Global J. Environ. Sci. Manage. 8(2): 225-236, Spring 2022, Serial #30

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

CASE STUDY

Laboratory analysis to determine the accurate characteristics of urban food waste

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ARTICLE INFO

Article History:
Received 25 June 2021
Revised 17 October 2021
Accepted 05 November 2021

Keywords:
Accurate determination
Characterization
Comparative analysis
Heat value
Waste management

ABSTRACT

BACKGROUND AND OBJECTIVES: Although the characteristics food waste have been well studied, some of the problems associated with result reporting have not been addressed. The related data are usually reported by referring to the global statistics, using the empirical models, and performing the laboratory analysis. The aims of the current study were to analyze the municipal food waste characteristics (including physical, proximate, ultimate and heating value analysis), monitor the differences among the laboratory methods, and highlight the significant differences among the food waste characteristics more accurately.
METHODS: Sampling was performed weekly at a disposal site located in Sari, Mazandaran, Iran. Food waste was extracted from the municipal solid waste samples. Moisture content, pH, organic matter, ash content, organic carbon, carbon to nitrogen ratio, low heating value and chemical equation of the waste were determined and compared by statistical indices.
FINDINGS: The results showed no significant difference between proximate analysis and global statistics for sampling including organic matter and moisture content. In ultimate analysis, statistical investigation of the laboratory results showed that Walkley and black, Kjeldahl, and dry ashing/ion chromatography methods had more accuracy compared to determination by elemental analyzer which puts direct impact on extracted chemical equation. In addition, heating value investigation by empirical models based on proximate analysis (13.6 MJ/kg) was closer to the bomb calorimeter results (13.4 MJ/kg) in average. However, the models developed based on ultimate analysis, including Dulong, Steuer, and Scheurer-Kestner, had a lower accuracy (with higher heating value of 1.4 to 5 MJ/kg). Surveying the reliable sources highlighted the gap in extracted chemical equation and heating value of the food waste with real amount. These findings provided appropriate information about solid waste management and characterization.
CONCLUSION: Investigation of the gap among laboratory methods revealed that determination method was a key factor in accurate characterization of food waste. Thus, without using the most accurate laboratory methods, the implementation of waste management plans would face major problems.

DOI: 10.22034/gjesm.2022.02.06

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
47	2	8

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Note: Discussion period for this manuscript open until July 1, 2022 on GJESM website at the "Show Article.

INTRODUCTION

Food waste (FW) contains a considerable portion of household solid waste with over 90% organic matter (OM) and 80% moisture (Meng *et al.,* 2015). FW includes fruits, vegetable scraps, and other organic discarded parts from households, institutional and industrial sources such as restaurants, school cafeterias, and canteens (Guo *et al.,* 2018). FW is mostly the kitchen waste produced by households and restaurant kitchens (Yang et al., 2013). The exponential increase in FW is regarded as a threat to the environment (Paritosh *et al.,* 2017). Adhikari *et al.* (2006) estimated that the annual amount of FW could increase from 278 to 416 million tons (2005-2025) in the Asian countries. FW accounts for 55% and 45% of the total municipal solid waste (MSW) produced in developing countries (Troschinetz and Mihelcic, 2009) and European countries, respectively (IPCC, 2006). According to the FAO, (2012) and the World Bank, (2012), approximately 1.3 billion tons of FW are generated in the food supply chain. However, a low percentage of the waste has been composted and much of it is disposed to the landfills or incinerated. EPA, (2016) estimated that FW, comprising 22% MSW, more than any other single material reached the landfills. The FW disposed at the landfill sites constitutes the largest source for emission of greenhouse gasses (Kamyab *et al.,* 2015a). In 2005, due to environmental impacts, Sweden applied a landfill prohibition on organic waste (EEA, 2013a). In addition, Germany has a ban on landfilling the unpretreated organic wastes (EEA, 2013b). Composting or energy recovery of food waste can be a sustainable solution for MSW management and may reduce the pressure on landfills (Kamyab *et al.,* 2015b). FW, as a large part of MSW, has been investigated by many researchers. According to Carmona-Cabello *et al.* (2018), FW chemical composition is the base of valorization process. Van Dooren *et al.* (2019) showed that bread (22%), dairy products (17%), vegetables (14%), fruit (12%) and meat (7%) were the main wasted food in Dutch households. Boumanchar *et al.* (2018) reported 50.5% carbon (C), 7.1% hydrogen (H), 2.1% nitrogen (N), 0.2% sulfur (S), 40.1% oxygen (O), 14.7 kJ/kg and higher heating value (HHV) as ash-free dry weight bases for FW ultimate analysis. Zhou *et al*. (2014) reviewed the physical and chemical compositions of MSW in China and found that food residue formed about 55.86% of the total MSW. They estimated the average moisture content of food residue (69.85%), ash content (20.98%), HHV (15,386 kJ/kg) as dry bases and proposed C257.3, H456.2, O168.3, N18, and S1 for chemical equation. Chen *et al.* (2019) studied the FW in Taiwan and recommended C333.3, H596.6, O183.3, N23.3, and S1 for chemical equation and 22.74 MJ/kg (dry basis) for HHV. Baawain *et al.* (2017) investigated MSW in Muscat and reported 40.5% carbon, 5.95% hydrogen, 2.39% nitrogen, 0.66% sulfur, 43.53% oxygen on dry mass for FW. However, Tchobanoglous *et al.* (1993) reported 70% moisture content, 48% carbon, 6.4% hydrogen, 2.6% nitrogen, 0.4% sulfur, 37.6% oxygen, 5% ash and 5.512 MJ/kg HHV (dry basis) as references for FW. The existence of accurate data on food waste characteristics, which has been poorly documented in Iran, is necessary in policy making and intervention strategies (van Herpen *et al.,* 2019). There are several problems for result reporting due to the complexities involved in data gathering and lack of a common ground on what is termed as FW (De Laurentiis *et al.,* 2020). Majority of the studies rely on secondary data sources which may not represent the accurate characterization of FW in the study area (Xue *et al.,* 2017) or, sometimes, the differences among the laboratory methods are not considered and investigated thoroughly by researchers. These defects have led to differences in the amount of FW reported and several inconsistencies in the characterization of FW (Adelodun *et al.,* 2021). Accordingly, the main study questions are: Which laboratory methods are more accurate in determining the important elements of FW such as organic carbon, nitrogen, sulfur, etc.? What are the differences between determining the heating value by bomb calorimeter and by empirical models? What are the differences between the chemical equation obtained from elemental analysis and secondary data sources? Such information is very important for MSW management planning (Raharjo *et al.,* 2018). Considering the inconsistencies in characterization of FW, direct characterization by different common laboratory methods is necessary to fill the knowledge and data gap in order to decide upon suitable FW management strategy. It is obvious that different factors, such as income level, consumption pattern, geographic location, source of energy, and climate, influence the waste characteristics in any region (Golhosseini and Jalili Ghazizadeh, 2021). The aim of this study was to statistically compare the common laboratory methods (namely proximate, ultimate and heating value analyses) used for the

