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Study on morphological composition of waste and the estimation of greenhouse gases from waste landfilling from the Republic of Moldova

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Abstract
The paper summarizes the research results on the development country specific emissions factors for the Greenhouse Gas Inventory (GHGI) for Source Category "5A Solid Waste Disposal on Land", namely the degradable organic carbon (DOC), fraction of degradable organic carbon which decomposes (DOCf) and fraction of methane. The factors are determined based on the results of the survey on composition of municipal solid waste, which was investigated during one year in the Republic of Moldova: from spring 2023 to 2024. The obtained on morphological composition and results refer to three seasons: spring, summer and autumn and offer the opportunity to observe the variations among the seasons. After finalizing the survey on morphological composition, the final results will be used for estimation of country specific emission factors, which will allow to estimate accurately the emissions of methane from landfilling of waste in the Republic of Moldova, necessary for development of policy framework and tracking the progress in achievement of NDC. It will also improve the Intergovernmental Panel for Climate Change (IPCC) methodologies and Emission Factors for assessing the GHG emissions originated from waste sector.

Keywords: *municipal waste, solid waste disposal site (SWDS), greenhouse gas, methane emissions, landfill gas, emission factors (EF)*

INTRODUCTION

Waste composition and characteristics are determinative in selecting technological alternatives to develop waste management strategies that can meet legislative requirements. However, assessment of possible technologies and scenarios within the framework of economic considerations is inevitable to obtain a sustainable waste management system. That is why solid waste management practices may vary in different countries having similar waste compositions and/or legislative considerations.

For example, in European countries, Landfill Directive 1999/31/EC [1] and Waste Framework Directive [2] introduced strict technical requirements for waste and landfills for preventing and reducing the negative effects of waste landfilling on environment. Landfilling accounted for 23 percent of EU municipal waste treatment in 2021. While the amount of municipal waste generated in EU has remained more or less stable in the past two decades, the share that is landfilled has fallen considerably. In 2021, recycling accounted for more than 30 percent of municipal waste managed in the European Union (EU-27). When combined with compositing, the overall recycling rate in the EU stood at almost 50 percent in 2021 [3].

Current situation with the management of municipal solid waste in Moldova is similar to the situation in other developing countries; it is in the budding stage and includes two basic elements: municipal solid waste generating sources and the landfills. In Moldova, the total Municipal Solid

Waste (MSW) generated in 2021 is 1.26 Mt., where 90 % of that waste was sent to landfills and only 10% are recycled. The biodegradables consist of more than 60% of MSW, while the share of recyclables vary between 5%÷12 %

The generating process of municipal solid waste is influenced by multiple factors, the most relevant being the population income, consumer behavior, the use of new packed products, as well as the demographic evolution. The recent increase in the wellbeing of the population and the evolution of the urbanization process resulted in an increased waste generation rate per capita, varying, according to the World Bank's studies, between 0.3 kg/per capita/day and 0.4 kg/per capita/day in rural areas and around 0.9 kg/per capita/per day in urban areas [4].

Republic of Moldova have identified waste as one of the key sectors to achieve their National Determined Contributions under the Paris Agreement. Though the waste sector emits less Green House Gases (GHG) compared to other sectors such as energy, it offers enormous opportunities of emission reduction. Moldova committed to reduce until 2030 GHG from the waste sector by 14% in unconditional scenario and 18% in the conditional, compared to 1990 [5].

According to the last GHG inventory data, waste sector accounts for 10,19% of the total national direct greenhouse gas emissions in the Republic of Moldova in 2021 (without the contribution of sector 4 "Land use, land use category change and forestry"), being the third major source of GHG emissions after the energy and agriculture sectors, while in 1990 is accounted for 3,72 % (see Fig. 1). It should be noted that sector 5 "Waste" represented a major source of CH_4 emissions, with a share of about 59 % of the total methane emissions recorded at the national level in 2021 [6].

