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Chemical and physical characterization of food waste to improve its use in anaerobic digestion plants

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ABSTRACT

Considerable amounts of expired food waste are generated every day. They are rich in organic carbon and in other elements, including nitrogen, phosphorus and potassium, which cannot be wasted. The present work tested expired food waste in terms of biogas production efficiency in anaerobic digestion (AD) process. A database was extrapolated from the tests carried out in order to obtain a complete list of physico-chemical and biochemical methane potential (BMP) of 88 expired food waste. Many studies are based on the analysis of a small number of samples, which are don't present a complete picture of all the types of food waste. The organic composition and other factors such as pH, temperature, C/N ratio of the samples varies considerably with the region, the season and the processing characteristics, resulting in methane yield variations, ranging from 216 to 1476 mL CH_4/gVS. Therefore, knowledge of the appropriate physical and chemical properties of the feedstock, working conditions and the effects of the inhibition of various components on the anaerobic digestion processes is a key element, necessary to optimize energy production from food waste.

1. Introduction

The EU directive of waste has introduced gradually a reduction in the disposal of organic waste in landfills, so this has to be either reused for the production of biochemicals, or compost or energy [1]. Energy production from expired food and expired food reduction chains are presented in the project i-Rexfo. This presents a business model which aims to demonstrate an innovative and sustainable energy supply chain to decrease food waste through a complete approach that enhances the integration, interaction and communication between production, distribution, use and end of life stages in a circular economy scenario [2].

The starting point are large-scale chain stores, gastronomic companies, plants producing and marketing food. The next part in the supply chain is represented by entrepreneurs operating in the field of waste management such as selective collection, donation, storage and logistics of expired food. The final part in the supply chain are companies that use expired food waste and transform it to produce renewable energy.

According to FAO [3], each year 1/3 of the food produced is lost or wasted: the economic loss is estimated around 7.500 T$. While 28% of available land and 250 km^3 of water is used to grow crops that are wasted, food waste produced and landfilled emits the equivalent of 3.3 Gtons of CO_2 (if it was a country it would be the third emitting country in the world). About 95 kg per capita of food is wasted each year by consumers in Europe [1]. Actually in Europe about 40 Mt of food waste is disposed of in landfills [4]. Landfilling not only consumes valuable land, it also causes air, water and soil pollution, releasing methane into the atmosphere and releasing chemicals and pesticides into the earth and in the groundwater. In particular, the quantities of CH_4 and CO_2 released by landfilling food depend on the carbon content of the food, the management of the waste site (particularly landfill gas recovery) and the percentage of the available carbon that decomposes [5].

When the food becomes not suitable for human consumption and its reuse as animal feed is not possible, food wastes are diverted to energy production systems, which are used for energy recovery in a sustainable and renewable way. Considering the necessity to stabilize the agri-food industry waste from the point of view of environmental protection, biotechnological methods are the most useful and economic methods. Bioconversion technologies, such as anaerobic digestion, are more suitable, compared to thermochemical conversion technologies, such as combustion and gasification, due to the raw material high moisture content [6]. Moreover, organic wastes are easily biodegradable substrates. The anaerobic digestion method converts the energy contained in food waste into a useful fuel (biogas) that can be stored. In addition, this method allows the transformation of organic waste into stable soil improvers and valuable products, such as fertilizers.

The anaerobic digestion process takes place with the participation of anaerobic microorganisms that decompose active substances, producing methane and carbon dioxide. The mechanisms of the process are divided

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into four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The first step is hydrolysis, during which organic polymers such as proteins, carbohydrates and fats are broken down by the enzymes of the bacteria into soluble monosaccharides and amino acids, and fatty acids. In the acidogenesis phase, the hydrolysis products and chemicals dissolved in water are processed to volatile fatty acids. Next we have the most important step called acetogenesis in which the volatile fatty acids are broken down into acetic acid, carbon dioxide and hydrogen. The last phase is methanogenesis. During this process mainly methane (CH_4) and carbon dioxide (CO_2) are produced with a small amount of other substances.

Anaerobic digestion takes place in fermentation reactors, called digesters, designed to maximize the methane yield of the different substrates. Currently, most anaerobic digesters are single-stage systems, these represent around 95% of large European plants [7]. However, it should be remembered that the anaerobic digestion systems that deal with different raw materials with a high content of solids may have changing specific conditions and operating characteristics. In particular, anaerobic digestion of food waste is a complex process that simultaneously digests all organic substrates (such as carbohydrates, lipids and proteins) [8]. This process is governed by several key parameters such as: temperature, VFA (Volatile Fatty Acids), substrate pH, ammonia, nutrients, trace elements and others. A good balance between nutrients and trace elements and a stable environment are necessary for microbial growth. Residence time and substrate/inoculum ratio must be chosen with particular attention, because they affect both the speed of digestion reactions and the possibility that they may take place. In the above-described reactions, the speed at which intermediate products are formed is also proportional to their degradation in the next reaction step. Any change in substrate conditions, such as pH, can slow down the course of hydrolysis and acidogenesis and have an unfavorable effect (by reducing the amount of intermediate components) on the course of subsequent phases, which are acetogenesis and methanogenesis. This situation does not stop the process. The process continues, but negative effects can be encountered that in the end result in a lower methane production in the final methanation phase.

According to Nagao et al. [9], the anaerobic digestion of easily degradable substrates is a delicate compromise between the speed with which the hydrolysis and methanogenesis phases occur, because methanogenic bacteria are very sensitive to high concentrations of volatile fatty acids which in high concentration imply a corresponding drop in pH. If the hydrolysis and acidogenesis phases occur with an excessive speed, the digestate can acidify excessively, inhibiting the methanogenesis phase. The optimum pH for the anaerobic digestion process is between 5.0–8.0 and depends on the phase of the process: a pH range comprised between 5.0 to 6.0 is suitable for acidogenic bacteria, while pH from 6.5 to 8.0 is more convenient for the methanogens [10]. The chemical composition of feedstocks has a great influence on the presence and concentration of system buffering components. The pH value determines the entire fermentation process. It is surely responsible for the development of methanogenic bacteria, because even not big fluctuations can cause disturbances in their reproduction [11]. The solution to tackle this problem is represented by appropriate process design for reducing unwanted acidification of the environment inside the fermentation reactor.

Temperature is a next very important element in the properly conducted anaerobic digestion process. Different types of bacteria require different temperatures. This dependency is related to the content water in cells. If the water content is low, the thermal resistance of organisms is greater [12].

In the above mentioned process, mainly mesophilic bacteria are used, for which the optimal temperature ranges are from 25 to 45 °C. Thermophilic bacteria, on the other hand, tolerate temperatures from 50 °C to 57 °C. Not only the microorganisms are affected by the temperature inside the reactor. The temperature also affects the reaction kinetics: bringing digestion from mesophilic to thermophilic conditions allows higher reaction rates, greater biogas production and leads to the destruction of pathogenic bacteria. However, the thermophilic process is more sensitive to the variation of environmental conditions than the mesophilic one [13].

Nitrogen, carbon compounds, phosphorus, potassium and other elements are some of the basic nutrients for the growth of microorganisms. An important element in process control is the C/N ratio.

The optimal value of carbon to nitrogen ratio is maintained in the range of 20–30 [14, 15]. If this value is exceeded, the nitrogen will be completely consumed by the bacteria and this will reduce the amount of biogas produced. If the ratio drops too much below, nitrogen will be released in the form ammonia and it will increase the pH of the environment. This condition may disturb the nitrogen balance and have a toxic effect on methanogenic bacteria.

The composition of food waste influences the physico-chemical characteristics of the waste itself, depending on the place where it is produced. Food waste consisting mainly of rice, pasta and vegetables contains high quantities of carbohydrates, while meat, fish and eggs have high concentrations of protein and lipids. However, food waste has general characteristics that can be extrapolated all over the world; it has a moisture content of 74–90%, a high percentage of volatile solids (around 85 ± 5%) and a pH of about 5.1 ± 0.7 [16]. Usually, a food waste is mainly composed of degradable carbohydrates (41–62%), proteins (15–25%) and lipids (13–30%) [17]. Furthermore, an important factor that influences the performance of the process, especially in the case of batch systems, is the ratio between the amount of substrate and the inoculum (S/I) which is used. The most important task in the case of a single stage reactor is to prevent the accumulation of volatile fatty acids, which can be avoided by increasing the quantity of inoculum, to avoid the irreversible acidification of the process [18]. In a single-stage systems, it is common practice to calculate the substrate-inoculum ratio as a function of the percentage of volatile solids of the two matrices [19]. Although theoretically the substrate/inoculum relationship only affects the process kinetics, the influence on methane production has been widely studied for a single-stage digester and specific studies were completed on the effect of this ratio on the digestion of different waste food [20, 21]. From these studies it emerged that the methane yield, obtained in a single stage batch digester, operating with an S/I ratio < 0.5, varies between 417 and 529 L CH4/kg VS [22–25].

The aim of this study has been to create a database that could be used to provide expired food waste biogas production efficiency in anaerobic digestion processes. The database has been extrapolated from the tests performed in the laboratory, in order to obtain a complete list of physico-chemical characteristics and the Biochemical Methane Potential (BMP) of numerous expired food wastes. The food wastes were divided into 15 main categories, which contained the most common food products available worldwide. The physico-chemical characterization of food wastes is one of the activities of the i-Rexfo project, which aims to use expired food for energy production. Many articles in this field contain descriptions of a small group of products and only selected characteristics are described, while in this paper an extensive database on different expired foods properties is presented. This gives useful data for the optimization of anaerobic digestion processes.

2. Materials and methods

Expired food was collected for about a year, from i-Rexfo project partners and collaborating malls and supermarkets, such as: food retailers, supermarkets, hotels, restaurants and households. The collected material was stored in appropriate conditions, until the moment of analysis. The food wastes were classified into 15 main categories (see Table 1), according to the FAO classification first used in the EU project FUSION [26]

Each major category includes a few of the most common products that were tested in this work. The obtained database collects a set of

Table 1
Food waste categories.

Number	Food Classification	Symbol used in our study
1	Dairy product	DP
2	Fats, oils and grease (FOG)	FOG
3	Ice cream	IC
4	Fruit and vegetable	FAV
5	Confectionary (canned good)	CCG
6	Cereals and cereals products	CP
7	Bakery wares	BW
8	Meat and Meat Products	MP
9	Fish and Fish products	FP
10	Eggs and Egg products	EP
11	Sweeteners and sweet good	SSG
12	Sauces, spices, soups	SS
13	Beverages	BEV
14	Ready to eat food or restaurant waste	REWE
15	Other expired food	OT

Table 2
Mineralization program for different types of Matrices: type B: milk, baby milk and yoghurt; type C: rice; type D: juice, cola and liquid tea; type A: the rest of the samples.