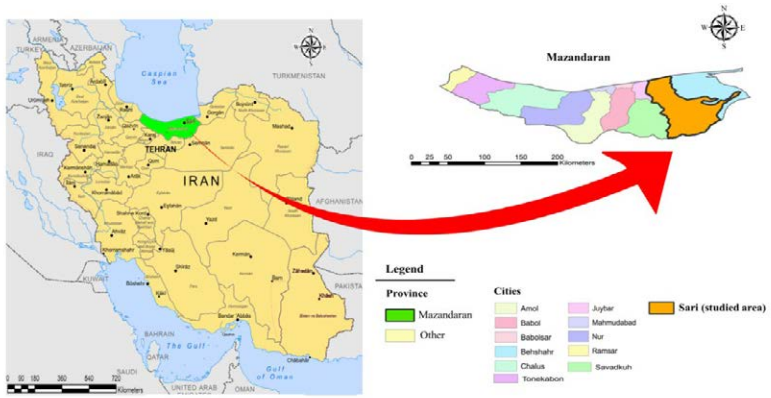

Fig. 1: Geographic location of the study area in Sari, Mazandaran Province, Iran

municipal food waste characterization in order to highlight the differences among them. Besides, comprehensive data on FW characterization in one of the Iranian cities was presented for the first time. In fact, the novelty of this work was establishing an infrastructure for laboratory characterization of FW to resolve the existing inconsistencies and present the characteristics of a region more accurately. To achieve these objectives, sampling was conducted at a disposal site located in Sari, Mazandaran province, Iran in 2021.

MATERIALS AND METHODS

The methods which were based on international standards for waste and recommended in Iran were selected for investigation. These methods had been used in various laboratories and studies to characterize the waste. Thus, their comparative analysis could provide a proper insight for choosing the most accurate method. As previously discussed, FW forms the largest fraction of waste reaching the landfills and is usually separated from other parts to recycle. Therefore, determining the accurate characteristics of FW may be helpful in making the right decision for their management.

Study area

This study was conducted in Sari, Mazandaran province, located in the north of Iran, where the summers are hot, muggy, dry, and clear and the winters are cold and partly cloudy. In this area, the annual temperature typically varies between 2 °C and 32 °C and rarely drops to -2°C or reaches 36° C (Weatherspark, 2021). Sari, as the capital city, is the largest and the most populous city of Mazandaran province. It is located between the northern slopes of the Alborz mountains and the southern coast of the Caspian Sea, and lies between latitudes of 360 33’ and 47.95” N and longitudes of 530 03’ and 36.32” E (Fig. 1).