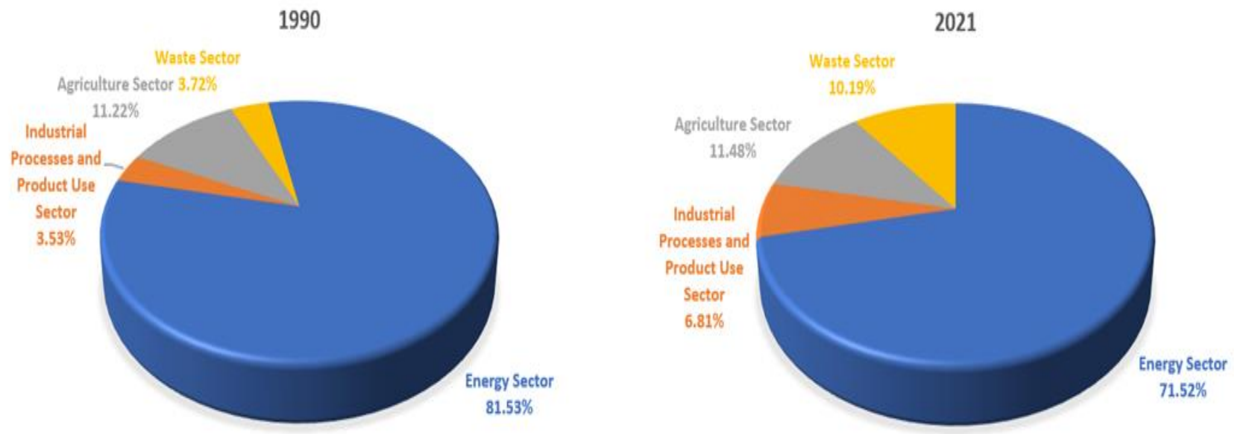

Fig. 1 Sectoral breakdown of the Republic of Moldova's total GHG Emissions in 1990 and 2021 years

Between 1990 and 2021, the total GHG emissions originating from Sector 5 'Waste' decreased from 1,690.2 kt CO_2 equivalent in 1990 to 1,490.4 kt CO_2 equivalent in 2021. The economic growth recorded in the last 20 years resulted in a higher level of welfare and industrial production, and increased consumption, which also results in a greater capacity to generate waste [6].

The impact of waste on the environment has alarmingly increased in recent years, and its mismanagement leads to contamination of soil and groundwater, as well as CH_4, CO_2, and toxic gas emissions with direct effects on public health and the environment.

Between 1990 and 2021, methane emissions from source category 5A 'Solid Waste Disposal' decreased by circa 6.5 %, from circa 43.86 kt in 1990, to circa 40.99 kt in 2021 [6].

In the Republic of Moldova, methane emissions from 5A 'Solid Waste Disposal' are estimated using the First Order Decay Method (IPCC FOD), with a Tier 3 approach, by using country-specific emission factors and parameters resulting from measurements and research conducted periodically at national level (for example, fraction DOC or degradable organic carbon in year x; fraction DOC_f or fraction DOC dissimilated; fraction of CH_4).

In this context, the main objective for this study has been to compile the results of the study on morphological composition of waste and laboratory analysis for three seasons and estimate the country specific values for DOC, DOC_f values and fraction of CH_4 also for three investigated seasons. After finalization of the survey on waste composition, the annual parameters shall be estimated.

MATERIALS AND METHODS

Figure 2 illustrates the share of biodegradable fractions in the waste stream in the RM, indicating a decrease from circa 77.0 per cent in 1986, to circa 54.0 per cent in 2001, with a further increase to 72.4 per cent in 2005, and a subsequent decrease to circa 58.9 per cent in 2016.

