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Advances in nutrient management make it possible to accelerate biogas production and thus improve the economy of food waste processing

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ABSTRACT

Foodwaste (hereinafter, FW) is the most voluminous solid waste and its amount is growing rapidly all over the world. The turning of FW into biogas via anaerobic fermentation is widely recognized as an environmentally responsible and economically reasonable option. Based on the knowledge obtained from agricultural biogas stations, the current methods of FW fermentation management are based on balancing the ratio of total carbon and nitrogen. However, it was repeatedly and independently reported that the stability of this process is low, resulting in many concessions in terms of prolonged hydraulic retention time or reduced biogas yield. Hence, biochemical as well as economic performance of the process is balanced by mixing of FW with agricultural residues. FW samples of various origin were collected and biochemically analyzed. The data indicate that FW originating from homes and luxury restaurants tends to be lignocellulose-based, whereas the levels of crude fiber (25% up to 27%) are higher than those from agricultural feedstock (18%). In contrast, FW from school canteens and inexpensive restaurants tends to be starch-based with high levels of amyloids (21% up to 23%) and fat (5% up to 7%). A novel method better reflecting the bioavailability of carbon and nitrogen to anaerobic consortia is proposed. It is demonstrated that the previous optimization methods could somehow reflect the availability of nutrients in agricultural feedstock, as carbonaceous and nitrogen sources are relatively equally biodegradable. Nevertheless, the biodegradability of FW is considerably different, which is why higher amounts of proteins and lipids lead to increased levels of ammonia and sulfide, resulting in an inhibitory effect on the metabolism of anaerobic consortia. Optimizing the anaerobic fermentation of FW by the new method outperforms the previous technique and makes it possible to process FW more intensively, or, more precisely, with higher profitability and lower proportion of ballast agricultural feedstock.

KEYWORDS: Biogas; anaerobic fermentation; energy recovery; bioeconomy; process management

Introduction

It is estimated that some 51% of the overall global municipal waste is considered to be FW (Xue et al. 2017). FW is also produced during food processing and preparation (Parfitt, Barthel, and Macnaughton 2010). Improper handling and storage, expiration of shelf life, transport, and the like cause additional losses (Machová and Vochozka 2019). Over 40% of food is wasted in the retail and consumer stages in developed countries, which is equal to food production in sub-Saharan Africa (Xu et al. 2018). In India, some 90% of food waste is generated in the early stage of the food supply chain. FW generation in Asia is expected to amount annually 416 million tons in 2025 (Dahiya et al. 2018). Henz and Porpino (2017) point out that Brazilian households discard some 30% of food because serving superfluous portions is a cultural trait in Latin countries. However, the large economic imbalance means that most of these residues do not become FW but are subsequently redistributed through a dense network of food banks. Analogically, Thai consumers save food only when eating alone (Pinpart, Asioli, and Balcombe 2019). In the EU, roughly 53% of FW is generated in households, 12% in the food service sector, and 5% in retail (Stenmarck et al. 2016). Thyberg, Tonjes, and Gurevitch (2015) argue that FW makes up nearly 15% of the disposed municipal waste in the USA. According to Xu et al. (2018) China generates more than 90 million tons of FW annually, mainly as food processing waste. The global quantity of FW is gigantic; it is one of the bulkiest parts of solid waste, much more than paper or plastic (FAO 2018). Undisciplined discharge of FW causes serious environmental pollution all over the world (Zhang et al. 2014). Katajajuuri et al. (2014) argue that FW from Finnish households generates emissions equal to local cars and its economic value is approaching 150 € per citizen annually. Nevertheless, the vast majority of developed countries have already banned the use of FW for animal feed and developing countries tend to follow the trend (Mourad 2016), because it is widely accepted that shorting of the food chain might lead to propagation of diseases (Zhang et al. 2014). China has also continued to strengthen the reuse of FW (Guo et al. 2018). The logic behind this measure is clear; easily biodegradable FW can be contaminated by pathogenic microorganisms (Kibler et al. 2018).