Sampling and physical composition

MSW sampling was performed weekly at a disposal site located in the study area (ASTM D5231-92, 2016). The sampling plan was based on random truck sampling determined by considering the available facilities and background information on the site location. About 50 kg garbage was randomly picked up from the arrival trucks of each zone and then mixed to make approximately 1 ton MSW for physical analysis. The sample was separated into eight major categories including food waste, plastics, rubber and leather, paper and cardboard, textiles, none flammable materials, woods, and other substances. Then, the extracted FW was prepared for laboratory analysis by quartering method. The age of the samples was about 24 hours since, in Sari, the households waste is daily gathered by the MSW collection system.

Analytical methods

The moisture content was determined according to the standard test method for moisture trough the analysis of coal and coke samples with the help of an electronic oven (Memmert, UNE 400, Germany) (ASTM D3173, 2017). OM and ash content were determined by ignition loss of the oven-dried sieved sample in a muffle furnace according to the standard

test method (ASTM D3174-12, 2018). In order to determine pH, each sample was mixed with water in 1:10 to make a solution and shaked at 300 rpm for 30 min (Sánchez-Monedero *et al.,* 2001). Elemental analysis including carbon, hydrogen, oxygen, nitrogen, and sulphur (CHONS) was conducted in an elemental combustion system (4010 CHONS analyzer, Costech, Italy) to obtain the weight percent of CHONS and chemical composition of food waste according to ASTM E777-17a, (2017) for carbon and hydrogen, and ASTM E775-15, (2021) and ASTM E778-15, (2021) for sulfur and nitrogen, respectively. Oxygen was measured by difference which is a common method in the laboratories with adequate instrument. Elemental analyzer instrument, through separate analysis of each element in the laboratory, makes the determination and comparison easier and provides other fundamental information on 1) Determining heating value according to chemical equation, 2) Determination of the C/N ratio as an important indicator, 3) Comparing the C and N values with the values obtained from other measuring methods, and 4) The data used to calculate the theoretical maximum biogas yields. In addition, the total organic carbon (TOC) for the assessment of the C/N ratio was determined via two different ways to compare and define the most suitable method. These two methods were 1) Dichromatometric oxidation (Walkley and Black, 1934), and 2) Applying a suitable factor of transformation to the total organic matter content (1/1.724) determined by ignition loss as 'Van Bemmelen' factor which is commonly used in soil organic matter studies (Heaton *et al.,* 2016). In addition to the elemental analyzer method, Kjeldahl method (Vapodest 30s, Gerhardt, Germany), which has been widely used to determine the nitrogen of waste, soil and compost in Iran, was used to determine the total Kjeldahl nitrogen (TKN). This method is typically used for the analysis of total sulfur and involves dry ashing followed by sulfate detection with ion chromatography (Dry ashing/IC method). The dry ashing/IC method was also applied to compare the results of the elemental analyzer method. In addition to the empirical models described in Table 1, a bomb calorimeter was used to determine the heating value of the FW samples (Chang *et al.,* 2007). Empirical models are more commonly used because they present more comparable data by relying on secondary sources instead of laboratory analyses which may not be accurate. This inconsistency has been highlighted in this study.

All the mentioned methods were also in accordance with the Iranian national standards. All the analyses were carried out in triplicate, and the deviation, averages, and correlation were investigated by the t-test and analysis of variance (ANOVA) to show the significant difference among the laboratory methods. In fact, ANOVA checks the impact of one or more factors by comparing the means of different samples, and helps to find out if there is a difference among the groups or not.

RESULTS AND DISCUSSION

The conducted laboratory analyses on MSW composition and physical and chemical properties of FW as well as heating value analysis of FW are described in the following sections.

Physical composition of MSW

Waste composition is influenced by many factors such as income level, level of economic development, cultural norms, geographical location, energy sources, and climate in any region (Golhosseini and Jalili Ghazizadeh, 2021). According to the World Bank report (2018), Iran is located in the Middle East and North Africa region (MENA) where FW is the predominant type of waste (Kaza *et al.,* 2018). Table 2 shows the extracted physical compositions of MSW in different regions of

Table 1: Heat value models based on physical, proximate and ultimate analyses

Models*	Equations	Reference
Proximate analysis:		
LHV =45B-6W	Traditional Eq.	JNMSWF, 1991
LHV =44.75B-5.85W+21.2	Bento's Eq.	JNMSWF, 1991
Ultimate analysis:		
LHV = 81C + 342.5(H-O/8) + 22.5S - 6(9H+W)	Dulong's Eq.	Wilson, 1977
LHV = 81(C-3xO/8) + 57x3xO/8 + 345(H-O/16) + 25S - 6(9H+W)	Steuer's Eq.	Wilson, 1977
LHV = 81 (C-3xO/4) + 342.5H + 22.5S + 57x3xO/4 - 6(9H+W)	Scheurer-Kestner's Eq.	Wilson, 1977

* LHV = Low heating value (Kcal/Kg); B = Combustible volatile matter (%); W = Moisture content (wt %); C = Carbon content (wt %); H = Hydrogen content (wt %); S = Sulfur content (wt %); O = Oxygen content (wt %), JNMSWF: Japan National Municipal Solid Waste Foundation.