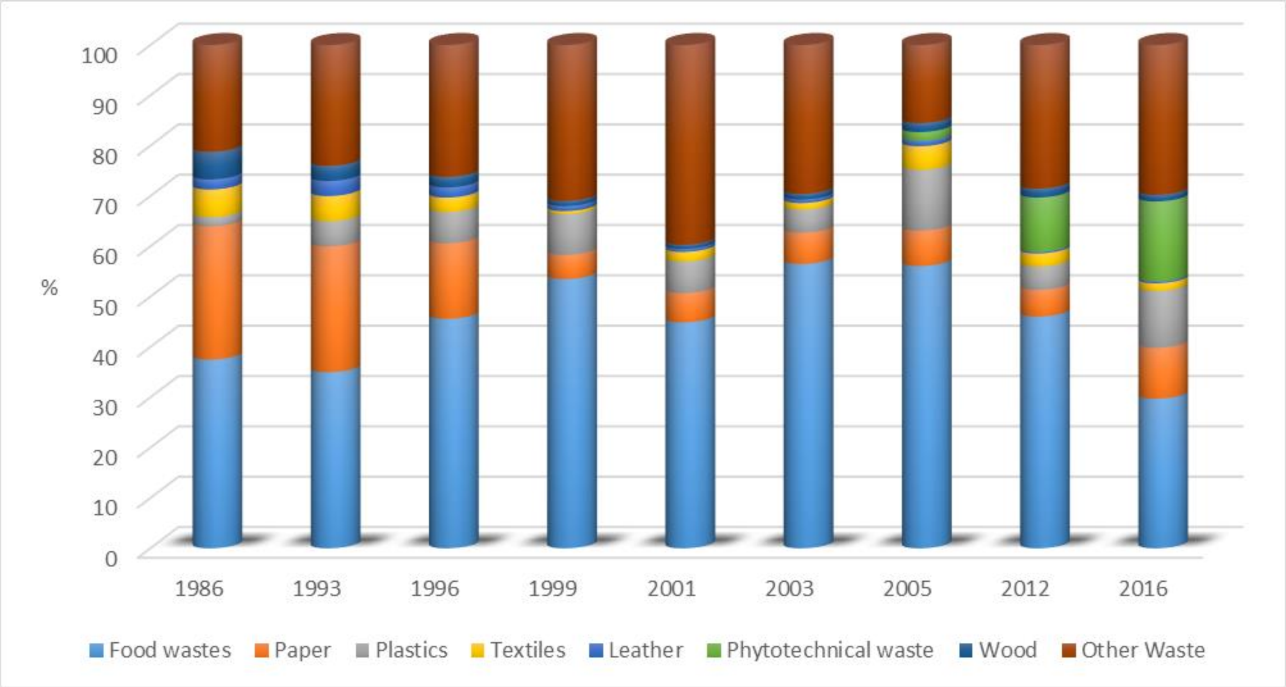

Fig. 2. Biodegradable waste in the Major Waste Streams in the Republic of Moldova for the period 1986÷2016.

Methodology of the survey on the waste composition

The 2023 study on morphological composition of waste will serve as basis to update the emission country-specific emission factors mentioned above. Tetra Tech is implementing the USAID funded Moldova Energy Security Activity (MESA). The objective of MESA is to strengthen Moldova's energy security by: (1) advancing physical and market integration of the Moldovan energy sector with Europe; (2) increasing renewable energy integration; and (3) increasing investment in energy efficiency and domestic power generation, particularly through increased adoption of renewable energy technologies [7].

Until 11 November 2019, the incineration and co-incineration of waste from any source was prohibited in the Republic of Moldova, except for medical waste. The 2019 revision to Article 17 'Incineration and co-incineration of waste', of the Law on Wastes no. 209/2016 [8] and the approval of the Regulation on incineration and co-incineration [9] has created greater opportunity for waste to energy (WTE) production in the country.

There is limited information on the morphological composition of MSW, which is needed to understand the available WTE opportunities. A study on the morphological composition of municipal solid waste will form the basis for determining the country's prospects for WTE production.

The waste characterization study covers two of eight possible Waste Management Regions (WMR 4 and 7). The WMRs are defined in the Waste Management Strategy of the Republic of Moldova for 2013-2027 period [10].

The waste composition survey started in May 2023 and will last approximately one calendar year, and will consist of four campaigns, covering the four seasons, in order to capture any seasonal variations (Table 1).

Table 1. Schedule of MSW surveys

1st campaign	May 2023
2nd campaign	June – August 2023
3rd campaign	September – November 2023
4th campaign	December 2023 - March 2024

A total of 176 samples will be collected during the entire survey. The samples are distributed between Chisinau and Balti municipalities, representative district centers and villages from WMRs 4 and 7.