Anaerobic fermentation is widely recognized as an economically and environmentally favorable process for the utilization of any biowaste (Maroušek, Strunecký, and Stehel 2019a). Given that the conversion efficiency of anaerobic fermentation is usually 50%, 1 kg of chemical oxygen demand from FW gives almost 16 mols of CH_4 (some 350 L) accounting for the energy output of roughly 14 kJ, which results in 3.9 kWh of electricity (Dahiya et al. 2018). However, it is repeatedly and independently reported that anaerobic fermentation of FW faces several technical (Ludbrook et al. 2019) and economic challenges (Milward et al. 2019) especially under a continuous thermophilic process (Vochozka, Rowland, and Šuleř 2019). There are indications that high levels of volatile fatty acids (short-chain carboxylic acids) in combination with high levels of easily available nitrogen result in process instability, foaming, and low buffer capacity (Xu et al. 2018). FW involves a high level of oils and fats that serve as additional energy source for anaerobic biota, hence intensifying biogas yields (Wiater and Horysz 2017). To make matters worse, it was also reported that an excessive content of proteins and lipids in FW leads to inhibitory effects from toxic ammonia or toxic sulfide concentration that increases with the anaerobic digestion taking place in higher pH and temperature (Hecht and Griehl 2009). Following the above, FW is considered an easily biodegradable, energy-rich but uncontrollable feedstock (Zhang et al. 2014). To balance these properties, FW is mixed with voluminous agricultural feedstock such as maize silage or straw (Hijazi et al. 2016). These, however, are slowly degradable, which prolongs the hydraulic retention times and hampers the stability (Kovacova et al. 2019) and overall financial performance of the process (Udell et al. 2019). For many decades, there has been globally established standard that the balance of key nutrients (carbon and nitrogen) is being analyzed via the ratio of total carbon and total nitrogen, also known as C/N, TC/TN, or TC/KN, whereas the recommended values should be in the range of 15 and 30 (Zhang et al. 2016).

Latest literature (Fersiz et al. 2017) recommends to better reflect the metabolism of anaerobic consortia and balance the ratio of carbonaceous and nitrogen-rich feedstock via analyses on total organic carbon and total nitrogen (also known as TOC/TN or TOC/KN), whereas the recommended values are in the neighborhood of 20. The concept of these ratios sounds rational since it is built on efforts to reflect the metabolism demands of prevailing conglomerates of anaerobic microorganisms (Maroušek et al. 2014). However, these methods ignore the availability of nutrients to anaerobic microorganisms (Kolář et al. 2008).

The FW management industry lacks the knowledge of key parameters regarding the stability and performance of the FW anaerobic fermentation process. Its definition would make it possible to propose appropriate technological measures in order to improve the economic process or to minimize its cost to humanity as a whole. Following the above, the research goal is to develop an analytical method that will outperform the current process management techniques (TC/KN and TOC/KN) in anaerobic fermentation of easily biodegradable feedstock.

Material and methods

A total of 80 samples of FW were collected (České Budějovice, Czech Republic) throughout the whole year of 2019, equally from each category: school canteen (145 students from 7 to 16 years, average expenditure 1.34 € per portion), inexpensive restaurants (average expenditure per customer 4.25 €), luxury restaurants (average expenditure per customer 32.1 €), and author's kitchens (average estimated portion price 3.5 €). After transportation to laboratory, each sample (1 kg) was homogenized via a kitchen mixer and frozen at -18°C until analysis. Feedstock that routinely enters the biogas station (50% of maize silage, 40% haylage, and 10% of fresh manure, all in fresh weight) was sampled shortly before testing. Dry weight was analyzed via heating at 105°C for 24 h that was followed by and weighting at room temperature whereas all the process was repeated until the deviation was lower than 1%. The content of hemicelluloses was calculated from a difference between the values of neutral detergent fiber (NDF) and acid detergent fiber (ADF). Lignin was calculated from ADF by subtracting the result after lignin oxidation with potassium permanganate. Because ADF contains lignin, cellulose, and mineral fraction, it was possible to determine the cellulose content by ashing the residue in a muffle furnace and by determination of mineral fraction. Fat was determined using the Soxhlet extractor and hexane of analytical grade according to Maroušek et al. (2013). A labile pool of carbon (LPC) was analyzed using the acid hydrolysis method (sulfur acid) in modification by Shirato and Yokozawa (2006), using the automatic high-sensitive nitrogen and carbon analyzer (NC-90A, Shimadzu). Starch was detected using the method of Caprita and Caprita (2016). Biological oxygen demand (BOD) and Chemical oxygen demand (COD), total nitrogen (TN), total organic nitrogen (TOC), Kjeldahl nitrogen (KN), and hot-water extractable nitrogen (HWN) were determined as stated in Maroušek et al. (2014). The sum of heavy metals (As, Cd, Cr, Hg, Ni, Pb, and V; ZHM); the sum of benzene, toluene, and xylene isomers (ZBTEX); the sum of polyaromatic hydrocarbons (ZPAH); adsorbable organic halides (ZAOH); the sum of aromatic hydrocarbon compounds that contain 10 up to 40 carbon atoms (ZC10-C40) and the sum of polychlorinated biphenyl congeners (ZPCB) were carried out according to Vochozka et al. (2016).