Stage	Time [min]	Temperature [˚C]	Power [W]
matrices type A e B			
1	15	200	1200
2	15	200	1200
matrices type C			
1	10	180	1200
2	15	180	1200
matrices type D			
1	15	180	1200
2	15	180	1200

data that summarize the main physico-chemical properties of different expired foods.

All tests were performed in laboratories of the Biomass Research Center of the University of Perugia. The parameters necessary to desing and optimally operate anaerobic digestion plants fed with expired food wastes were investigated. The acidity or alkalinity of the samples was analyzed by pH measurement. The total solids and volatile solids were measured by thermogravimetric analysis (TGA). The quantity of phosphorus and potassium (indicated respectively as TP and TK) were measured by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). The Total Kjeldhal Nitrogen (TKN) method was used for determination of the protein, while the Soxhlet method wasd used for the determination of the lipid content. The amount of carbohydrates was calculated by difference. The maximum theoretical methane yield was measured with the BMP test. The Carbon and Nitrogen elements concentration, which was used to calculate the ratio between C/N and Total Organic Carbon (TOC) were analyzed by elementary analysis (CHN). The physico-chemical properties, with their corresponding units, are listed in Table 2. All the tests were replicated three times.

3. Results

3.1. Reagents and chemicals

The water used in all the analysis was ultrapure water (15 MΩ cm), obtained from Purelab and produced with the Elga Labwater purification system. The high purity nitric acid (HNO_3) and hydrogen peroxide (30% H_2O_2 solution) used for ICP-OES analysis were of ultrapure and bought from Merck. The solvent used for the Soxhlet method was hexane bought from CarloErba, while the extraction thimbles where bought from Sigma-Aldrich. The 95% sulfuric acid (H_2SO_4) and boric acid (H_3BO_3) used for the Kjeldahl method came from Sigma-Aldrich. The Sigma-Aldrich Multi Element 4 and Phosphorous were used as reference standards for ICP-Analysis. Nitrogen, oxygen, argon and helium were high purity gasses bought from Air Liquide.

3.2. Instrumentation and sample preparation

3.2.1. Elementary analysis

The instrument used in our work was the LECO Truspec CHN Elemental Analyzer. The samples were previously dried. Then, the samples were weighed in tin foil cones. The mass used for the analysis was between 0.05 - 0.1 mg. The tin foil cones were sealed and introduced into the furnace where the temperature of combustion was set to 950 ˚C. After combustion the gasses were transported by a helium flow and were separated by a GC column into water, CO2 and NOx. Finally, the gasses were detected by a thermal conductivity detector (TCD) for the measure of NOx and an infrared detector for the measure of carbon dioxide and water vapor. At the end of the tests, a report on hydrogen, nitrogen and carbon concentration was generated in accord to the ASTM D5373 protocol.

3.2.2. Thermogravimetric analysis

The thermogravimetric analysis was carried out using the LECO TGA-701 analyzer. The thermogravimetric balance allows the determination of the amount of ashes, moisture, fixed carbon and volatile substances on solid or liquid samples. The mass of the sample was around 2 - 3 g and it was put in ceramic crucibles. The crucibles were kept in a closed furnace with nitrogen atmosphere and the temperature ramp increased up to 900 ˚C. For the final report the ASTM D5142 protocol was used.

3.2.3. Analysis of pH

In the anaerobic digestion process the pH parameter plays an important role, since an acid pH of the tested substrates could inhibit the methanization phase, it is necessary to accurately determine this parameter. For the analysis of pH the EPA Method 9045d was used [27]. The pH was measured by mixing the sample with distilled water and determining the pH of the resulting aqueous solution using the portable HI9124 pH meter, equipped with a probe for detecting pH and temperature (respectively mod. HI7071 and model HI1330B by Hanna Instruments), which was used to compensate the effects of temperature on the pH value.

3.2.4. The Soxhlet method for lipid content

The Soxhlet method is the most commonly used for extracting lipids in foods [28]. The Soxhlet method used in our work was recognized by the Association of Official Analytical Chemists (AOAC) as the standard method for the determination of crude lipids. The Soxhlet measuring procedure was characterized by several steps, involving initial drying of samples, semi-continuous washing and homogenization of the samples with the organic solvent. Each sample was prepared in the same way. First an extraction flask was washed and then dried in an electrical oven at 100 ˚C. Next the extraction flask was cooled and weighed. A milled and dried sample was put into the cellulose thimble at the height of $\frac{3}{4}$ of the total length. Then the cellulose thimble was put into the extractor and 200 ml of hexane was added into the flask. To carry out the distillation everything was heated for 6 h at the temperature of 65 ˚C. Finally, to obtain the crude lipid the rotary evaporator was used to evaporate the solvent. The fat percentage was obtained from the following equation:

$$L[\%] = ((w\_2 - w\_1))/w_0 \times 100 \quad (1)$$

where w_2 is the weight of the flask containing the extracted lipids; w_1 is the weight of the empty flask; w_0 is the original weight of the sample; L is a percentage of fat from the sample [29].

3.2.5. The Kjeldhal method for nitrogen and protein content

In the Kjeldahl procedure, proteins and other organic food components in the sample were heated and digested catalytically in sulfuric

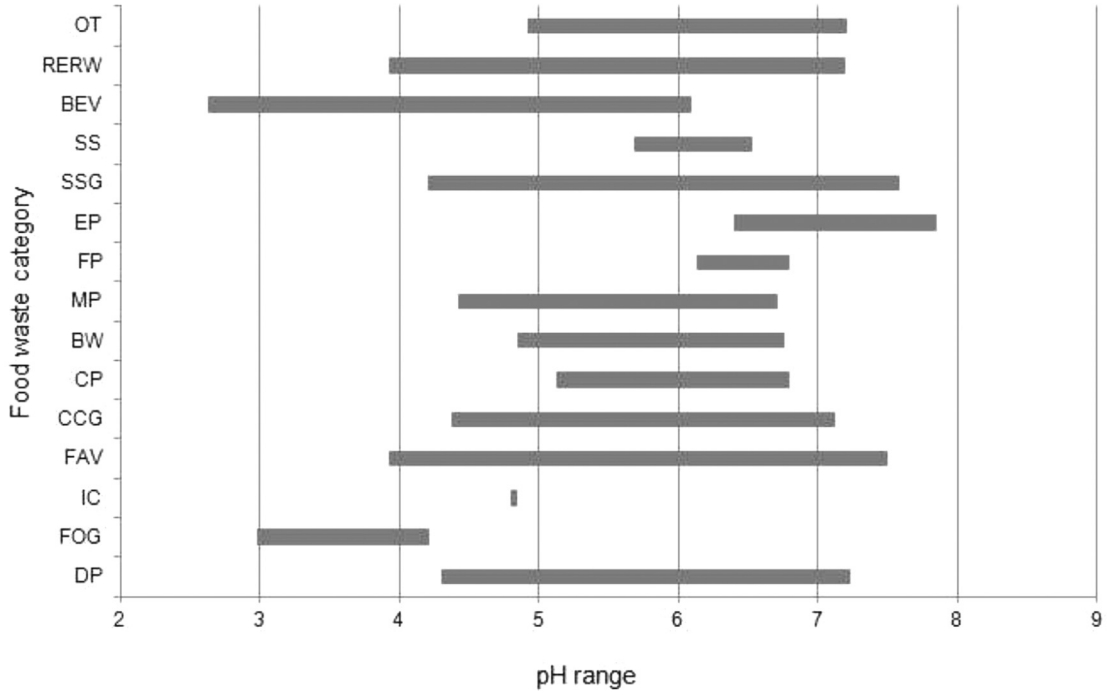

Fig. 1. pH range of food waste.

acid and the proteins contained in it were decomposed into ammonia, which reacts with sulfuric acid to produce ammonium sulfate [30]. First the sample was weighed into a Kjeldahl flask. Next 20 ml of distilled water and 10 ml of 96% sulfuric acid were added. The flask was carefully heated for 4 h. After the heating time was complete, the flask was cooled and 50 ml of distilled water were added. Then 20 ml of 40% NaOH were added into the digested sample and the mixture was left to cool down in the Kjeldhal apparatus using a water flow in the reflux condenser. Then the mixture was placed into a 250 ml conical flask. Ammonia was released by distilling the ammonia absorbed on 20 ml of boric acid (H_3BO_3) and then titrated with a standard sulfuric acid solution. The protein content is calculated by multiplying the TKN by the conversion factors present in the literature. For most samples a conversion factor of 6.25 (equivalent to 0.16 g nitrogen per gram of protein) was used. The exceptiona are represented by milk, cheese and rice for which the conversion factors were calculated according to the data given in the Literature [31].

3.2.6. Methanogenic potential by BMP test

The Biochemical Methane Potential test (BMP) is an essential information to determine sludge dilution or concentration in the real anaerobic digestion plant and the resulting biogas and energy which are produced. The methanogenic potential was measured in batch bottles for BMP test, which are used to measure the yield and the composition of biogas from different substrates at different conditions. Each bottle has a capacity of 1 L and is equipped with probes for pressure, temperature and pH measurement and biogas sampling, in order to analyze its composition. The vessels were maintained at constant temperature (40 °C) in a thermostatic bath (Fig. 1e). The pressure sensors used to measure biogas production were connected to a system for data acquisition. Biogas was sampled with air tight syringes and then analyzed by a Varian CP-4900 micro-GC gas-chromatograph.

The inoculum used in this test was obtained from an industrial anaerobic digester, also partner of the i-REXFO project. Therefore, it was assumed to be microbiologically adequate for degrading the diverse substrates proposed for the BMP test. Their pH was 7.2 and C/N ratio was about 17.82. The amount of inoculum used in the test bottles was determined on the basis of the amount of volatile solids. A preliminary study was conducted to determine appropriate substrate concentrations and I/S ratios for the tests. It was concluded that a minimum I/S ratio of 0,3 was required to ensure process start-up, during the first 3 days of the test. The BMP tests were terminated when daily methane production during a three consecutive days period was less than 1% of the cumulated production of methane.