Table 2: The mean average physical compositions of MSW in different regions (dry base wt %)

Region[1]	Paper	Woods	Rubber and leather	Plastic	Food waste	Other	Non-flammable
MENA	13	1	2	12	58	8	6
South Asia	10	1	2	8	57	15	7
East Asia and Pacific	15	2	1	12	53	12	5.6
Europe and Central Asia	18.6	1.6	1	11.5	36	21	11
Sub-Saharan Africa	10	1	-	8.6	43	30	8
Latin America and the Caribbean	13	1	1	12	52	15	7
North America	28	5.6	9	12	28	3.6	13.8
Global	17	2	2	12	44	14	9
Current study[2]	12.4	3.3	0.1	5	58.7	16.5	4

[1] All the data is according to the World Bank report (Kaza *et al.,* 2018)
[2] The data are the average of seven consecutive days sampling

the world. Obviously, weight fraction of FW has the highest percentage among other components of MSW. The results indicated a good conformity between the literature and the field study on FW generation. Thus, the secondary source showed no significant difference in determining the percentage of FW in MSW. Zhou *et al*. (2014) reported that food residue formed about 55.86% of the total MSW. However, the amounts of FW generated significantly differed depending on housing types and seasons (Adelodun *et al.,* 2021).

Physical and chemical properties of FW

Heterogeneous nature of FW, as a critical problem of using it as a resource, requires a comprehensive analysis of its physicochemical properties (Bayard *et al.,* 2018).

Proximate and ultimate analyses

Proximate analysis of FW covering its moisture content, pH, organic matter and ash was performed in triplicate, and the average values were presented (Table 3). The results were compared to the data presented in the environmental engineering book published by Kiely, (1997) as a secondary source. Moreover, ultimate analysis was used to determine the percentage of each individual element in the FW including carbon, hydrogen, oxygen, nitrogen, sulfur, and ash. For better comparison, the typical data on ultimate analysis of FW were presented according to the well-known solid waste management books written by Tchobanoglous, *et al.* (1993) and Pichtel, (2005) (Table 3). These books were employed to compare the results obtained in the current study. According to Table 3, in the proximate analysis, the results of moisture content and OM represented a high precision besides good accuracy relative to the reference (70%). Carmona-Cabello *et al.* (2020) reported a heterogeneous composition of FW with moisture content of 52.1 to 73.9%. In the ultimate analysis, the average contents of hydrogen (7.15%) and oxygen (35.17%) were close to the reference, while those of carbon (41.91%), nitrogen (1.96), sulfur (0.87%) and ash (12.94%) were far from the reference (carbon 48%, hydrogen 6.4%, nitrogen 2.6 0%, sulfur 0.4%, oxygen 37.6% and ash 5%). Baawain *et al.* (2017) investigated FW in Muscat and reported carbon, hydrogen, nitrogen, sulfur and oxygen as 40.5%, 5.95%, 2.39%, 0.66%, and 43.53%, respectively. However, Boumanchar *et al.* (2018), in their study, reported carbon, hydrogen, nitrogen, sulfur, and oxygen as 50.5%, 7.1%, 2.1%, 0.2%, and 40.1% for FW, respectively. In the present study, the coefficients of variation were higher in C, N, S, C/N, and ash than in H and O contents. This difference could be attributed to two factors: 1) the nature of FW that varied in any region (Golhosseini and Jalili Ghazizadeh, 2021), and 2) application of different measurement methods which may lead to different results. Therefore, for better investigation, the parameters, such as carbon, nitrogen, sulfur, and ash, in two or three determination methods were compared and the obtained results were analyzed using the t-test and ANOVA or other statistical indexes.