Feedstock was mixed in 72 random combinations and analyzed for TC, TOC, HWC, KN, HWC, and methane yields. Data visualization was carried out using Python code according to VanderPlas (2016). Methane yields (VCH4 S) were analyzed using the OxiTopControl accurate methane measuring system (MERCK, Germany) according to the manual, main steps (Eqs. 1-10) follows.

The calculation on the methane yields (VCH4 S) of the feedstock:

$$n = p.V/RT \quad (1)$$

where:

n = the number of gas moles

P = pressure [hPa]

R = ideal gas constant 8.134 J mol °K^{-1}

T = temperature [°K]

V = volume [ml]

The calculation on carbon dioxide and methane:

$$nCO_2g\ CH_4 = (\Delta p.Vg/RT).10^{-4} \quad (2)$$

$$\Delta p = p_1 - p_0 \quad (3)$$

where: *p*0 = initial pressure. Anaerobic fermentation was carried out at 35°C for 60 days. The OxiTopControl containers were stirred gently throughout the time. Subsequently, the process was interrupted by injecting 1 mL HCl (19%). The amount of carbon dioxide is calculated as follows:

$$nCO_2\ l = \{[p_2(Vg - VHCl) - p_1.Vg]/RT\}.10^{-4} \quad (4)$$

After 1 mL of 30% KOH is injected, the amount of carbon dioxide in the liquid residue is calculated as follows:

$$n_{CO2\ l,\ CO2\ g} = \{[p_3(Vg - VHCl - VKOH) - p_2(Vg - VHCl)]/RT\}.10^{-4} \quad (5)$$

where:

Δp = the difference in pressures [hPa]

Vg = the volume of the gas space of the fermentation vessel [ml]

P1 = gas pressure before HCl application [hPa]

p2 = gas pressure before KOH application [hPa]

p3 = gas pressure after KOH application [hPa]

T = absolute temperature

V_{HCl} = the volume of added HCl [ml]

$_{KOH}$ = the volume of added KOH [ml]

The calculation of methane is carried out as follows:

$$nCH_4 = \left(n_{CO2\ g\ CH4} + n_{CO2\ l}\right) - n_{CO2\ l\ CO2}g \quad (6)$$

The total amount of carbon is calculated as follows:

$$n_{CO2\ g\ CH4} + n_{CO2\ l} = n_{total} \quad (7)$$

The total yield of methane from the feedstock is calculated as follows:

$$Y_{CH4} = \frac{(V_{CH4C} - V_{CH4e})}{S} = \frac{V_{CH4S}}{S}\left[lg^{-1}\right] \quad (8)$$

where:

$V_{CH4\ C}$ = the volume of methane obtained from the carbonaceous source

V_{CH4e} = the volume of methane obtained from the inoculum added

S = feedstock quantity at the start of the process [g]

The overall biodegradability is calculated as follows:

$$D_C = \frac{C_g}{C_s}.100 \quad (9)$$

where:

C_s = the amount of carbon in the original feedstock

C_g = the amount of carbon transformed into methane

C_g is calculated as follows:

$$C_g = \frac{12pV_{CH4S}}{RT} \quad (10)$$

where:

K = temperature (°K)

R = ideal gas constant

p = pressure

$V_{CH4\ S}$ = the total production of methane, which is diminished by the methane production of the inoculum

Results and discussion

At first, it should be stated that no trace of ZBTEX, £PAH, £AOH, XC10-C40 or ZPCB was detected in any of the analyzed feedstock (Table 1). Given that one of the latest analytical methods were used, it can be assumed that none of these substances is present in the samples. Traces of ZHM were detected (21.7 mg kg-1 at the most); however, the numbers are far below the values reported in other literature (Hafid et al. 2017). These results suggest that none of the downstream reactions was affected by the inhibition of anaerobic consortia (Kibler et al. 2018) and the materials obtained can be used for wider generalization. The characteristics of FW from households are revealed to be remarkably different from FW that originates in public catering. In particular, the dry matter content of household FW is significantly higher (by a fifth to a quarter more than public catering). In general, it is about 10% higher compared to earlier studies (Hafid et al. 2017). Dahiya et al. (2018) assume that a possible explanation is that an increasing number of households tend to compost biowaste in their gardens or use it to feed small animals (hens, pigs, and the like). Therefore, home FW waste consists increasingly of solid residues such as large bones or large pits of fruits. Similar results are reported by authors who conducted research in less populated areas (Xu et al. 2018). Household FW shows also remarkably low level of amyloids. It is assumed that lower content of starch in household FW is a result of better portions management (leaving for the next day), striving for a healthy diet, and tailor-made cooking (according to own taste). This is indirectly confirmed by low amounts of labile pool of carbon. Regarding public catering, FW from luxury restaurants is closest to FW from households. In comparison to other options of public catering, it shows the lowest amount of amyloids (less than 14%) and fat (as low as 3%) with a higher amount of crude fiber (only 2 less than in household FW). In agreement with Katajajuuri et al. (2014) this composition of food indicates a bigger share of fruit and vegetables and a smaller amount of carbohydrates. It shows out that the combination of these factors leads to lowest KN among all FW. FW from inexpensive restaurants revealed the highest levels of fat (more than 7%) and amyloids (almost 23%). These findings are in agreement with Chmiel et al. (2018), who indicate that these characteristics are related to cooking methods associated with reduction of production cost and with a typical offer in fast foods. Kim et al. (2011) pointed out that it is especially the high starch and fat values that make up the energy component of the FW that originates in inexpensive restaurants.

Table 1. FW characteristics, the confidence interval for significance level a = 0.05 was calculated according to a Q--test for low amounts of values. All the analyses were constant during the year (no analysis ever deviated from the average by more than 10%).

	School canteens FW	Luxury restaurants FW	Inexpensive restaurants FW	Home FW	Agricultural feedstock
Dry matter [% w/w]	45.9 ± 8.3	43.8 ± 5.7	40.6 ± 5.4	51.4 ± 3.9	19.3 ± 5.1
Crude fiber (cellulose + hemicellulose + lignin) [% w/w]	14.8 ± 2.7	25.2 ± 3.8	16.4 ± 2.8	27.1 ± 2.1	18.0 ± 1.2
Fat [% w/w]	7.2 ± 0.4	3.4 ± 0.5	7.4 ± 0.9	4.5 ± 1.0	2.8 ± 2.9
KN (mg kg^{-1})	27.2 ± 11.3	23.4 ± 4.2	25.9 ± 4.1	28.1 ± 2.2	10.3 ± 7.1
Amyloids [% w/w]	20.9 ± 3.3	13.9 ± 3.4	22.9 ± 3.3	10.5 ± 1.3	0.0 ± 0.0
CH_4 (L kg^{-1})	221 ± 41	243 ± 21	231 ± 53	238 ± 29	180 ± 17
Biodegradability (%)	42.5 ± 3.5	26.3 ± 3.8	44.9 ± 4.4	40.8 ± 3.7	38.2 ± 3.1
Labile pool of carbon (g kg^{-1})	504.0 ± 13.4	55.7 ± 7.7	630.6 ± 22.1	49.0 ± 8.3	75.3 ± 9.6
BOD (g kg^{-1})	92.6 ± 21.9	67.3 ± 15.5	96.0 ± 18.4	66.3 ± 22.1	52.3 ± 19.0
COD (g kg^{-1})	106.1 ± 8.9	94.7 ± 11.0	133.6 ± 14.8	90.3 ± 8.5	65.4 ± 10.1
HWN (g kg^{-1})	25.3 ± 4.5	21.1 ± 7.9	23.8 ± 5.4	26.7 ± 4.8	8.9 ± 4.2
ΣAOH (mg kg^{-1})	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
ΣBTEX (mg kg^{-1})	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
$\Sigma C_{10}–C_{40}$ (mg kg^{-1})	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
ΣHM (mg kg^{-1})	16.4 ± 1.2	17.5 ± 1.4	15.1 ± 1.0	21.7 ± 2.1	13.9 ± 3.5
ΣPAH (mg kg^{-1})	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
ΣPCB (mg kg^{-1})	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