Table 2. Distribution of samples between target regions and municipalities, schedule of MSW surveys

Indicators	WMR4		WMR7		1 village from WMR 4 and 7	Total
	1 municipality	2 districts from WMR4	1 municipality	2 districts from WMR7		
Number of containers	10	2	6	2	2	22
Number of samples per container	2	2	2	2	2	10
Total number of samples per season	20	4	12	4	4	44
Total number of samples (All seasons)	80	16	48	16	16	176

The analysis of the composition of the municipal solid waste follows the European Commission's Methodology for the Analysis of Solid Waste (SWA-Tool) [11], comprising the following steps:

1. *Pre-investigation stage*, which includes background information for the municipality, district, and WMR level to undertake a waste composition analysis. This stage will form the basis of the subsequent waste analysis planning stage. It will also provide the background necessary for an effective evaluation of the outcomes of the waste composition analysis;
2. *Analysis Design and Planning*, which includes planning the type of sampling, number and type of strata, level of sampling, type of sampling unit(s), calculation of the number of sampling units and sample size and generation of random sample plan municipal solid waste (i.e., household, similar waste and commercial-based waste);
3. *Execution of Waste Analysis*, which includes collection of samples, sorting and analysis of samples for municipal solid waste (household, similar waste and commercial-based waste), by considering the health and safety rules in place;
4. *Evaluation of Waste Analysis*, which includes evaluation of raw data on the basic weight results of the sorting procedure for each sampling unit and presentation of results for each determination campaign (sampling period), including information on raw data, statistical calculations, evaluation of single results of strata, extrapolation of the overall results, of the waste quantifications, and graphical presentation of the results of waste composition analysis.

Waste sampling and sorting was and shall be carried out during each of the four seasons to capture seasonal variations in consumption and waste generation. Events, such as Easter, Christmas, and other festivities, leading to abnormal waste generation patterns must be avoided. To obtain the most representative results, four determination campaigns (sampling periods) will be carried out to determine the composition in each consecutive season.

The fractions (% per weight) of the waste are determined, according to the categories from table 3.

Table 3. Fractions of waste primary and secondary categories

Primary category	Primary category code	Secondary category	Secondary category code
Organic	OR1	Biodegradable Kitchen/Canteen Waste	OR1 01
		Biodegradable Garden/Park Waste	OR1 02
		Other Biodegradable Waste	OR1 03
Wood	W2	Untreated Wood	W2 01
		Treated Wood	W2 02
Paper and cardboard	PC3	High gloss paper/card and wallpapers	PC3 01
		Paper/card - packaging	PC3 02
		Newspapers	PC3 03
		Other Paper/card- non packaging	PC3 04
Plastic	PL4	Plastic Film -packaging	PL4 01
		Plastic Film - non packaging	PL4 02
		Dense Plastic Bottles/Jars (P)	PL4 03
		Dense Plastic - other packaging	PL4 04
		Dense Plastic -non packaging	PL4 05
Glass	G5	Glass Container Packaging Clear	G5 01
		Glass Container Packaging Brown	G5 02
		Glass Container Packaging Other	G5 03
		Miscellaneous Non-Packaging Glass	G5 04
Textile	T6	Clothes	T6 01
		Non-clothing textiles	T6 02
Metals	M7	Ferrous Packaging	M7 01
		Non-ferrous Packaging	M7 02
		Miscellaneous Ferrous	M7 03
		Miscellaneous Non-ferrous	M7 04
Hazardous waste	H8	Batteries/Accumulators	H8 01
		Miscellaneous hazardous waste	H8 02
Complex products	C9	Composite/Complex Packaging	C9 01
		Composite/Complex Non-packaging	C9 02
		Mixed WEEE	C9 03
Inert	IN10	Soil and Stones	IN10 01
		Miscellaneous inert	IN 10 02
Others	U11	Nappies	U11 01
		Health Care/Biological Wastes	U11 02
		Miscellaneous Categories	U11 03
Fines	F12	10 mm sieved fraction	F12 01

The samples were analyzed in Romania in the Wastes Laboratory of National Research and Development Institute for Industrial Ecology ECOIND. The Laboratory is accredited according to SR EN ISO/IEC standards. The applied standards are similar to the American Society for Testing and Materials (ASTM) standards. Table 4 indicate measured indicators, analytical techniques applied and relevant standards used and will be used in the next campaigns.