3.2.7. Acid digestion method and ICP-OES analysis to determine potassium (K) and phosphorus (P) content in the samples

The digestion of the samples is one of the most critical steps before ICP-OES analysis, because foods in general are very complex matrices, with very variable structure, chemical composition and content of organic material. For food, the procedure must be able to digest the organic material and separate the inorganic fraction present in the samples. The acid digestion of the samples was carried out with Milestone ETHOS ONE Microwave-assisted extractor. The mass of the samples employed during acid digestion was about 0.5 g. The sample was placed in a teflon vessel. The oxidizing solution was nitric acid (HNO_3 at 67%) and hydrogen peroxide (H_2O_2 at 30%). For the matrices of type A food wastes 8 ml of oxidizing solution was added (7:1 HNO_3 and H_2O_2). For the type B matrices such as milk, baby milk and yoghurt, the oxidizing solution was 9 ml (7:2 HNO_3 and H_2O_2). For the rise (matrices type C) the volume ratio was 5:1, respectively for HNO3 and H2O2, while for the matrices (D), such as juice, cola and liquid tea 8 ml of HNO_3 and 2 ml of H_2O_2 were used. The samples were mineralized under the conditions shown in Table 2.

After mineralization the samples were transferred to a 50 mL conical glass vessel and brought to a final volume with ultrapure water. Then, the samples were analyzed with the Perkin-Elmer Optima 8000 ICP-OES Spectrophotometer. The calibration of the instrument was done using a nebulizer flow of 0.65 L/min; a radio frequency power of 1450 W; and a sample flow of 1.10 mL/min (see Table 3). The metal standards were prepared by appropriate dilutions of stock solution to have a final solution of metal in 10% HNO_3. The elements analyzed were potassium (K) and phosphorus (P) for which five-points calibration curves were recorded. Each sample was analyzed three times. The concentrations of K and P obtained from the analysis were expressed as a percentage in mass.

Table 3
The calibration of the ICP instrument for K and P elements analysis.

Element	Wavelength [nm]	Plasma(L_{Ar} /min)	Aux (L/min)	Neb (L/min)	Power(watt)	Plasma mode
K	766.48	8	0.2	0.65	1450	Radial
P	214.91	8	0.2	0.65	1450	Axial

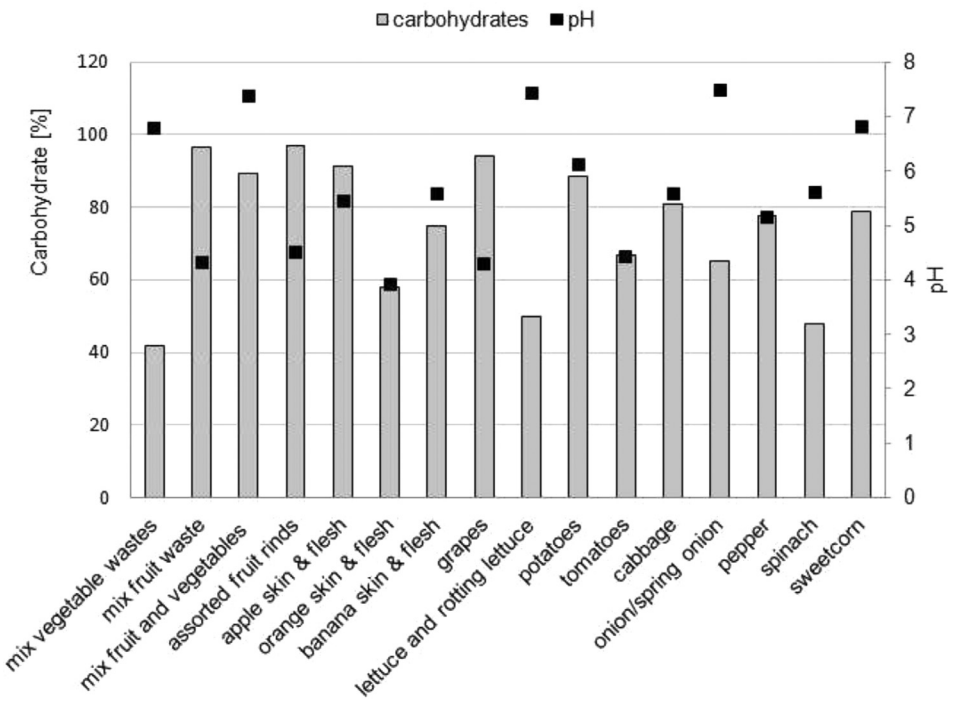

Fig. 2. Dependence of pH on percentage of carbohydrate in FAV samples.

3.3. Database of analyzed expired food waste

The physico-chemical characterization of the 88 types of food waste substrates is presented in Table 4. From the database it can be seen that the physical and chemical characteristics of the samples belonging to different categories are quite different.

3.3.1. The pH of the expired food samples

The pH influences the solubility of the compounds, and the correct growth of the microorganisms. The pH in a digester reactor is an important parameter, which is used to determine process stability. Under optimal conditions the pH in a properly running one-stage fermentation process should be slightly basic, thus ensuring optimal activity of methanogenic bacteria. For food waste digestion, it is recommended to maintain a pH of 6.8–7.5 with maximum biogas production observed at the pH of 7.0 [32]. In order to inhibit the unfavorable decrease of pH and stabilize the anaerobic digestion process, other substrates with a more basic pH (inoculum) are added. Fig. 1 shows the pH range of all types of food waste, which have been analyzed.

From the literature [33], we know that anaerobic digestion of fruit and some vegetables without the addition of other substrates is not possible, because some of them contain a very high content of simple sugars, which cause acidification of the substrate. From Fig. 1, we can observe that the concentration of hydrogen ions in the FAV ranged from 3.93 to 7.50. Since this group had the greatest variety of substrates, therefore the dependence of pH on carbohydrate concentration is presented in the Fig. 2

As shown in Fig. 3 the most favorable pH contains a mixture of fruits and vegetables, lettuce and rotting lettuce and onion/spring onion with pH equal to 7.40, 7.44, 7.50, respectively and low carbohydrates content. The lowest values of pH such as 3.93, 4.30 and 4.32 had oranges skin, grapes and mixed fruit waste with high carbohydrates content. A similar situation was done in the category of BW and BEV, where the pH values ranged from 4.85 to 6.76 and from 2.63 to 6.1, respectively. These samples contain a high amount of carbohydrates such as the Cola sample which contains 99.1% of carbohydrates and has a pH equal 2.63. Similar case respect to acid substrates such as Cola, is represented by some fruit juices in which sugar is present in great quantity [34]. The pH of all the samples contained in the category FOG was low and ranged from 2,98 to 4.21. FOG pH was associated with the presence of fatty acids that dissociate during hydrolysis. The obtained values were in accordance with the literature data [35]. FOG wastes are commonly used as co-substrates in the anaerobic digestion process. This kind of waste has a great potential to increase methane yield, but also increases the presence of inhibitors [36]. In the DP food waste the lowest pH value was 4.30 for yoghurt and the highest value was 7.23 for butter. As it can be seen from Table 4, yogurt contains a significant amount of carbohydrates, compared to other products in this group. In the categories of MP and FP the average pH value was around 6 for both groups. The pH ranged from 4.42 to 6.71 and from 6.13 to 6.80 for meat and fish samples, respectively. These samples contain high protein and lipid concentration, which can cause inhibition of the anaerobic bacteria. Also, the EP samples were rich in lipid and protein and were the only group where the pH of all substrates was near 7. Other categories which contained high amounts of carbohydrates were CP, SSG, SS, RERW with pH values comprised between 5.13–6.80, 4.20–7.59, 5.68–6.53, 3.93–7.20, respectively. In the SSG group the lowest pH (4.20) was that of jelly which contained 99.14% of carbohydrate, while the highest pH (7.59) was obtained for sugar samples with 91.72% of carbohydrates. This fact can be explained by the different protein content and that other substances such as pectin and acid are added to the jelly [37]. In RERW a pH of 3.93 was obtained for tomato sauce, because acidifying

Table 4
Chemical characterization of 88 different food waste. The average values for each category are shown in bold.