Nitrogen determination

Nitrogen determination was done using two common methods: 1) CHONS analyzer, 2) and TKN (Table 4). Using the TKN, the values were found to be in the range of 1.3% and 3.25% with an average value of 2.3% ± 0.57% (Selvam *et al.,* 2021). An independent samples t-test was also done as shown in Table 5. As can be seen in Table 6, at a confidence level of 95%, data significance (sig) parameters were higher than

Table 3: Proximate and ultimate analyses of the food waste*

n\Statistical items\Ref	Proximate analysis (wt%)				Ultimate analysis based on elemental analyzer (wt%)						
	MC_w	OM_d	A_d	pH	C	H	O	N	S	A_d	C/N
1	73	89.6	10.4	6.15	43.1	7.8	38.05	1.53	0.8	8.72	28.17
2	70.3	81.6	18.4	6.42	41.27	7.08	35.01	2.34	1	13.3	17.64
3	68	84.4	15.6	6.21	42.35	7.2	36.89	1.38	0.8	11.38	30.69
4	72.8	82.6	17.4	6.44	45.6	6.85	31.7	2.1	0.75	13	21.71
5	71.2	75.5	24.5	7.02	34.59	6.9	37.55	1.96	0.7	18.3	17.65
6	70.7	82.2	17.8	6.75	47.49	7.3	29.85	2.43	1.12	11.81	19.54
7	74.3	77.9	22.1	6.43	38.94	6.95	37.15	1.96	0.9	14.1	19.87
Ave	71.5	81.97	18.02	6.49	41.91	7.15	35.17	1.96	0.87	12.94	22.18
SD	2.09	4.53	4.53	0.30	4.27	0.33	3.19	0.39	0.14	2.94	5.20
SE	0.79	1.71	1.71	0.11	1.61	0.12	1.21	0.15	0.05	1.11	1.96
CV%	2.92	5.53	25.13	4.68	10.18	4.58	9.08	19.86	16.04	22.68	23.42
Kiely, 1997	70	83.3	16.7	-	-	-	-	-	-	-	-
Pichtel, 2005	-	-	-	-	48	6.4	37.6	2.6	0.4	5	18.46

*n: Sample's number; Ref: Reference; w: Wet basis; d: Dry basis; N: Number of samples; Ave: Average; SD: Standard deviation; SE: Standard error; CV: Coefficient of variation.

Table 4: Ash, nitrogen and sulfur determination in the samples through different laboratory methods

Component	Methods	1	2	3	4	5	6	7	Ave
Ash	CHONS analyzer	8.72	13.3	11.38	13	18.3	11.81	14.1	12.94
	Furnace	10.4	18.4	15.6	17.4	24.5	17.8	22.1	18.03
N	CHONS analyzer	1.53	2.34	1.38	2.1	1.96	2.43	1.96	1.95
	Kjeldahl	1.68	1.835	1.7	1.648	1.742	1.98	1.918	1.78
S	CHONS analyzer	0.8	1	0.8	0.75	0.7	1.08	0.9	0.86
	Ashing/IC	0.65	0.9	0.71	0.67	0.65	0.92	0.82	0.76

0.05. It meant that the variance and average of two groups were not significantly different from each other. However, the value of coefficient of variation (CV) in the Kjeldahl method was lower (7.12%) than its value in the CHONS analyzer determination (19.86%). Thus, it could be concluded that Kjeldahl method was more precise than elemental analyzer, and both methods led to lower average results compared to the mentioned references.

Sulfur determination

The results of determining the total sulfur by dry combustion method (elemental analyzer) and ashing/ion chromatography method have been shown and compared in Tables 4 and 5. Evidently, the sulfur content in the elemental method was slightly higher than its content in the Ash/IC method. However, other statistical indexes showed a perfect agreement between both methods, implying that there was no significant difference between them. Comparison of the results indicated that both methods were precise and the sulfur content of the FW was approximately twice the content mentioned in the references, which was the characteristic of the FW in the studied region.

Ash determination

Considering the waste samples in the CHONS analyzer and ash as the final residual, the ash percent of each sample was calculated (Table 4). In other methods, the ash percent was determined through sample combustion in 550 ^{0}C in a furnace for approximately 4 hours. The results have been shown in Table 5 and the variances are compared using the t-test (Table 5). Obviously, at a confidence level of 95%, sig>0.05 meant that the variances of two groups were equal, while sig. (2-tailed)<0.05 meant that the averages were not equal and significantly differed. The CV was not significantly different in furnace method and CHONS analyzer, implying that both methods were precise. It should be noted that OM also plays an

Table 5: Comparing the laboratory methods by independent samples t-test

t-test	Ash		N		S	
	CHONS analyzer	Furnace	CHONS analyzer	Kjeldahl	CHONS analyzer	Ashing/IC
Number of samples	7	7	7	7	7	7
Mean	12.9443	18.0286	1.9571	1.7861	0.86	0.76
SD	2.93619	4.53016	0.38862	0.1272	0.14	0.12
SE	1.10977	1.71224	0.14688	0.04808	0.05	0.04
%CV	22.68	25.13	19.86	7.12	14.85	14.38
Sig.*	-	0.423	0.071	-	0.728	-
Sig. (2-tailed)	-	0.028	0.29	-	0.165	-

*Significance

Table 6: Statistical analysis of carbon determination, test of homogeneity of variances, ANOVA, and multiple comparisons through different laboratory methods