Ghobadi et al. (2018) highlighted an increased fat content in inexpensive restaurants which is largely responsible for the high biogas yield, but also the low stability of the anaerobic fermentation process. Inexpensive restaurants and school catering showed a higher amount of fat and carbohydrates, revealing a higher amount of cheaper side dishes (sauces based on flour) and fatter (the cheapest) meat which altogether results in high BOD and COD. With regards to all the analyses, crude fiber represented by cellulose, hemicellulose, and lignin was in the range of 15% to 25%, which was almost identical to the findings of other studies (Pagliaccia et al. 2019). Carbohydrate content in the range of 10% to 20% and the highest levels of labile carbon (almost 631 g kg-1) is also in good agreement with other literature (Xu et al. 2018). The content of fat in all the investigated FW samples was 3.4% to 7.4% and its amount was generally lower than the amount found in comparable studies (Kim et al. 2011). Esteves and Devlin (2010) report equivalent fat content in an extensive study of FW in Wales. Pagliaccia et al. (2019) found slightly higher fat content in Intalian FW. Neves et al. (2008) report values up to three times higher from Portugal. Recalculated protein content, based on nitrogen concentration in the studied FW, varied analogously to the amount of fat. It was equal to the amount found in the studies already mentioned, about 1-5% lower than the amount reported by U^kun Kiran et al. (2014) and/or up to five times lower than the amount reported by Morales-Polo, Del Mar Cledera-Castro, and Moratilla Soria (2018). A higher amount of dry matter than in comparable studies was probably caused by a lower amount of water in the food. The FW from all types of public catering commonly had twice as much dry matter than the standard agricultural feedstock that, making its transport cheaper per energy unit. In general, the FW used in the presented study had a comparable amount of crude fiber and carbohydrates; nevertheless, the amount of fat and proteins was slightly lower than reported in the literature. Levels of labile pool of carbon, BOD, and COD are in good agreement with other literature (Dahiya et al. 2018). Following the above, it can be stated that the feedstock used is in no way exceptional and the subsequently obtained knowledge can be generalized.

As reminded in the Introduction chapter, in contemporary literature, there is a prevailing view that anaerobic fermentation should be optimized via TC/KN (Zhang et al. 2016) or TOC/KN (Fersiz et al. 2017). However, experiments with different mixtures of various FW and agricultural feedstock (Figure 1) indicate that the portability of this knowledge into FW fermentation process management has its limitations.