Food wastes	pH	TS	VS	TOC	TKN	Fat	Protein	Carbo hydrate	TP	TK	C/N mixture	BMP
		% wb	% wb	%	%	%	%	%	% db	% db		mLCH4/gVS
Dairy product (DP)	**6,29**	**38,54**	**36,65**	**29,72**	**1,58**	**28,43**	**14,05**	**57,51**	**1,33**	**0,87**	**14,46**	**468**
Cheese	5,93	49,86	42,63	29,8	2,90	23,20	18,50	58,30	1,14	0,17	17,38	561
Milk	6,76	10,96	10,56	5,39	1,66	15,60	33,40	51,00	1,70	1,10	3,32	231
Baby milk	7,15	11,38	10,89	4,41	1,95	23,80	10,35	65,85	1,06	1,69	17,30	315
Yogurt/yogurt drink	4,3	30,90	30,30	12,80	0,91	5,10	14,30	80,60	0,70	0,14	14,06	450
Cottage cheese	6,37	39,56	37,27	51.00	1,54	19,50	4,50	76,00	1,09	0,60	17,31	591
Butter	7,23	88,58	88,22	74,90	0,51	83,40	3,27	13,33	2,30	1,50	17,38	660
Fats, oils and grease (FOG)	**3,55**	**60,75**	**59,29**	**65,64**	**0,64**	**91,19**	**1,23**	**7,59**	**0,12**	**0,08**	**29,79**	**598**
Vegetable oil	3,50	75,40	71,63	86,10	0,35	100	0	0	0,01	0,00	48,50	586
Used vegetable oil	3,20	99,10	98,88	74,63	0,22	100	0	0	0	0,01	26,9	648
FOG from food processing	3,01	99,90	99,62	70,28	0,69	99,80	0,20	0	0	0,00	20,15	801
FOG from restaurant	2,98	99,90	99,75	68,47	0,84	99,90	0,10	0	0	0,00	19,53	836
Suspended FOG	3,10	26,72	22,97	69,10	0,53	100	0	0	0	0,00	30,50	402
Settled FOG	4,21	12,84	11,26	64,38	1,44	100	0	0	0,05	0,02	33,12	413
Ice cream (IC)	**4,84**	**11,38**	**10,91**	**26,50**	**0,37**	**38,60**	**8,30**	**53,10**	**0,28**	**0,53**	**29,80**	**502**
Fruit and vegetable (FAV)	**5,69**	**13,87**	**12,17**	**19,57**	**0,62**	**1,36**	**5,20**	**39,01**	**0,67**	**3,28**	**18,56**	**384**
Mixed vegetable wastes	6,80	24.00	22,34	8,15	0,49	0.87	15.30	83.83	0,99	8,55	14,81	425
Mix fruit waste	4,32	20,36	18,04	19,66	0,55	0,21	3,10	96,69	0,31	2,99	26,93	331
Mixed fruit vegetables (MFV)	7,40	7,70	7,10	40.00	1,10	0,31	10,75	89,25	0,33	2,80	36,36	425
Assorted fruit rinds	4,51	17,16	15,08	14,27	0,49	0,24	2,86	96,90	0,36	2,88	13,31	253
Apple skin & flesh	5,47	27,65	21,53	47,60	0,12	1.60	7.10	91.30	0,18	0,89	16,22	305
Orange skin & flesh	3,93	15,32	14,94	5,75	0,88	1.50	40.80	57.70	0,48	1,44	9,61	433
Banana skin & flesh	5,59	18,12	17,64	5,64	0,77	1.70	23.40	75.00	0,31	2,54	11,20	238
Grapes	4,30	12,19	10,39	6,63	0,88	0,21	5,49	94,30	1,15	3,16	17,61	552
Lettuce and rotting lettuce	7,44	7,53	6,19	41,70	0,05	9.10	40.90	50.00	1,34	10,45	16,48	296
Potatoes	6,12	11,92	10,55	11,10	1,33	0,80	10,50	77,90	0,99	4,95	38,89	345
Tomatoes	4,44	5,57	5,49	4.00	0,05	4.80	28.60	66.70	1,23	3,41	18,39	476
Cabbage	5,59	7,86	7,20	46,80	0,56	1,40	17,80	80,80	0,04	0,09	7,96	256,50
Onion/spring onion	7,50	10,33	8,01	38,40	0,47	1.10	33.60	65.30	0,95	2,18	7,47	480
Pepper	5,15	7,30	6,47	4,46	0,52	5.60	16.70	77.80	1,09	4,16	22,47	430
Spinach	5,63	8,69	7,47	10,90	1,17	8.90	43.20	47.90	0,36	0,73	20,59	395
Sweetcorn	6,82	20,14	16,22	8,02	0,40	7.50	13.70	78.70	0,52	1,22	18,65	514
Confectionary (CCG)	**5,72**	**22,93**	**18,43**	**17,38**	**1,24**	**2.79**	**24.38**	**72.83**	**0,91**	**2,61**	**22,02**	**439**
Crushed and diced tomatoes	4,37	10,05	9,60	3,80	0,05	4.70	25.60	69.80	1,52	3,45	24,87	435
Green beans	5,55	26,78	20,67	11,40	3,77	2.70	32.30	65.00	0,70	2,99	21,86	495
Bagged lettuce mixes	7,12	6,42	5,87	40,80	0,04	2.90	32.40	64.70	1,40	4,72	16,79	282
Canned peas	6,73	25,46	19,82	10,70	1,99	3.50	31.20	65.30	0,85	1,13	21,48	520
Canned fruit	4,84	45,93	36,21	20,20	0,32	0,10	0,50	99,40	0,09	0,77	25,11	463
Cereals product (CP)	**5,84**	**90,33**	**75,21**	**41,79**	**2,07**	**3.83**	**11,19**	**84.98**	**0,64**	**0,35**	**20,70**	**506**
Breakfast cereals	6,10	92,70	88,00	38,30	1,86	2,10	11,6	86,30	0,33	0,85	21,49	360
Corn flakes	5,90	91,95	78,96	36,80	1,71	0,80	11,08	88,12	0,07	0,16	21,49	354
Cheerios	5,13	91,19	69,96	41,30	1,52	0,56	8,8	90,64	1,39	0,47	26,14	547
Cereal bar	6,77	92,41	75,6	35,40	1,40	5,60	7,72	86,68	0,23	0,33	22,55	524

(*continued on next page*)

Table 4 (*continued*)

Food wastes	pH	TS	VS	TOC	TKN	Fat	Protein	Carbo hydrate	TP	TK	C/N mixture	BMP
		% wb	% wb	%	%	%	%	%	% db	% db		mLCH4/gVS
Quick oats	6,50	89,97	71,29	43,20	2,96	6,80	15,34	77,86	2,32	0,35	18,65	599
Oatmeal	6,80	90,12	72,25	44,30	2,63	7,10	12,60	80,30	0,65	0,54	16,89	594
Bakery wares (BW)	**5,50**	**88,81**	**71.51**	**43,14**	**2,37**	**6,03**	**12,92**	**81,05**	**0,44**	**0,15**	**19,85**	**526**
White bread	4,98	89,34	71,25	47,00	1,91	0,40	10,90	88.70	0,50	0,13	21,36	507
Sliced bread	4,85	90,17	72,19	45,60	1,87	0,45	10,73	88.82	0,22	0,23	21,71	520
Flour	6,76	88,59	69,62	40,70	2,89	1,00	16,50	82.50	0,48	0,11	18,99	540
Sandwich	5,60	85,31	71,59	53,50	1,78	18,30	7,20	74.50	0,59	0,10	28,79	560
Crackers	5,29	90,62	72,9	28,90	3,38	10,00	19,30	70.70	0,43	0,18	8,42	505
Meat Products (MP)	**6,20**	**46,99**	**41,60**	**25,18**	**4,32**	**57.74**	**25.17**	**17.10**	**0.76**	**0,63**	**16.96**	**412**
Mixed meat	5,42	14,4	13,5	25,01	4,75	63.22	23.57	13.21	0,54	0,61	18,06	421
Beef cooked	5,85	68,2	63,04	22,80	5,23	59.82	32.70	7.480	0,38	0,32	17,46	440
Pork cooked	6,57	35,97	29,31	29,00	4,89	55.69	28.62	16.69	0,34	0,33	19,72	572
Chicken cooked	6,60	42,17	38,82	21,73	3,58	67.30	22.40	10.30	2,11	0,74	16,21	329
Lamb cooked	6,30	43,18	40,12	26,51	4,29	54.48	27.20	18.32	0,12	0,17	17,69	386
Ham scraps	6,71	61,74	58,69	44,20	3,57	59.73	21,87	18.40	0,82	0,62	17,7	358
Sliced meat	6,30	61,51	53,66	46,10	3,69	45.80	23,10	31.10	0,94	1,31	12,39	376
Offal	5,90	58,37	54,12	32,66	3,95	55.86	21,87	22.27	0,85	0,96	16,43	420
Fish products (FP)	**6,49**	**46,12**	**39,25**	**17,72**	**4,38**	**65.53**	**27,48**	**6.98**	**1,48**	**1,46**	**17,59**	**826**
canned tuna fish	6,13	62,61	58,10	26,50	4,23	62.15	26,47	11.38	0,72	0,73	16,32	401
freeze fish	6,80	21,00	17,91	11,91	4,93	63.06	30,83	6.12	1,30	2,13	17,87	1476
fresh fish	6,70	31,25	26,65	19,22	6,15	58.97	38,43	2.60	3,66	2,46	18,24	1170
fish flesh (salmon)	6,30	40,60	33,39	18,34	3,94	61.28	25,03	13.69	0,71	0,85	19,36	509
Fish and shellfish	6,52	75,12	60,21	12,63	2,66	82.2	16,66	1.10	0,97	1,13	16,17	576
Egg products (EP)	**7,43**	**49,64**	**22,77**	**16,26**	**3,04**	**73.06**	**19,00**	**7.94**	**0,88**	**1,13**	**15,16**	**458**
Whole egg	7,85	48,49	31,19	11,25	3,11	71.85	19,45	8.70	0,98	0,51	10,57	289
Cooked eggs	7,80	26,97	24,07	19,37	4,23	65.62	26,48	7.90	1,14	3,50	15,99	587
Pickled eggs	6,40	37,89	25,63	19,63	2,34	76.62	14,62	8.45	0,74	0,11	16,94	539
Raw eggs	7,68	85,20	10,20	14,8	2,47	77.86	15,44	6.70	0,66	0,40	17,14	417
Sweeteners and sweet good (SSG)	**5,49**	**70,51**	**63,94**	**32,98**	**1,01**	**16,21**	**5,85**	**77,89**	**0,23**	**0,43**	**26,57**	**433**
Sugar	7,59	99,95	95,11	42,3	1,32	0	8,28	91,72	0,002	0,004	30,76	284
Sweet cream	6,28	30,90	27,90	33,87	1,28	54,00	5,00	41,00	0,07	0,22	26,27	380
Chocolate pudding	5,13	84,32	69,63	43,50	1,06	4,80	6,65	88,55	0,55	1,18	18,13	527
Cakes	5,01	54,92	44,66	27,20	0,94	22,50	5,89	71,61	0,27	0,38	28,63	451
Jelly	4,20	96,4	94,79	40,70	0,14	0	0,86	99,14	0,01	0,01	29,57	423
Mousse	6,40	32,91	26,87	15,16	1,17	17,20	7,19	75,61	0,11	1,12	13,84	487
Other dessert (wafers,etc.)	3,80	94,19	88,62	28,16	1,13	15,00	7,10	77,90	0,60	0,10	38,77	480
Spices, soups (SS)	**6,09**	**46,44**	**34,58**	**23,85**	**1,82**	**1.35**	**11.32**	**87.33**	**0,42**	**2,03**	**13,82**	**374**
Condiments	5,68	91,56	67,46	47,70	1,87	3,26	11,67	85,07	0,15	0,40	17,91	226
Canned soup	6,07	22,27	17,81	11,80	2,56	0,48	15,80	83,72	0,41	1,59	11,19	457
Soup	6,53	25,48	18,47	12,05	1,04	0,30	6,49	93,50	0,71	4,10	12,36	440
Beverages (BEV)	**4,25**	**36,36**	**33,69**	**4,75**	**2,13**	**0,07**	**14.98**	**84.95**	**0,23**	**1,66**	**12,66**	**434**
Cola beverage	2,63	93,60	88,70	4,93	2,36	0,20	0,70	99.10	0,06	2,79	2,08	373
Tea beverage	6,10	1,52	1,51	3,50	3,68	0,02	23,00	76.98	0,39	2,05	17,62	425
Fruit juices (orange)	4,01	13,97	10,86	5,82	0,35	0	21.21	78.80	0	0,15	18,27	504
Ready to eat food or restaurant waste (RERW)	**5,88**	**64,84**	**44,18**	**39,50**	**2,91**	**19,05**	**15,59**	**65.36**	**0,56**	**1,96**	**15,90**	**582**
Food from conference	7,20	68,45	54,93	32,20	2,53	14,21	15,88	69,91	0,29	0,27	12,67	568
Food from hotel	7,00	96,1	27,30	56,20	4,81	44,20	26,50	29,30	0,63	3,56	11,67	495
Piece of pizza	5,94	87,19	73,12	48,6	4,23	6,60	24,70	68.70	0,32	0,27	15,28	394
French fries	5,35	22,58	18,53	48,39	2,11	29,60	5,40	65.00	0,76	3,56	21,59	349
Gravy (tomato sauce)	3,93	49,90	47,02	12,10	0,87	0,66	5,46	93,88	0,80	2,16	18,29	1108