Table 4. Indicators, analytical techniques and standards applied

Indicator	Analytical technique	Test standard
Humidity	Gravimetric	CEN/TS 15414 - 2
Superior Calorific Value	Calorimetric bomb method	EN 15400
Carbon Hydrogen Nitrogen	Combustion GC-TCD	EN 15407
Loss on combustion organic matter	Gravimetric	EN 15935
Ash	Gravimetric	EN 15403
Sulfur	Calorimetric bomb method UV-Vis Spectrometry	EN 15408
Chlorine	Calorimetric bomb method Volumetric	EN 15408
Oxygen	Calculation by difference	EN ISO 16993
Metals	ICP-Mass spectrometry	EN 16171:2017 EN ISO 54321:2021

The result for humidity were used to convert the wet basis of the waste into dry basis, which is necessary to estimate the country specific emission factors.

IPCC methodology for estimation of CH_4 emissions

In order to estimate methane emissions from solid waste disposal, the 2006 IPCC Guidelines recommends using the First Order Decay Method, with three alternative methodological approaches – Tier 1, 2 and 3; the Tier 1 method uses mainly default activity data and default EFs; the Tier 2 method uses only default emission factors partially, requiring country-specific activity data on waste disposal at SWDS for historical periods longer than 10 years; the Tier 3 method uses national statistical data on solid waste disposal for more relevant periods (for example, longer than 25 years), with country-specific emission factors and parameters resulting from measurements and research conducted periodically at national level (for example, degradable organic carbon; fraction DOC dissimilated and Lo – methane generation potential, etc.).

In the Republic of Moldova, methane emissions from 5A 'Solid Waste Disposal' were estimated using the First Order Decay Method (IPCC FOD), with a Tier 3 approach. The methane emissions were estimated using Equation (1) from the 2006 IPCC Guidelines (Volume 5, Chapter. 3) [12]:

$$CH_4 = \left[\sum_x \mathrm{CH4\ generated}_{x,T} - R_T\right] \times (1 - OX_T) \quad (1)$$

where: CH_4 Emissions is amount of methane generated in year T, kt; T is inventory year; x is waste category or type/material; R_T is recovered methane in year T, kt; OX_T is oxidation factor in year T (fraction).

One key input in IPCC FOD model is the amount of degradable organic matter (DOC) in waste disposed into SWDS (Solid Waste Disposal Sites). This value is estimated using data on disposal of different waste categories (MSW – Municipal Solid Waste, sludge, industrial and other waste) and the different waste types/material (food, paper, wood, textiles, etc.) included in these categories, or alternatively as mean DOC in bulk waste disposed.

Degradable organic carbon (DOC) is the organic carbon that is accessible to biochemical decomposition. It is based on the composition of waste and can be calculated from a weighted average of the carbon content of various components of the waste stream – cardboard, textiles, waste from gardens, parks and other non-food waste, food waste and wood waste. DOC can be estimated using Equation (2) provided by the 2006 IPCC Guidelines (Volume 5, Chapter 3) [12]:

$$DOC = \sum_i (DOC_i \times W_i) \quad (2)$$

where: DOC is fraction of degradable organic carbon in bulk waste, kt C/kt waste; DOC_i is fraction of degradable organic carbon in waste type; W_i is fraction of waste type *i* by waste category.

Fraction of degradable organic carbon that decomposes (DOCf) is the fraction of degradable organic carbon, which is ulteriorly converted to biogas and reflects the fact that part of the carbon either decomposes or decomposes extremely slowly in SWDS. It is considered that DOC_f value is dependent of the temperature from the anaerobic area of the site, revealed by the following relation: 0.014T + 0.28 (Tabasaran, 1981). The recommended default value in the 2006 IPCC Guidelines (Volume 5, Chapter 3) [12] is 0.5.