Component	Methods	1	2	3	4	5	6	7	Ave
C	Elemental analyzer	43.1	41.27	42.35	45.6	34.59	47.49	38.94	41.91
	Walkley and Black	48.7	37.8	48	37	30.8	42	33.8	39.73
	Van Bemmelen	49.78	45.33	46.89	45.89	41.94	45.67	43.28	47.55

Test of homogeneity of variances (VAR00001)			
Levene statistic	df1+	df2	Sig.
3.774	2	18	0.043

ANOVA (VAR00001)					
	Sum of Squares	df	Mean square	F	Sig.
Among groups	227.957	2	113.978	4.763	0.022
Within groups	430.696	18	23.928		
Total	658.652	20			

Multiple comparisons (Dependent variable: (VAR00001) Games-Howell				
(I) Method	(J) Method	Mean Difference (I-J)	SE	Sig.
Elemental analyzer	Walkley and Black	2.17714	3.04439	0.760
	Van Bemmelen	-5.64143*	1.89361	0.034
Walkley and Black	Elemental analyzer	-2.17714	3.04439	0.760
	Van Bemmelen	-7.81857	2.76681	0.054
Van Bemmelen	Elemental Analyzer	5.64143*	1.89361	0.034
	Walkley and Black	7.81857	2.76681	0.054

+ df: Degrees of freedom.
* The mean difference is significant at the 0.05 level.

important role in select the accurate method. Referring to Table 3, the OM determination using furnace gives both precise and accurate values for FW according to the global statistics with low SD and CV. Consequently, the ash content left over from furnace gave a more accurate value compared to the elemental analyzer method.

Total organic carbon determination

As previously mentioned, TOC was determined in three ways. TOC and total carbon as well as TKN and total nitrogen sometimes have been used ambiguously. Selvam *et al.* (2021) reported that the TOC values of FW from a canteen in Beijing ranged from 29.7% to 56.3% with an average value of 45.6% ± 9.8% which can be compared to the value obtained in the present study. Analysis of variance followed by the Games-Howell Post Hoc test was conducted for carbon determination methods according to Table 6. Results of variance homogeneity (sig=0.043<0.05) showed that variances of the three methods were not equal, and ANOVA test (sig=0.022<0.05) showed that the group means were not equal. Thus, the Post-Hock multiple comparison demonstrated that the Van Bemmelen method had a significant difference with the other two methods. CV values in the Walkley and Black method and Elemental analyzer were 10.2% and 17.2%, respectively. The results showed that organic carbon determination by the Walkley and black method was more precise compared to the other two methods. The

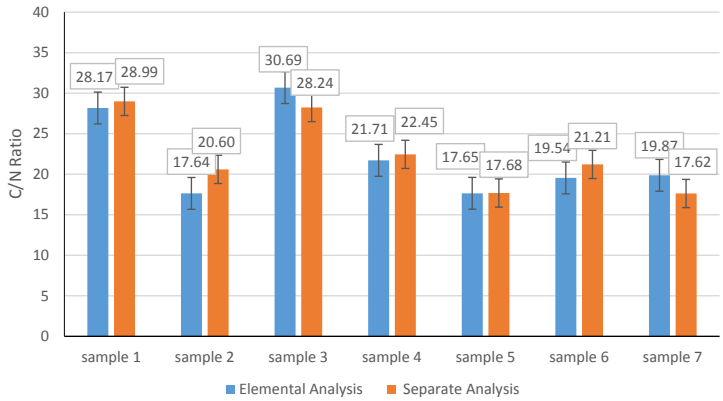

Fig. 2: Carbon to nitrogen ratio of food waste in different methods

low heating value (LHV) of the samples determined by bomb calorimeter method demonstrated that TOC determination by the Walkley and Black method led to closer results when it was used in different empirical models compared to determination of C by elemental analyzer. Thus, the Walkley and Black method was more accurate method rather than other two methods.

C/N ratio determination

Carbon to nitrogen ratio is one of the major parameters in controlling the nutrient balance in composting process (Norbu *et al,* 2005). It can help to determine the biodegradability of any biomaterial (Lü *et al.,* 2018). The C/N ratio of FW ranges from 9.3 to 24.5 with an average value of 17.3 ± 3.7 (Selvam *et al.,* 2021). For better investigation, the C/N ratios obtained from separate analysis (Walkley and Black plus Kjeldahl method) and elemental analyzer are compared (Fig. 2).

Statistical investigations showed that the average and variances were not significantly different from each other. However the CV value in a separate analysis (19.03%) was lower than its value in the elemental analyzer (21.69%). As already discussed, separate analysis of C and N was more precise and accurate. Thus, the average C/N ratio of the separate analysis (22.4), which was higher than the reference (18.46) and the average C/N ratio (14.9-16) reported by Carmona-Cabello *et al.* (2020), could be reported as an accurate amount for FW in this region (Pichtel, 2005).