(*continued on next page*)

Table 4 (*continued*)

Food wastes	pH	TS	VS	TOC	TKN	Fat	Protein	Carbo hydrate	TP	TK	C/N mixture	BMP
		% wb	% wb	%	%	%	%	%	% db	% db		mLCH4/gVS
Other (OT)	**6,38**	**58,85**	**47,13**	**42,36**	**2,13**	**16,96**	**18,58**	**64,46**	**0,19**	**0,57**	**18,95**	**352**
Plain pasta	7,15	42,26	40,77	29,57	2,07	6,00	14,00	80,00	0,12	0,10	14,26	326
Meat pasta	7,21	38,18	34,06	36,87	2,33	14,00	19,30	66,70	0,35	0,20	15,77	216
Rice	6,13	89,88	71,76	40,50	1,51	1,00	8,00	91,00	0,16	0,11	17,99	463
Cafeteria wastes (CW)	6,22	14,25	13,50	48,95	1,96	4,00	17,00	79,00	0,17	0,89	24,90	370
Tea	4,92	92,62	63,60	48,20	3,74	0,01	23,40	76,59	0,39	2,05	12,89	235
Spent coffee grounds	6,13	38,01	32,21	46,40	1,95	60,12	39,88	0	0,05	0,45	18,22	378
Chocolate	6,89	96,78	73,99	46,00	1,36	33,60	8,49	57,91	0,06	0,18	28,64	477

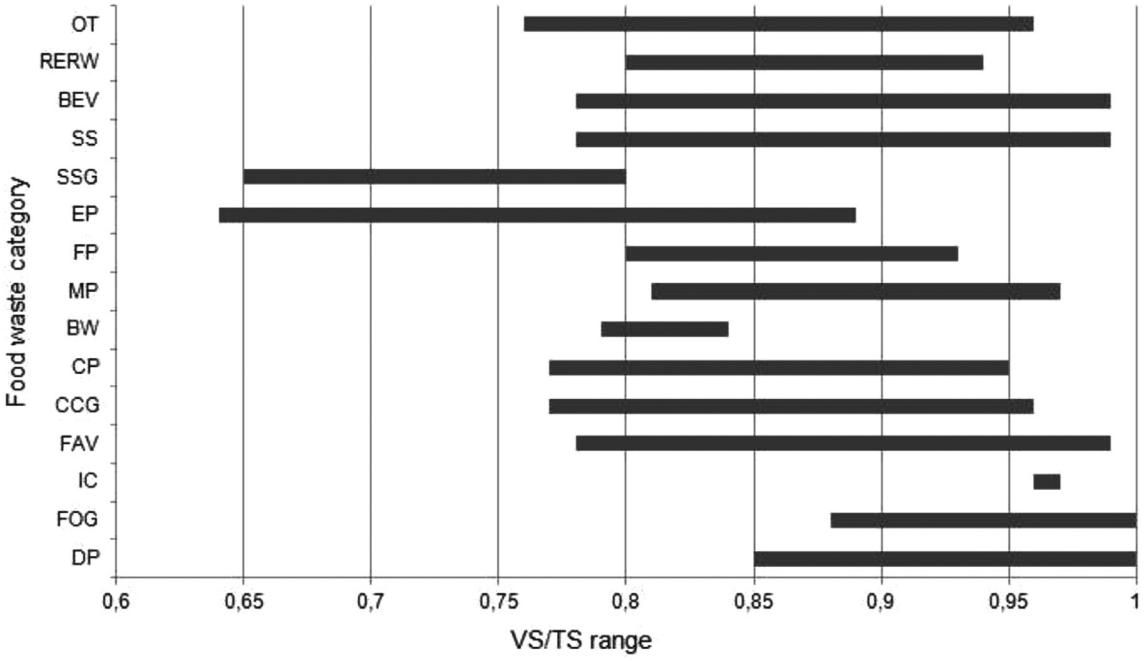

Fig. 3. Ranges in the ratio between volatiles and total solids.

of tomatoes with citric acid is recommended to allow for safe processing conditions [38]. A category with very different substrates was OT with pH values ranging between 4.92–7.21, respectively. The composition of the organic compounds in these samples was very diverse. In the carbohydrate-protein-rich group, named as CCG, the pH was between 4.37–7.12.

3.3.2. *The ratio of volatile and total solids*

The ratio of volatile and total solids (VS/TS) is commonly used to monitor the organic matter content of the digester feedstock. The percentage of volatile solids (VS) represents the biodegradable fraction, while the percentage of total solids (TS) can be used to determine the speed of the digestion process. Fig. 3 shows the VS/TS range value of all the analyzed expired food waste categories. As shown in Fig. 3, food waste has a higher ratio of volatiles to total solids. In many categories, the average (VS/TS) value was over 0.8 (80%). The high VS/TS value means that more feedstock can be consumed by the bacteria during the fermentation process. In addition, the raw material with a higher VS/TS ratio can produce more biogas and also less digestate after the digestion process [39].

3.3.3. *The carbon-to-nitrogen ratio of the mixture: inoculum-substrate*

The amount of carbon and nitrogen or carbon-to-nitrogen ratio C/N present in the substrates or in a digested mixture is one of the main parameters to evaluate the anaerobic digestion process stability. The C/N ratio is characteristic of the given raw material, depending on the availability of carbon and nitrogen present in the substrate. A high carbon-to-nitrogen ratio indicates rapid consumption of nitrogen by microorganisms and lower gas production. On the other hand, a lower C/N ratio results in production of ammonia and exceeding pH values that can inhibit microorganisms that produce methane [40]. It is know that a C/N ratio between 20 and 30 is optimal for maximum biogas generation. Fig. 4 shows the C/N ratio for all the categories of food wate once they were mixed with the inoculum.

As it can be seen from Fig. 4, the C/N ratio varied considerably in each group. With a high C/N ratio, the methane yield increases. The categories that had the range of C/N ratio near to the optimal value were: IC (28.8); CCG (16.79–25.11), CP (16.89–26.14), RERW (11.67–21–59), FP (16.32–19.36) and OT (12.89–28.64). The groups with prevalent low C/N ratio were: DP (3.32–17.38), MP (12.39–19.72), BW (8.42–28.79), EP (10.57–17.14), SS (11.19–17.91) and BEV (2.08–18.27). The groups with medium-high C/N ratio were: SSG (13.84–30.76), FOG (19.53–33.12). To increase the methane efficiency, food waste with low carbon content should be mixed with food waste having high nitrogen content or vice versa; in this way an optimal carbon-nitrogen (C/N) ratio will be achieved [41]. See Table 4 for more details on each sample in a given category.

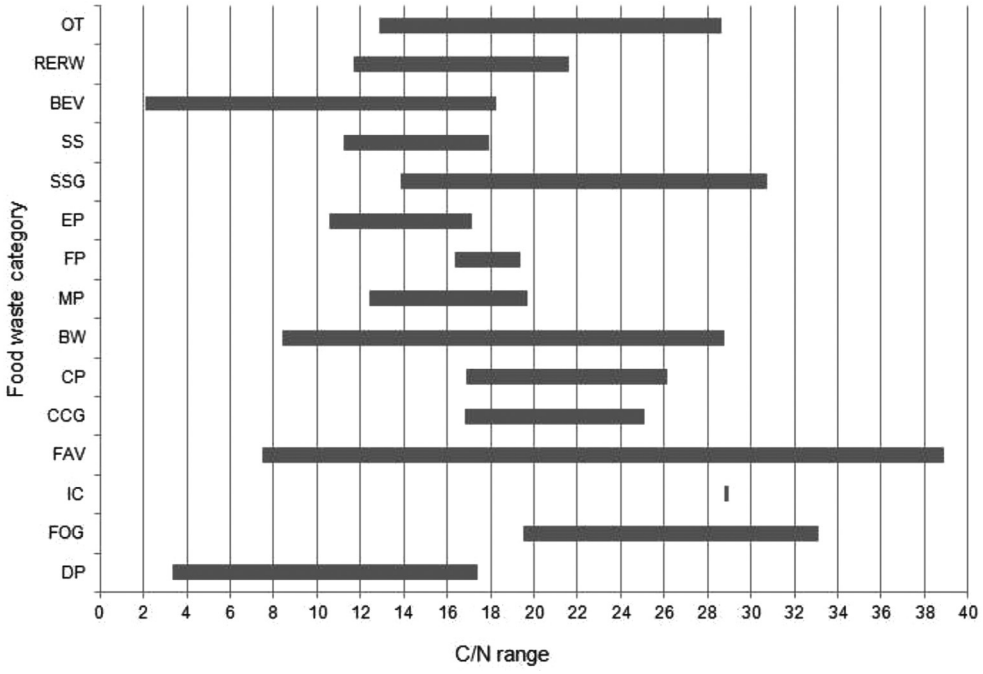

Fig. 4. Carbon-to-nitrogen ranges of expired food wastes.