Function finder revealed that the most accurate function (in terms of lowest sum of absolute value of absolute error) to the data was z = a/(b+ cx+dy+fxy)+g, where a = 9.27 (std err = 5.13 10^{-4}; t-stat = 1.21 10^{-3}; p-stat 2.92 10^{-6}; 95% confidence intervals 7.73 10^{2} and 1.08 10^{2}); b = -3.08 (std err = 3.45 10^{-5}; t-stat = 3.73 10^{-2}; p-stat 5.66 10^{-3}; 95% confidence intervals 2.08 10^{2} and 2.45 10^{2}); c = -9.24 (std err = 8.37 10^{-4}; t-stat = 5.88 10^{-3}; p-stat 3.21 10^{-5}; 95% confidence intervals 3.38 10^{2} and 1.09 10^{2}); d = -1.47 (std err = 9.12 10^{-7}; t-stat = 6.53 10^{-4}; p-stat 4.31 10^{-5}; 95% confidence intervals 4.15 10^{2} and 2.03 10^{2}); f = 5.01 (std err = 2.77 10^{-5}; t-stat = 5.27 10^{-8}; p-stat 3.37 10^{-5}; 95% confidence intervals 8.31 10^{2} and 9.08 10^{2}) and g = 4.03 (std err = 2.74 10^{-5}; t-stat = 5.75 10^{-4}; p-stat 2.34 10^{-5}; 95% confidence intervals 7.73 10^{2} and 1.08102) showed the lowest sum of absolute value of absolute error (degrees of freedom (error) = 212; degrees of freedom (regression) = 210; x2 = 4.03; R2 = 0.81; R2 (adjusted) = 0.77); model F-statistic p-value = 4.13 10-14; model log-likehood = -124.46; root mean squared error = 3.22.

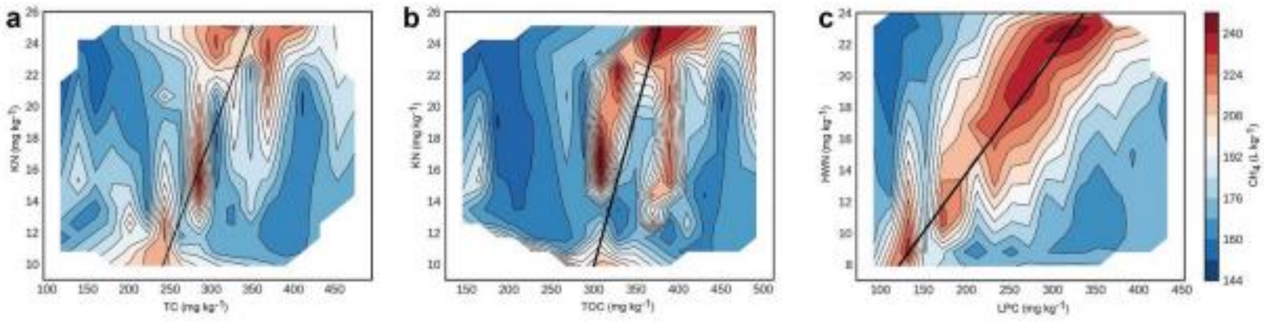

Figure 1. Methane yields visualization (wireframe three-dimensional contour via 3-dimensional function of the lowest sum of absolute value of absolute error) proves that analyzes that better reflect the biological acceptability of nutrients enable better control of process performance. A refers to routine TC/KN standard method, B refers to advanced TOC/KN method that is lately recommended in literature, and C refers to newly proposed LPC/HWN method.

Further analysis indicates that TN values (250-350 mg kg^{-1}) were corresponding to KN values of 10 up to 24 mg kg^{-1}, respectively, the TC/KN ratio was in the neighborhood of 15 (see the inclined black line in Figure 1 A). Given that recommended values for TC/KN are between 15 and 30 (Kibler et al. 2018), one can argue that reported data are, to a limited extent, but still in line with existing literature. TC/KN equal to 15 is not outside the recommended values and allows controlling the process so that it does not collapse (except for a small area around 320 mg kg^{-1} TC and 18 mg kg^{-1} CN). Nevertheless, data visualization clearly declares that this ratio is far from reliable across the whole range of samples and the speed of biogas production in the neighborhood of TC/KN equal to 15 is the slowest (on average 193.54 CH4 L kg^{-1} during 60 days), which hampers the process economy.

