugmentation strategies on the anaerobic digestion of chicken feathers. Bioresour. Technol. (2012). http://dx.doi.org/10.1016/j.biortech.2012.06.047

[48] Ebner, J. H., Labatut, R. A., Lodge, J. S., William, A. A., Trabold, T. A.: Anaerobic co-digestion of commercial food waste and dairy manure: Characterizing biochemical parameters and synergistic effects. Waste Manage. In Press (2016). http://dx.doi.org/10.1016/j.wasman.2016.03.046

[49] Lisboa, M. S., Lansing, S.: Characterizing food waste substrates for co-digestion through biochemical methane potential (BMP) experiments. Waste Manage. (2013). http://dx.doi.org/10.1016/j.wasman.2013.09.004

[50] Luna-delRisco, M., Normak, A., Orupõld, K.: Biochemical methane potential of different organic wastes and energy crops from Estonia. Agron. Res. 9 (1–2), 331–342 (2011)

[51] Yan, Y., Chen, H., Xu, W., He, Q., Zhou, Q.: Enhancement of biochemical methane potential from excess sludge with low organic content by mild thermal pretreatment. Biochem. Eng. J. (2013). http://dx.doi.org/10.1016/j.bej.2012.10.011

[52] Lü, F., Xu, X., Shao, L., He, P.: Importance of storage time in mesophilic anaerobic digestion of food waste. J. Environ. Sci. In Press (2016). http://dx.doi.org/10.1016/j.jes.2015.11.019

[53] Browne, J. D., Murphy, J. D.: Assessment of the resource associated with biomethane from food waste. Appl. Energ. (2013). http://dx.doi.org/10.1016/j.apenergy.2012.11.017

[54] Elbeshbishy, E., Nakhla, G., Hafez, H.: Biochemical methane potential (BMP) of food waste and primary sludge: Influence of inoculum pre-incubation and inoculum source. Bioresour. Technol. (2012). doi: 10.1016/j.biortech.2012.01.025

[55] Hernández-Shek, M. A., Cadavid-Rodríguez, L. S., Bolaños, I. V., Agudelo-Henao, A. C.: Recovering biomethane and nutrients from anaerobic digestion of water hyacinth (Eichhornia crassipes) and its co-digestion with fruit and vegetable waste. Water Sci. Technol. (2016). doi: 10.2166/wst.2015.501

[56] Wall, D. M., O'Kiely, P., Murphy, J. D.: The potential for biomethane from grass and slurry to satisfy renewable energy targets. Bioresour. Technol. (2013). http://dx.doi.org/10.1016/j.biortech.2013.09.094

[57] Xue, Y., Liu, H., Chen, S., Dichtl, N., Dai, X., Li, N.: Effects of thermal hydrolysis on organic matter solubilization and anaerobic digestion of high solid sludge. Chem. Eng. J. (2015). http://dx.doi.org/10.1016/j.cej.2014.11.005

[58] Yap, S. D., Astals, S., Jensen, P. D., Batstone, D. J., Tait, S.: Pilot-scale testing of a leachbed for anaerobic digestion of livestock residues on-farm. Waste Manage. (2016). http://dx.doi.org/10.1016/j.wasman.2016.02.031

[59] Mou, Z., Scheutz, C., Kjeldsen, P.: Evaluating the biochemical methane potential (BMP) of low-organic waste at Danish landfills. Waste Manage. (2014). http://dx.doi.org/10.1016/j.wasman.2014.06.025

[60] Cavaleiro, A. J., Ferreira, T., Pereira, F., Tommaso, G., Alves, M. M.: Biochemical methane potential of raw and pre-treated meat-processing wastes. Bioresour. Technol. (2013). http://dx.doi.org/10.1016/j.biortech.2012.11.083

[61] Lesteur, M., Latrille, E., Maurel, V. B., Roger, J. M., Gonzalez, C., Junqua, G., Steyer, J. P.: First step towards a fast analytical method for the determination of Biochemical Methane Potential of solid wastes by near infrared spectroscopy. Bioresour. Technol. (2011). doi: 10.1016/j.biortech.2010.10.044

[62] Nielfa, A., Cano, R., Vinot, M., Fernández, E., Fdz-Polanco, M.: Anaerobic digestion modeling of the main components of organic fraction of municipal solid waste. Process Saf. Environ. (2015). http://dx.doi.org/10.1016/j.psep.2015.02.002

[63] Nuchdang, S., Khemkhao, M., Techkarnjanaruk, S., Phalakornkule, C.: Comparative biochemical methane potential of paragrass using an unacclimated and an acclimated microbial consortium. Bioresour. Technol. (2015). http://dx.doi.org/10.1016/j.biortech.2015.02.049

[64] Yin, F., Wang, D., Li, Z., Ohlsen, T., Hartwig, P., Czekalla, S.: Study on anaerobic digestion treatment of hazardous colistin sulphate contained pharmaceutical sludge. Bioresour. Technol. (2015). http://dx.doi.org/10.1016/j.biortech.2014.11.091

[65] Kinnunen, V., Ylä-Outinen, A., Rintala, J.: Mesophilic anaerobic digestion of pulp and paper industry biosludge–long-term reactor performance and effects of thermal pretreatment. Water Res. (2015). http://dx.doi.org/10.1016/j.watres.2015.08.053