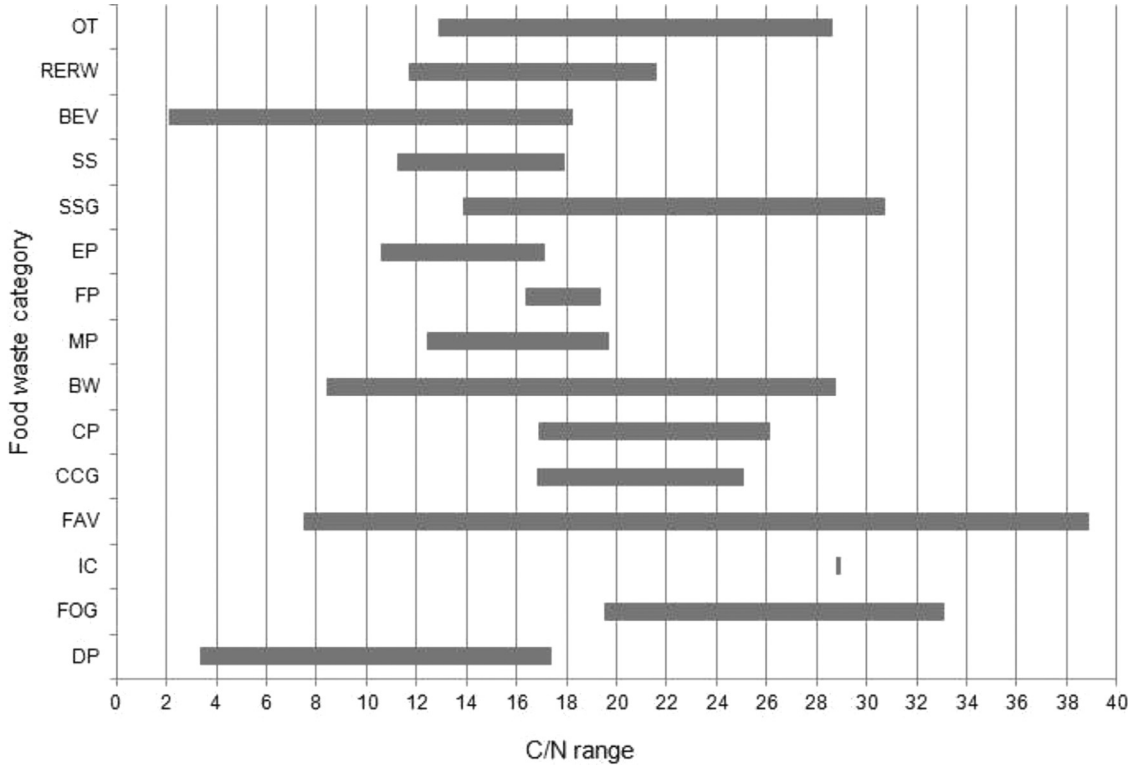

Fig. 5. Average organic composition of analyzed categories.

3.3.4. The carbohydrates, protein and lipids content in the substrates

The anaerobic digestion of food waste is challenged by the properties of the waste. Food waste consists of three principal organic components: carbohydrates, proteins and lipids, which have different theoretical methane yields and bioconversion rates [42]. As it can be seen from Fig. 5, the analyzed food samples can be divided into three types: carbohydrate-rich, protein-rich and lipid-reach feedstock.

During the anaerobic digestion process, high-protein waste produces excessive amounts of ammonia and volatile fatty acids (VFA) [36]. Excessive accumulation of VFA during methane production may cause a decrease in pH, which negatively affects methanogenic microorganisms. The carbohydrate-rich feedstock could result in unfavorable carbon/nitrogen (C/N) ratios in the product, due to its limited nutrients content and rapid acidification [43]. The production of biogas depends on the percentage of various organic compounds in the waste. From Fig. 5 it can be seen that high lipid wastes were, MP, FP, EP, as well as vegetable fat waste contained in the FOG group. The average values of the organic content of food waste based on lipids was 57.74, 65.53,

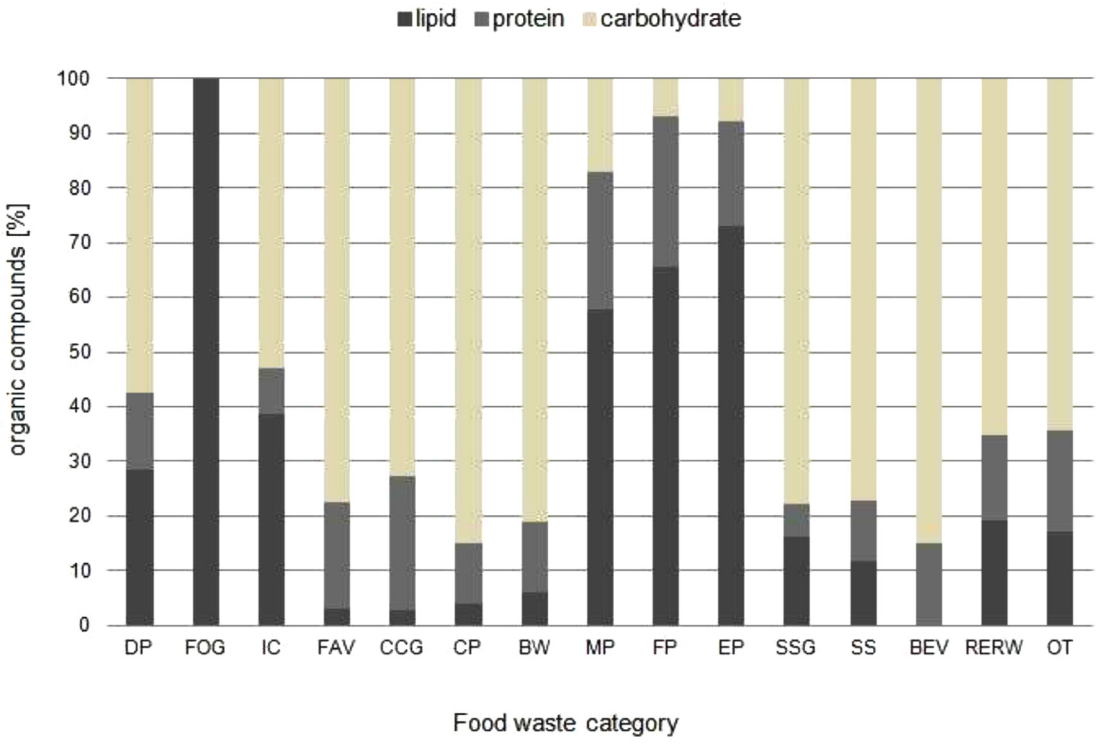

Fig. 6. Average BMP yield of each category.

73.06 and 99.95%, respectively. Due to the high methane production potential, this waste is an attractive substrate for anaerobic digestion. It is estimated that 1.014 dm^3 of methane can be obtained from 1 g of fat. While with the same amount of carbohydrates and protein, the production methane is 0.415 and 0.496 dm^3, respectively [44]. The high carbohydrate content feedstock were FAV, CCG, CP, BW, SSG, SS, BEV, RERW, OT with a glucide content of: 77.38%, 77.83%, 81.05%, 77.93%, 77.18%, 84.95%, 65.36%, respectively. Studies of the anaerobic digestion process have shown that carbohydrates are processed faster and lipids are processed slower [45]. It should be added that lipids higher biogas yields. The DP and IC categories with 57.51% and 53.1% of carbohydrate content also had a high lipid content (28.43% in DP and 38.6% in IC). The lipid-rich material can lead to a rapid pH drop and formation of long fatty acids causing problems during anaerobic digestion [46]. High-protein content was observed in MP, FP, EP, CCG and a large number of food wastes contained in the group of FAV with average results amounting to: 25.17%, 27.18%, 19.00%, 24.38% and 18.96%, respectively. In the FAV category, the protein-rich material was represented by vegetables, with two exceptions: orange skin/flesh (40.80%) and banana skin/flash (23.40%).

3.3.5. The evaluation of the biochemical methane potential (BMP)

The BMP yield varies with the content of carbohydrates, proteins, and lipids. Lipids provide the highest biogas yield, but require a long retention time, due to their slow biodegradability, whereas carbohydrates and proteins show faster conversion rates but lower gas yields. Furthermore, lipids are suitable for biogas production, due to the high number of C and H atoms in their molecule, which implies a high theoretical methane potential [42]. From Fig. 6 it can be seen that some categories with a high content of lipids such as FP, FOG, DP IC, had a higher BMP than categories with a higher average concentration of carbohydrates. This happened with few exceptions, such as: RERW, BW, CP.

The Fig. 7 shows how the biochemical methane potential ranged in the different categories. In the REWE the BMP yield ranged between 349 and 1108 ml CH4/g VS. In the DP category the BMP content ranged from 231 to 660 ml CH4/g VS.

The lowest results of BMP was observed in milk [47], where the amount of lipid was low and the C/N of the mixture was only 3.32. On the other hand, butter had the highest BMP, because it had the highest fat content of any substrate in this category. An interesting category of lipid-rich feedstock was FOG, where the samples such as Fog from food processing and Fog from restaurant had the highest biochemical methane yield: 801 ml CH4/g VS and 836 ml CH4/g VS, respectively. This can be explained by their C/N ratio, which is close to 20. In the FP the methane yield ranged from 401 ml CH_4/g VS to 1476 ml CH_4/g VS, with two samples where BMP was 1170 and 1476 ml CH_4/g VS for fresh and freezed fish. The obtained high BMP results for lipid-rich feedstocks, as fish samples, was confirmed by Cadavid-Rodríguez et al. [48], where the cumulative methane yield was equal 1084 mL CH4/g VS. High methane production can be explained by the higher protein content, besides there was a high lipid content in both fish samples, compared to other substrates in the tested category. Another category that belongs to lipid-rich materials is MP. This group contains has a high amount of lipids and also a high amount of proteins, between 20 and 32%. The cumulative methane yields in MP were in the range of 358–572 ml CH4/g VS. The BMP of FAV category ranged from 238 An exception was the lettuce sample with 40.80% of protein and BMP equal to 296 ml CH_4/g VS. The values obtained for the FAV category were near to those obtained by Gunaseelan [49]. The category of CCG had a high carbohydrates content, but also a significant amount of protein (24–32%). An exception was represented by canned fruit which had low protein content (0.5%). The cumulative methane yield in CCG ranged from 282 to 520 ml CH4/g VS. In the other carbohydrate-rich substrates, such as BW, CP, BEV, SS and SSG the average BMP yield was: 526 ml CH_4/g VS, 496 ml CH_4/g VS, 434 ml CH_4/g VS, 390 ml CH_4/g VS, and 433 ml CH_4/g VS, respectively. The range of methane potential yield in carbohydrate-reach feedstock was between 226 ml CH_4/g VS and 599 ml CH_4/g VS.