The ratio of TOC/KN (Figure 1 B) was detected in the neighborhood of 18 (TOC 300 up to 350 mg kg-1 and KN 10 up to 24 mg kg^{-1}). This value is close to the findings of Dai et al. (2016), who recommend the TOC/KN to be 17. Nevertheless, it should be noted that the finding of Dai et al. (2016) comes from the most widespread types of agricultural biogas plants. However, biogas plants that operate on farms process mainly phytomass feedstock that is of lignocellulosic nature with low levels of labile pool of carbon (Xu et al. 2018). A closer look to data visualization of TOC/KN reveals that the reliability of this method is only slightly better than the older TC/KN ratio and there are still significant opportunities in process optimization (area around 330 mg kg-1 TC and 13 mg kg^{-1} CN can significantly slowdown the fermentation process). Generally speaking, the biogas production is medium (on average 213.07 CH4 L kg^{-1} during 60 days), which makes it possible to produce more biogas in a shorter time and thus improve financial indicators.

Plotted results clearly show that the LPC/HWN ratio (equal to 14) shows the highest reliability (Figure 1 C). There is only one minor exception, in the immediate vicinity of 160 to 170 LPC mg kg^{-1} and 10 HWN mg kg-1. Average methane yield obtained is 226.44 CH4 L kg^{-1} during 60 days. Such a result can be interpreted as a 17% higher methane yield than with the oldest TC/KN method or a 6% higher methane production in comparison to the modern TOC/KN ratio. Given that the financial results of biogas plants are on average from more than half defined by revenues from biogas production (Stehel, Horak, and Vochozka 2019) and subsequent electricity sale (the rest are revenues from waste heat and fermentation residues, Machová and Vrbka 2018), one can assume that incorporation of LPC/HWN method might improve financial performance by more than 8% in comparison to conventional TC/KN method or by some 3% in comparison to process that is being managed by modern TOC/KN ratio. With regard to the economic considerations, it should also be reminded that KW showed more than double the amount of nitrogen in the fermentation residues; therefore, it creates new opportunities for nutrient recovery (Mardoyan and Braun 2015).

In summary, methane yield from FW in reported study is in the range of 0.22 to 0.25 L g^{-1} of dry mass. It was higher than 0.18 L g^{-1} found in the agricultural substrate that is routinely used in biogas plants. Such values are similar to 0.21 L g^{-1} of Neves et al. (2008) and other reports. Pagliaccia et al. (2019) reported 0.44 L g^{-1}; however, the higher utilization of organic matter in this study was caused by higher temperature (55°C). The thermophilic operation of a biogas plant compared to a mesophilic operation generally gives approximately one-third higher yield with up to 5% higher concentration of methane in the captured biogas; nevertheless, the energy consumption to heat the digester rises twofold (Maroušek et al. 2019b).

Conclusion

Anaerobic fermentation of FW contains reserves in biogas yield, which affects process economy. It is recommended to pay attention to the metabolic requirements of anaerobic microorganisms, in particular to their ability to obtain these key nutrients via their extracellular enzymes. The established analyses of TC/KN or TOC/KN that originate from experience with lignocellulose fermentation are not invalid and may prevent process collapse. However, to achieve better process optimization, it is recommended to better reflect the bioavailability of carbon and nitrogen and implement the newly proposed LPC/HWN analysis. Because FW is often rich in nitrogen, it is advisable to devote future research to nutrient recovery from fermentation residues. Further research should focus on finding methods that more accurately reflect the availability of key nutrients to consortia.

Nomenclature list

ADF	acid detergent fiber
AMN	anaerobically mineralizable nitrogen
BOD	biological oxygen demand
COD	chemical oxygen demand
Δp	pressure difference
FW	food waste
HWN	hot–water extractable nitrogen
KN	Kjeldahl nitrogen
LPC	labile pool of carbon
NDF	neutral detergent fiber
n	the number of gas moles
P	pressure
R	ideal gas constant (8.134 J mol °K^{-1})
$p0$	initial pressure
∑AOH	adsorbable organic halides
∑BTEX	sum of benzene, toluene and xylene isomers
$\sum C_{10}$–C_{40}	sum of aromatic hydrocarbon compounds that contain 10 up to 40 carbon atoms
∑HM	sum of heavy metals
∑PAH	sum of polyaromatic hydrocarbons
∑PCB	sum of polychlorinated biphenyl congeners
T	temperature
TN	total nitrogen
TON	total organic nitrogen
V	volume

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