Heating value

The heating value of FW was determined by a laboratory bomb calorimeter and calculated based on empirical models according the proximate and ultimate analyses results. Table 7 shows the results obtained from different samples compared to the LHV extracted from the reference (Tchobanoglous *et al*., 1993).

The models developed based on proximate analysis (Traditional: 13.64 and Bento: 13.68 MJ/kg) showed an almost better conformity (p-value <0.05) with the lab scale analysis (13.38 MJ/kg) because there was no different parameter determination methods in the proximate analysis (OM and MC). On the other hand, most of the empirical models developed based on the ultimate analysis, which had been obtained by elemental analyzer, had a significant difference (p-value <0.05) with the results of bomb calorimeter, except for the Dulong's equation which gave the closest results (14.82 MJ/kg) compared to Steuer's equation (16.71) and Scheurer-Kestner's equation (18.47 MJ/kg). Knowing that C was a key factor in LHV calculations, the average TOC obtained by the Walkley and Black method was replaced by the average TOC obtained by the elemental analyzer method, leading to more accurate results in the bomb calorimeter method in all models. This provided stronger reasons for achievement of more accurate data on FW characterization by separate analysis. In addition, the heating values of FW based on the secondary source elemental analysis (Table 2) were very far from the real amount (2.15 to 6.06 MJ/kg) (Tchobanoglous *et al*., 1993). Chen *et al.* (2019) studied the FW in Taiwan and reported 22.74 MJ/kg (dry basis) higher heating value. Zhou *et al*. (2014) reviewed the physical and chemical compositions of MSW in China and reported 15,386

Table 7: LHV based on bomb calorimeter test (MJ/kg) compare to other models (dry basis) (Tchobanoglous *et al.*, 1993)

Sample No.	Model based on lab scale analysis	Models based on ultimate analysis			Models based on proximate analysis	
	Bomb calorimeter	Dulong's equation	Steuer's equation	Scheurer-Kestner's equation	Traditional equation	Bento's equation
1	11.75	15.45	17.49	19.40	15.03	15.07
2	13.07	14.59	16.47	18.22	13.59	13.64
3	14.11	14.80	16.77	18.63	14.18	14.22
4	11.15	16.28	17.99	19.57	13.72	13.77
5	12.93	11.60	13.60	15.50	12.42	12.48
6	14.74	17.88	19.50	20.98	13.70	13.75
7	15.96	13.15	15.14	17.00	12.80	12.85
Ave.	13.38	14.82	16.71	18.47	13.64	13.68
Reference	-	15.53	17.53	19.44	13.89	13.97

Table 8: Chemical equation (with water) for determination of food waste in different ways (Tchobanoglous *et al.*, 1993)

N	Based on elemental analyzer	Based on the most accurate method	Reference
1	$C_{143.8}H_{1501.9}O_{697.5}N_{4.38}S_1$	$C_{162.5}H_{1501.9}O_{697.5}N_{4.8}S_1$	$C_{320.43}H_{2566.07}O_{1227.72}N_{14.88}S_1$
2	$C_{110.2}H_{1059.9}O_{491.9}N_{5.36}S_1$	$C_{100.9}H_{1059.9}O_{491.9}N_{4.2}S_1$	
3	$C_{141.3}H_{1222.9}O_{565.68}N_{3.95}S_1$	$C_{160.2}H_{1222.9}O_{565.68}N_{4.8}S_1$	
4	$C_{162.3}H_{1549}O_{720.5}N_{6.41}S_1$	$C_{131.7}H_{1549}O_{720.5}N_5S_1$	
5	$C_{131.9}H_{1559}O_{736.7}N_{6.4}S_1$	$C_{117.5}H_{1559}O_{736.7}N_{5.7}S_1$	
6	$C_{117.4}H_{1002.9}O_{453.46}N_{5.15}S_1$	$C_{103.8}H_{1002.9}O_{453.46}N_{4.42}S_1$	
7	$C_{115.5}H_{1378.5}O_{655}N_5S_1$	$C_{117.9}H_{1378.5}O_{655}N_{4.9}S_1$	
Ave.	$C_{129.9}H_{1286.2}O_{598.2}N_{5.2}S_1$	$C_{125.8}H_{1286.2}O_{598.2}N_{4.7}S_1$	

kJ/kg as dry basis for FW. It could be concluded that it was not wise to conduct waste management planning based on secondary sources and literature without a comprehensive laboratory analysis.

Chemical equation

After determining the most accurate method, the chemical fequation based on elemental analysis, the best laboratory method and the mentioned references were compared (Table 8).