[66] Haak, L., Roy, R., Pagilla, K.: Toxicity and biogas production potential of refinery waste sludge for anaerobic digestion. Chemosphere (2016). http://dx.doi.org/10.1016/j.chemosphere.2015.09.099

[67] Abelleira-Pereira, J. M., Pérez-Elvira, S. I., Sánchez-Oneto, J., de la Cruz, R., Portela, J. R., Nebot, E.: Enhancement of methane production in mesophilic anaerobic digestion of secondary sewage sludge by advanced thermal hydrolysis pretreatment. Water Res. (2015). http://dx.doi.org/10.1016/j.watres.2014.12.027

[68] Witarsa, F., Lansing, S.: Quantifying methane production from psychrophilic anaerobic digestion of separated and unseparated dairy manure. Ecol. Eng. (2015). http://dx.doi.org/10.1016/j.ecoleng.2014.05.031

[69] Eiroa, M., Costa, J. C., Alves, M. M., Kennes, C., Veiga, M. C.: Evaluation of the biomethane potential of solid fish waste. Waste Manage. (2012). http://dx.doi.org/10.1016/j.wasman.2012.03.020

[70] Rico, C., Montes, J. A., Muñoz, N., Rico, J. L.: Thermophilic anaerobic digestion of the screened solid fraction of dairy manure in a solid-phase percolating reactor system. J. Clean Prod. (2015). http://dx.doi.org/10.1016/j.jclepro.2015.04.101

[71] Ferreira, L. C., Nilsen, P. J., Fdz-Polanco, F., Pérez-Elvira, S. I.: Biomethane potential of wheat straw: Influence of particle size, water impregnation and thermal hydrolysis. Chem. Eng. J. (2014). http://dx.doi.org/10.1016/j.cej.2013.08.041

[72] Suhr, K. I., Letelier-Gordo, C. O., Lund, I.: Anaerobic digestion of solid waste in RAS: effect of reactor type on the biochemical acidogenic potential (BAP) and assessment of the biochemical methane potential (BMP) by a batch assay. Aquacult. Eng. (2015). http://dx.doi.org/10.1016/j.aquaeng.2014.12.005

[73] Naroznova, I., Møller, J., Larsen, B., Scheutz, C.: Evaluation of a new pulping technology for pre-treating source-separated organic household waste prior to anaerobic digestion. Waste Manage. (2016). http://dx.doi.org/10.1016/j.wasman.2016.01.042

[74] Naroznova, I., Møller, J., Scheutz, C.: Characterisation of the biochemical methane potential (BMP) of individual material fractions in Danish source-separated organic household waste. Waste Manage. (2016 b). http://dx.doi.org/10.1016/j.wasman.2016.02.008

[75] Fernández-Cegrí, V., Raposo, F., de la Rubia, M. A., Borja, R.: Effects of chemical and thermochemical pretreatments on sunflower oil cake in biochemical methane potential assays. J. Chem. Technol. Biotechnol. (2012). doi: 10.1002/jctb.3922

[76] Rincón, B., Rodríguez-Gutiérrez, G., Bujalance, L., Fernández-Bolaños, J., Borja, R.: Influence of a steam-explosion pre-treatment on the methane yield and kinetics of anaerobic digestion of two-phase olive mil solid waste or alperujo. Process. Saf. Environ. (2016). http://dx.doi.org/10.1016/j.psep.2016.04.010

[77] Riau, V., De la Rubia, M. A., Pérez, M.: Upgrading the temperature-phased anaerobic digestion of waste activated sludge by ultrasonic pretreatment. Chem. Eng. J. (2015). http://dx.doi.org/10.1016/j.cej.2014.08.032

[78] Yoon, Y.-M., Kim, S.-H., Shin, K.-S., Kim, C.-H.: Effects of Substrate to Inoculum Ratio on the Biochemical Methane Potential of Piggery Slaughterhouse Wastes. Asian Australas. J. Anim. Sci. (2014). http://dx.doi.org/10.5713/ajas.2013.13537

[79] Ferreira, L. C., Souza, T. S. O., Fdz-Polanco, M., Pérez-Elvira, S. I.: Thermal steam explosion pretreatment to enhance anaerobic biodegradability of the solid fraction of pig manure. Bioresour. Technol. (2014). http://dx.doi.org/10.1016/j.biortech.2013.11.050

[80] Ferreira, L. C., Donoso-Bravo, A., Nilsen, P. J., Fdz-Polanco, F., Pérez-Elvira, S. I.: Influence of thermal pretreatment on the biochemical methane potential of wheat straw. Bioresour. Technol. (2013). http://dx.doi.org/10.1016/j.biortech.2013.05.065

[81] Apples, L., Lauwers, J., Gins, G., Degrève, J., Impe, J. V., Dewil, R.: Parameter Identification and Modeling of the Biochemical Methane Potential of Waste Activated Sludge. Environ. Sci. Technol. (2011). doi: 10.1021/es1037113

[82] Triolo, J. M., Pedersen, L., Qu, H., Sommer, S. G.: Biochemical methane potential and anaerobic biodegradability of non-herbaceous and herbaceous phytomass in biogas production. Bioresour. Technol. (2012). http://dx.doi.org/10.1016/j.biortech.2012.08.079