In the end, the amount of methane formed from decomposable material is found by multiplying the *CH_4 fraction in generated landfill gas* and the CH_4/C molecular weight ratio and can be estimated using Equation (3) provided by the 2006 IPCC Guidelines (Vol. 5, Chapter. 3) [12]:

$$\mathrm{CH_4 generated}_T = \mathrm{DDOC}_m \mathrm{decomp}_T \times F \times 16/12 \quad (3)$$

where: $CH_{4\ \mathrm{generated\ in\ year}\ T}$ is amount of CH4 generated from decomposable material; $DDOC_{m\ \mathrm{decomp}\ T}$ is $DDOC_{m\ \mathrm{decomposed\ in\ year}\ T}$, kt; F is fraction of CH_4, by volume, in generated landfill gas (fraction);

16/12 is molecular weight ratio CH_4/C (ratio).

The 2006 IPCC Guidelines (Volume 5, Chapter 3) [12] recommends the use of a default 0.5 value for the fraction of CH_4 in landfill gas (F). Still, it is known that the F value can vary between 0.4 and 0.6, depending on several factors which can influence the process of degradation of solid household waste, including the morphological composition of MSW [13].
For all the previous inventories of GHG emissions from waste sector, the country-specific DOC and DOC_f values were calculated based on waste morphologic composition studies, performed between 1986 and 2016, while using the 'MSW Learning Tool' created by the University of Florida [14] based on the laboratory experiments conducted by Dr Morton Barlaz [15÷17] and further investigations by Chandler and Van Soest [18, 19]. The biogas composition was estimated based on the Buswell extended equation, using data on the morphological composition of waste, which also served as the basis to estimate DOC and DOC_f values, using formulas (4). Buswell equation provides stoichiometric calculation on the products from the anaerobic breakdown of a generic organic material of chemical composition $C_\alpha H_\beta O_\gamma N_\delta S_\sigma$.

$$C_\alpha H_\beta O_\gamma N_\delta S_\sigma + A_1 H_2O \rightarrow A_2 CH_4 + A_3 CO_2 + A_4 NH_3 + A_5 H_2S \quad (4)$$

where $A_1 = \alpha - \beta/4 - \gamma/2 + 3\delta/4 + \sigma/2$, $A_2 = \alpha/2 + \beta/8 - \gamma/4 - 3\delta/8 - \sigma/4$, $A_3 = \alpha/2 - \beta/8 + \gamma/4 + 3\delta/8 + \sigma/4$, $A_4 = \delta$, $A_5 = \sigma$
and molecular formula subscriptions, α, β, γ, δ and σ represent the molar proportion of mass fraction of elements carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S) as input elements in the organic fraction of biomass. The factor of SH_2 is 1.
Table 5 contains the input data needed to estimate the molar masses of C, H, O, N and S.

Table 5. Composition of waste, in summer season, the humidity and the percent by weight for C, H, O, N and S

Component	Composition	Dry/wet	Percent by weight (dry basis)				
	%	%	C	H	O	N	S
Food wastes	33.05	19.4	0.394	0.053	0.350	0.017	0.003
Paper	1.55	82.7	0.408	0.053	0.412	0.001	0.001
Cardboard	6.20	82.7	0.408	0.053	0.412	0.001	0.001
Plastics	12.91	94.9	0.761	0.107	0.098	0.003	0.000
Textiles	3.59	92.2	0.579	0.066	0.293	0.015	0.001
Rubber	0.10	84.0	0.780	0.100	0.000	0.020	0.000
Leather	0.10	84.0	0.600	0.080	0.116	0.100	0.004
Yard wastes	18.25	25.7	0.443	0.056	0.392	0.022	0.002
Wood	0.07	89.7	0.501	0.060	0.405	0.005	0.000
Molar mass (g/mole)			12.011	1.008	15.9994	14.0067	32.060

RESULTS AND DISCUSSION

The obtained results from sampling, based on 6 out of 8 sampling campaigns, indicate that solid waste composition varies seasonally. The results are presented in the table 5.