Unlike heating value, the average FW chemical equation was not significantly different in the elemental analyzer and laboratory determination methods, except for in C and N contents. It was, however, significantly different from the average FW chemical equation in the references (Tchobanoglous *et al.*, 1993). In addition, some researchers obtained the chemical equation of FW. For example, Chen *et al.* (2019) reported $C_{333.3}H_{596.6}O_{183.3}N_{23.3}S_1$ the chemical equation of FW in Taiwan, and Zhou *et al.*, (2014) reported $C_{257.3}H4_{56.2}O_{168.3}N_{18}S_1$ as the chemical equation of FW in China. The big gaps among the chemical compositions of FW indicated the complex nature of waste in different regions. Therefore, the FW chemical equation referring to a reliable source or literature did not have a good accuracy and required a comprehensive laboratory analysis.

CONCLUSION

The FW was extracted from MSW and subjected to a comprehensive comparative laboratory analysis to determine the accurate methods and characteristics. The results showed the high precision and consistency of the physical composition of the prepared MSW (especially in the FW by 58.7%, moisture content by 71.5%, organic matter by 81.9%, oxygen by 35.1%, and hydrogen content by 7.1%) with the global statistics. Compared to the analysis of instrumental elements, carbon determination based on the Walkley and Black method, nitrogen based on Kjeldahl method,

sulfur based on Ion chromatography method and ash determination using furnace had higher precisions. Investigation of the heating value presented a good conformity of the models developed based on proximate analysis, including traditional (13.64 MJ/kg) and Bento's equations (13.68 MJ/kg), with the laboratory results (13.38 MJ/kg). The models developed based on ultimate analysis, including Dulong (14.82 MJ/kg), Steuer (16.71 MJ/kg), and Scheurer-Kestner (18.47 MJ/kg), led to lower accuracies and higher LHVs (1.4 to 5 MJ/kg) compared the bomb calorimeter method (13.38 MJ/kg). For FW, the heating value extracted from the secondary data sources ranged 15.5-19.4 MJ/kg, while the real amount was 13.38 MJ/kg in average in the study area. The final chemical equation ($C_{125.8}H_{1286.2}O_{598.2}N_{4.7}S_1$) was obtained according the most accurate determination methods for the FW. However, the secondary data sources presented a different chemical equation ($C_{320.43}H_{2566.07}O_{1227.72}N_{14.88}S_1$). The results from this study could establish an infrastructure for the laboratory characterization of FW and resolve the inaccuracies and inconsistencies. It could also help in representing the characteristics for any region more accurately and implementing proper waste management plans such as composting or energy recovery. The limitations faced in this study were the existing knowledge gap for characterization of FW in Iran and the fact that FW characteristics could be influenced by many parameters. Further studies should be conducted to extend the related knowledge at regional or national level. Moreover, the characteristics of the MSW, from which the FW was extracted, and validation of leachate characteristics could be investigated in future studies.

AUTHOR CONTRIBUTIONS

A. Charkhestani performed the experiments and literature review, gathered data, compiled the data, analyzed and interpreted the data, prepared the manuscript text. D. Yousefi Kebria performed the manuscript edition.

ACKNOWLEDGEMENT

The authors would like to acknowledge Shiraz Municipality Waste Management Organization for providing a specialized laboratory of waste for performing the laboratory analyses.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

ANOVA	Analysis of variance
A_d	Ash (dry basis)
ASTM	American Society for Testing and Materials
Ave	Average
C	Carbon
CHONS	Carbon, Hydrogen, Oxygen, Nitrogen, and Sulfur
C/N	Carbon to nitrogen ratio
CV	Coefficient of variation
d	Dry basis
df	Degrees of freedom
Eq.	Equation
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
F	Frequency
FW	Food waste
H	Hydrogen

HHV	High heating value
IC	Ion chromatography
IPCC	Intergovernmental Panel on Climate Change
JNMSWF	Japan National Municipal Solid Waste Foundation
Kcal/kg	Kilocalories per kilogram
kJ/kg	Kilojoules per kilogram
LHV	Low heating value
MC	Moisture content
MJ/kg	Megajoules per kilogram
MSW	Municipal Solid Waste
MENA	Middle East and North Africa
n	Sample number
N	Nitrogen
O	Oxygen
OC	Organic carbon
OM	Organic matter
pH	Power of hydrogen
P-Value	Probability value
Ref.	Reference
rpm	Round per minute
S	Sulfur
SD	Standard deviation
SE	Standard error
Sig	Significance
TKN	Total Kjeldahl nitrogen
TOC	Total organic carbon
TOM	Total organic matter
w	Wet basis
Wt	Weight

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HOW TO CITE THIS ARTICLE

Charkhestani, A.; Yousefi Kebria, D., (2022). Laboratory analysis for determining the accurate characterizations of urban food waste. Global J. Environ. Sci. Manage., 8(2): 225-236.

DOI: 10.22034/gjesm.2022.02.06

url: https://www.gjesm.net/article_247092.html