3.3.6. Nutrient content

Anaerobic bacteria need nutrients such as carbon, nitrogen, phosphorus, sodium, magnesium and some others in smaller amounts. The

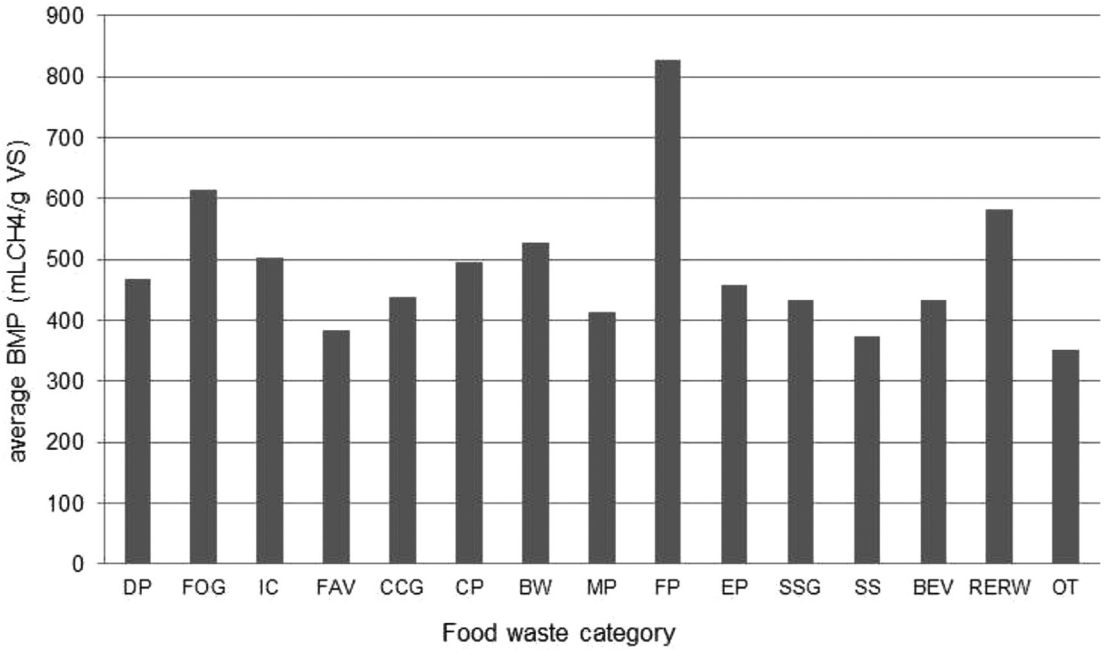

Fig. 7. BMP range in each category.

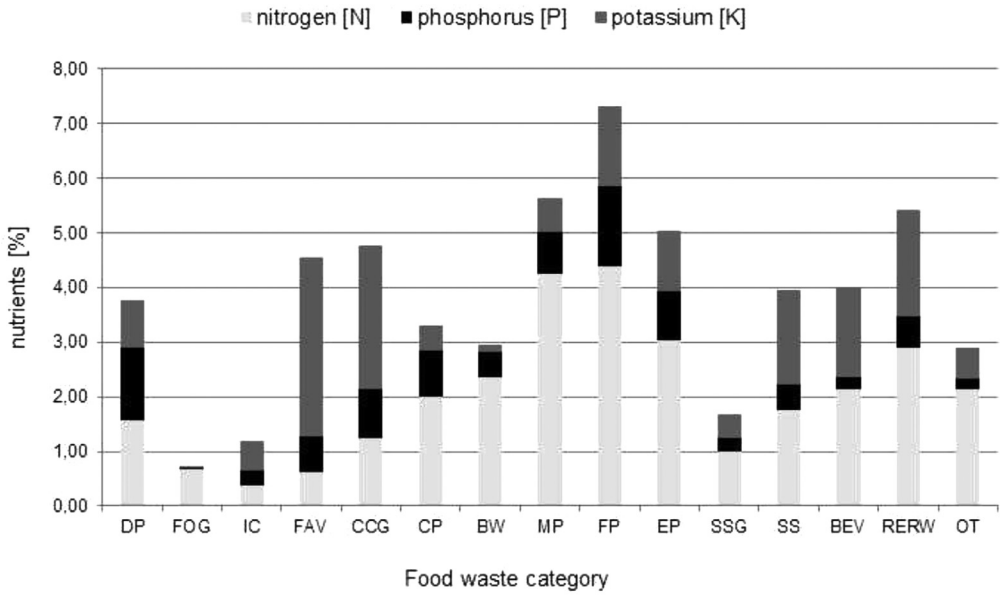

Fig. 8. Average nutrient content in each category.

appropriate concentration of nutrients should slightly exceed the optimal concentrations required by methanogenic bacteria, because nutrient deficiencies may inhibit the growth of bacteria. It is worth adding that the substrates usually provide more than sufficient amounts of nutrients and their deficiencies are rare. Any nutrient can become toxic if its concentration is too high. An example is nitrogen, where the imbalance between a high content of nitrogen and a low carbon content results in the formation of ammonia, which is toxic to methanogenic bacteria. Digestate also is characterized by a high content of mineralized nitrogen, phosphorus and potassium and a high stability. As it can be seen from the Fig. 8, the whole FOG category had the lowest average nitrogen content (less than 1%) and low phosphorus and potassium amount. Other low nitrogen content groups were: IC, SSG.

The categories such as MP, FP, EP, RERW were nitrogen-rich samples, with nitrogen in excess of 3%. In the FP category the sample with the highest content of nitrogen was fresh fish (6.15%). The potassium-rich samples were contained in the FAV category, for example: lettuce with 10.45% concentration, mixed vegetable wastes with 8.55% concentration, tomatoes with 4.95% concentration and pepper with 4.16% concentration (see Table 4). In CP also, there were samples with a higher potassium content, such as: crushed tomatoes (3.45%), green beans (2.99%) and bagged lettuce mixes (4.72%) (see Table 4). The highest average values of potassium concentration were those of 3.28%, 2.61%, which were measured for FAV and CCG categories. In the other groups the content of K was below 2%. When it comes to phosphorus, the highest content of this element was found in fresh fish (3.66%), chicken cooked (2.11%), quick oats (2.32%) and butter (2.30) (see Table 4). The highest average value of phosphorus was in FP and DP categories with concentrations equal to 1.47% and 1.33%, respectively.

4. Conclusions

Anaerobic digestion is a viable method for the conversion of food waste and other organic materials into methane-rich biogas. However, when applied at high organic loading rates, using only food waste as feedstock it can lead to an unstable process. The nutrient composition of the substrates directly affects microbial growth and biogas production. The pH of the substrate supports faster acclimatization of the microbial population to changing environments and solubilizes certain nutrients which can then be easily used by microbes. The pH will drop if the number of acetogenic bacteria exceeds the number of methanogenic bacteria, which can inhibit the methanogenic phase. Therefore, the pH should be kept in the optimal range. A pH of 7.0–7.5 is preferred for a healthy population of methanogens. For food waste digestion, it is recommended to maintain the pH in a range comprised between 6.8 - 7.2, with maximum biogas production observed at a pH equal to 7.0. While a significant reduction in biogas production occurs at pH below 5.0 and over 8.0 in batch conditions [50]. In this study the raw materials pH values vary from 2.63 to 7.85. In the fermentation process it is important to keep the right proportion between carbon and nitrogen ratio (C/N). If this relation is too high, carbon may not be completely converted and therefore it is not possible to obtain adequate methane yield. With an excess of nitrogen, ammonia can be produced. The problem of the toxic effects of ammonia occurs in the fermentation of raw materials with high protein content. As a result of the decomposition of organic nitrogen, NH_3 is formed, which already in low concentrations inhibits the growth of bacteria and can even lead to the inhibition of their entire population. The carbon-to-nitrogen ratio (C/N) in a mixture of sample and inoculum, which is analyzed in our work, is between 7.96–48–50. Regarding the carbohydrate, proteins or lipids content, many studies have indicated a faster conversion rate in products containing significant amounts of carbohydrates than in fats. But also, the fats provide higher biogas production efficiency when they are co-digested with other substrates, such as FOG. In food samples which are tested in our work, the content of individual organic compounds was: 0- 100% for lipid, 0- 40.80% for protein, 0–99.1% for carbohydrates. While, the composition range of nutrient content was: 0–3.66% for phosphorus, 0–10.45% for potassium and 0.05–6.15% for nitrogen. The organic composition and other factors such as pH, temperature, C/N ratio of the samples varies considerably with the region, the seasons and the processing characteristics, resulting in methane yield variations ranging from 216 to 1476 mL CH_4/ g VS. Therefore, knowledge of the appropriate physical and chemical properties of the feedstock, working conditions and the effects of inhibition of various components is a key element, necessary for an effective control of the anaerobic digestion process.

Declaration of Competing Interest

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

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References

[1] M. Donner, R. Gohier, H. De Vries, A new circular business model typology for creating value from agro-waste, Sci. Total Environ. 716 (2020), doi:10.1016/j.scitotenv.2020.137065.
[2] F. Liberti, V. Pistolesi, S. Massoli, P. Bartocci, G. Bidini, F. Fantozzi, I -REXFO LIFE: an innovative business model to reduce food waste, Energy Procedia 148 (2018) 439–446, doi:10.1016/j.egypro.2018.08.118.
[3] J. Gustavsson, C. Cederberg, U. Sonesson, Global Food Losses and Food Waste - extent, causes and Prevention, FAO, 2011 ISBN 978-92-5-107205-9.
[4] European Commission, 2010. Preparatory Study on Food Waste Across EU 27, Technical Report 2010; 054, ISBN 978-92-79-22138-5.
[5] J. Bogner, E. Matthews, Global methane emissions from landfills: new methodology and annual estimates 1980–1996, Global Biogeochem. Cycles. 17 (2) (2003) 1065–1083, doi:10.1029/2002GB001913.
[6] S.Y. Lee, R. Sankaran, K.W. Chew, et al., Waste to bioenergy: a review on the recent conversion technologies, BMC Energy 1 (2019) 4, doi:10.1186/s42500-019-0004-7.
[7] M. Logan, M. Safi, Piet Lens, C. Visvanathan, Investigating the performance of internet of things based anaerobic digestion of food waste, Process Saf. Environ. 127 (2019) 277–287, doi:10.1016/j.psep.2019.05.025.
[8] T. Menzel, P. Neubauer, S. Junne, Role of microbial hydrolysis in anaerobic digestion, Energies 13 (2020) 5555, doi:10.3390/en13215555.
[9] N. Nagao, N. Tajima, M. Kawai, C. Niwa, N. Kurosawa, T. Matsuyama, Maximum organic loading rate for the single-stage wet anaerobic digestion of food waste, Bioresour. Technol. 118 (2012) 210–218, doi:10.1016/j.biortech.2012.05.045.
[10] A. Nsair, S. Onen Cinar, A. Alassali, H. Abu Qdais, K. Kuchta, Operational parameters of biogas plants: a review and evaluation study, Energies 13 (2020) 3761, doi:10.3390/en13153761.
[11] N. Lackner, A.O. Wagner, R. Markt, P. Illmer, pH and Phosphate induced shifts in carbon flow and microbial community during thermophilic anaerobic digestion, Microorganisms 8 (2020) 286, doi:10.3390/microorganisms8020286.
[12] R.M. Syamaladevi, J. Tang, R.;. Villa-Rojas, S. Sablani, B. Carter, G. Campbell, Influence of water activity on thermal resistance of microorganisms in low-moisture foods: a review, Comprensive reviews in food science and food safety 15 (2) (2006) 335–370, doi:10.1111/1541-4337.12190.
[13] J.K. Kim, B.R. Oh, Y.N. Chun, S.W. Kim, Effects of temperature and hydraulic retention time on anaerobic digestion of food waste, J. Biosci. Bioeng. 102 (2006) 328–332, doi:10.1263/jbb.102.328.
[14] A. Rabii, S. Aldin, Y. Dahman, E. Elbeshbishy, A review on anaerobic co-digestion with a focus on the microbial populations and the effect of multi-stage digester configuration, Energies 12 (2019) 1106, doi:10.3390/en12061106.
[15] A.A.S. Ghaleb, S.R.M. Kutty, Y.-.C. Ho, A.H. Jagaba, A. Noor, A.M. Al-Sabaeei, N.M.Y. Almahbashi, Response surface methodology to optimize methane production from mesophilic anaerobic co-digestion of oily-biological sludge and sugarcane bagasse, Sustainability 12 (2020) 2116, doi:10.3390/su12052116.
[16] H. Fisgativa, A. Tremier, P. Dabert, Characterizing the variability of food waste quality: a need for efficient valorisation through anaerobic digestion, Waste Manag 50 (2016) 264–274, doi:10.1016/j.wasman.2016.01.041.
[17] C. Braguglia, A. Gallipoli, A. Gianico, P. Pagliaccia, Anaerobic bioconversion of food waste into energy: a critical review, Bioresour. Technol. 248 (Part A) (2018) 37–56, doi:10.1016/j.biortech.2017.06.145.
[18] M. Kawai, N. Nagao, N. Tajima, C. Niwa, T. Matsuyama, T. Toda, The effect of the labile organic fraction in food waste and the substrate/inoculum ratio on anaerobic digestion for a reliable methane yield, Bioresour. Technol. 157 (2014) 174–180, doi:10.1016/j.biortech.2014.01.018.
[19] P. Pagliaccia, A. Gallipoli, A. Gianico, D. Montecchio, C.M. Braguglia, Single stage anaerobic bioconversion of food waste in mono and co-digestion with olive husks: impact of thermal pretreatment on hydrogen and methane production, Int. J. Hydrogen Energy 41 (2) (2016) 905–915, doi:10.1016/j.ijhydene.2015.10.061.
[20] X. Liu, R. Li, M. Ji, L. Han, Hydrogen and methane production by co-digestion of waste activated sludge and food waste in the two-stage fermentation process: substrate conversion and energy yield, Bioresour. Technol. 146 (2013) 317–323, doi:10.1016/j.biortech.2013.07.096.
[21] F. Lü, L. Hao, M. Zhu, L. Shao, P. He, Initiating methanogenesis of vegetable waste at low inoculum-to-substrate ratio: importance of spatial separation, Bioresour. Technol. 105 (2012) 169–173, doi:10.1016/j.biortech.2011.11.104.
[22] J. Ariunbaatar, A. Panico, L.;. Frunzo, G. Esposito, P.N.L. Lens, F. Pirozzi, Enhanced anaerobic digestion of food waste by thermal and ozonation pretreatment methods, J. Environ. Manage. 146 (2014) 142–149, doi:10.1016/j.jenvman.2014.07.042.
[23] J.D. Browne, J.D. Murphy, Assessment of the resource associated with biomethane from food waste, Appl. Energy. 104 (2013) 170–177, doi:10.1016/j.apenergy.2012.11.017.
[24] V. Facchin, C. Cavinato, F. Fatone, P. Pavan, F. Cecchi, D. Bolzonella, Effect of trace element supplementation on the mesophilic anaerobic digestion of foodwaste in batch trials: the influence of inoculum origin, Biochem. Eng. J. 70 (15) (2013) 71–77, doi:10.1016/j.bej.2012.10.004.
[25] M.A. Voelklein, A. Jacob, R. O' Shea, J.D. Murphy, Assessment of increasing loading rate on two-stage digestion of food waste, Bioresour. Technol. 202 (2016) 172–180, doi:10.1016/j.biortech.2015.12.001.
[26] Food use for social innovation by optimizing waste prevention strategies, European Project FUSION (2012).
[27] Method 9045D: soil and waste pH, part of test methods for evaluating solid waste. 2004
[28] S. Nielsen, Food analysis laboratory manual, Fat Content Determination, 3rd Edition, 2017 ISBN 978- 3-319- 44127- 6.
[29] A.M.C. Davies, N.P. Boley, Food analysis, Anal. Proc. 21 (1984) 2.
[30] D. Jones, Percentages of nitrogen in foods and feeds, United States Dep. Agric. (1931) 16–21.
[31] Food energy - methods of analysis and conversion factors; chapter 2: METHODS OF FOOD ANALYSIS. FAO. Report of a Technical Workshop. Rome, 3-6 December 2002; ISBN 92-5-105014-7
[32] S. Hegde, T.A. Trabold, Anaerobic digestion of food waste with unconventional co-substrates for stable biogas production at high organic loading rates, Sustainability 11 (2019) 3875, doi:10.3390/su11143875.
[33] E.A. Scano, C. Asquer, A. Pistis, L. Ortu, V. Demontis, D. Cocco, Biogas from anaerobic digestion of fruit and vegetable wastes: experimental results on pilot-scale and

preliminary per-formance evaluation of a full-scale power plant, Energy Convers. Manag. 77 (2014) 22–30, doi:10.1016/j.enconman.2013.09.004.
[34] A. Reddy, D.F. Norris, S.S. Momeni, B. Waldo, J.D. Ruby, The pH of beverages in the United States, The Journal of the American Dental Association 147 (4) (2016) 255–263, doi:10.1016/j.adaj.2015.10.019.
[35] J. Long, T. Aziz, F.L. de los Reyes, J.J. Ducoste, Anaerobic co-digestion of fat, oil, and grease (FOG): a review of gas production and process limitations, Process Saf. Environ. Prot. 90 (2012) 231–245, doi:10.1016/j.psep.2011.10.001.
[36] E.J. Martínez, V. Redondas, J. Fierro, X. Gómez, A. Morán, Anaerobic digestion of high lipid content wastes: FOG Co-digestion and milk processing fat digestion, J. Residuals Sci. Tech. 8 (2) (2011) 53–60.
[37] D. Smith, Fruit Jellies. Food processing for entrepreneurs series, Food and nutrition safety (2006) G1604.
[38] D.P. Aykas, K. Rodrigues Borba, L.E. Rodriguez-Saona, Non-destructive quality assessment of tomato paste by using portable mid-infrared spectroscopy and multivariate analysis, Foods 9 (2020) 1300, doi:10.3390/foods9091300.
[39] D.M.D. Gray, P. Suto, C. Peck, Anaerobic digestion of food waste, Final Report (2008) No. EPA-R9-WST-06-004.
[40] B. Puyuelo, Se. Ponsá, T. Gea, A. Sánchez, Determining C/N ratios for typical organic wastes using biodegradable fractions, Chemosphere 85 (4) (2011) 653–659, doi:10.1016/j.chemosphere.2011.07.014.
[41] M.I. Tanimu, T.I. Mohd-Ghazi, R.M. Harun, A. Idris, Effect of carbon to nitrogen ratio of food waste on biogas methane production in a batch mesophilic anaerobic digester, Int. J. Innov. Technol. Manag. 5 (2) (2014) 116–119, doi:10.7763/IJIMT.2014.V5.497.
[42] G. Esposito, L. Frunzo, A. Giordano, F. Liotta, A. Panico, F. Pirozzi, Anaerobic co-digestion of organic wastes, Rev Environ Sci Biotechnol. 11 (2012) 325–341, doi:10.1007/s11157-012-9277-8.
[43] K. Paritosh, S.K. Kushwaha, M. Yadav, N. Pareek, A. Chawade, V. Vivekanand, Food waste to energy: an overview of sustainable approaches for food waste management and nutrient recycling, Biomed Res Int. (2017) 2370927, doi:10.1155/2017/2370927.
[44] I. Angelidaki, W. Sanders, Assessment of the anaerobic biodegradability of macropollutants, Rev Environ Sci Biotechnol 3 (2004) 117–129.
[45] A. Spyridon, A. Vasileios, J.W. Gerrit, A technological overview of biogas production from biowaste, J. Eng. 3 (3) (2017) 299–307, doi:10.1016/J.ENG.2017.03.002.
[46] Y. Sun, D. Wang, Y. Yan, W. Qiao, W. Wang, T. Zhu, Effects of lipid concentration on anaerobic co-digestion of municipal biomass wastes, Waste Manage. 34 (2014) 1025–1034, doi:10.1016/j.wasman.2013.07.018.
[47] F. Fantozzi, V. Pistolesi, S. Massoli, A. Pugliese, G. Bidini, Anaerobic digestion of spoiled milk in batch reactors: technical and economic feasibility, Energy Procedia 81 (2015) 309–318, doi:10.1016/j.egypro.2015.12.101.
[48] L.S. Cadavid-Rodríguez, M.A. Vargas-Muñoz, J. Plácido, Biomethane from fish waste as a source of renewable energy for artisanal fishing communities, Sustain. Energy Technol. Assess. 34 (2019) 110–115, doi:10.1016/j.seta.2019.05.006.
[49] V. Gunaseelan, Biochemical methane potential of fruits and vegetable solid waste feedstocks, Biomass Bioenergy 26 (2004) 389–399, doi:10.1016/j.biombioe.2003.08.006.
[50] Liu Guangqing, Liu Xiaoying, Li Yeqing, He Yanfeng, Z. Ruihong, Influence of pH adjustment and inoculum on anaerobic digestion of kitchen waste for biogas producing, J. Biobased Mater Bioenergy 3 (2015) 390–395, doi:10.1166/jbmb.2011.1161.