Table 6. Seasonable waste composition results in the Republic of Moldova, 2023 (%)

Waste categories	Spring 2023	Summer 2023			Autumn 2023		
	May	June	July-August	Average	September	October	Average
Organic	54.67	47.54	62.96	55.25	58.98	71.99	65.48
Wood	0.03	0.14	0.00	0.07	0.04	0.06	0.05
Paper	5.81	9.44	6.06	7.75	8.44	6.17	7.30
Plastic	8.72	12.67	13.16	12.91	10.87	7.09	8.98
Glass	3.53	8.36	5.32	6.84	4.87	2.70	3.78
Textile	1.49	4.08	3.09	3.59	1.61	1.81	1.71

Metals	1.64	2.01	2.00	2.00	2.31	0.73	1.52
Hazard waste	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Complex products	1.89	2.31	1.48	1.89	0.83	1.00	0.92
Inert	7.34	1.31	0.80	1.05	6.39	4.78	5.59
Others	6.20	2.32	2.62	2.47	1.93	1.11	1.52
12 mm sieved fraction	8.66	9.83	2.52	6.18	3.71	2.56	3.13

In Table 6 and figure 3, it can be observed that the organic fraction (food and garden waste) predominates in all study localities and in all seasons, with the following percentages: from 54÷55 % in spring-summer to approximately 65.5 % in autumn.

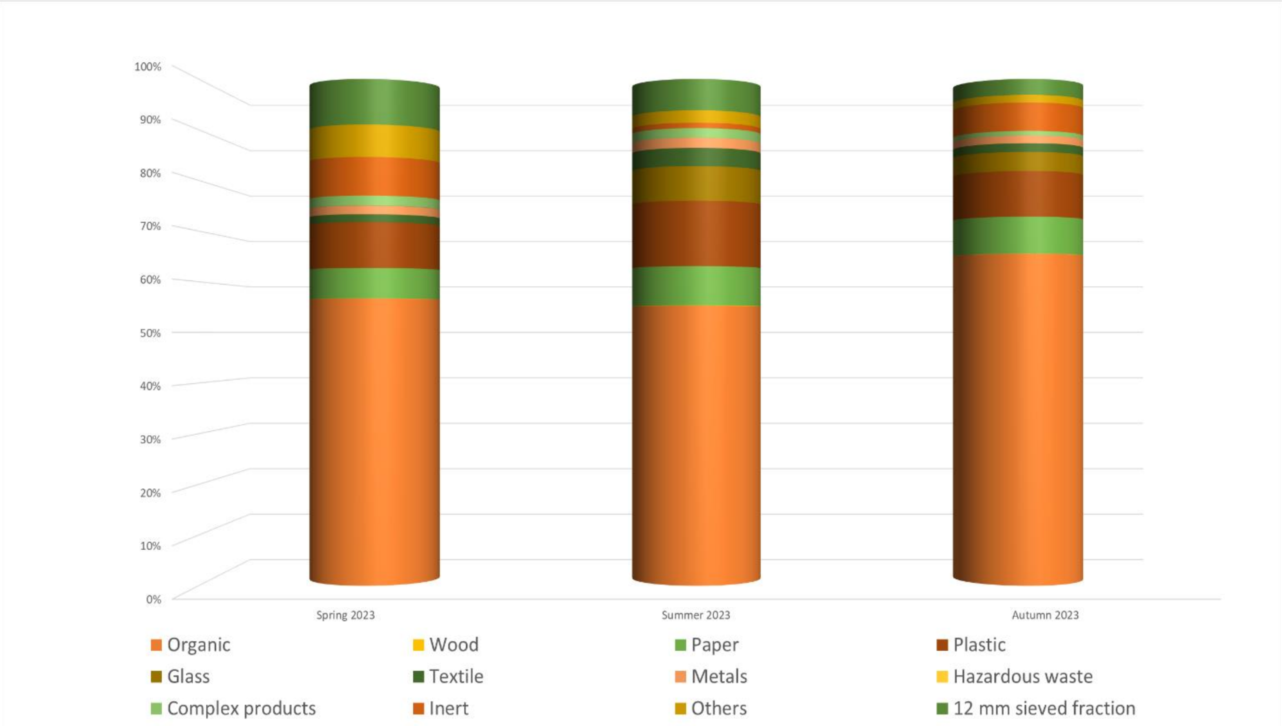

Fig. 3. Variation of municipal waste composition in spring, summer and autumn, wet basis, %

Results of estimation of DOC, DOC$_f$ and fraction of CH$_4$

Data on municipal solid waste composition is used for the estimation of national value for DOC and DOC$_f$ for all the seasons, which are presented in the figure 4. The DOC value in autumn is significantly higher comparing to other seasons, due to the higher share of organic fraction.

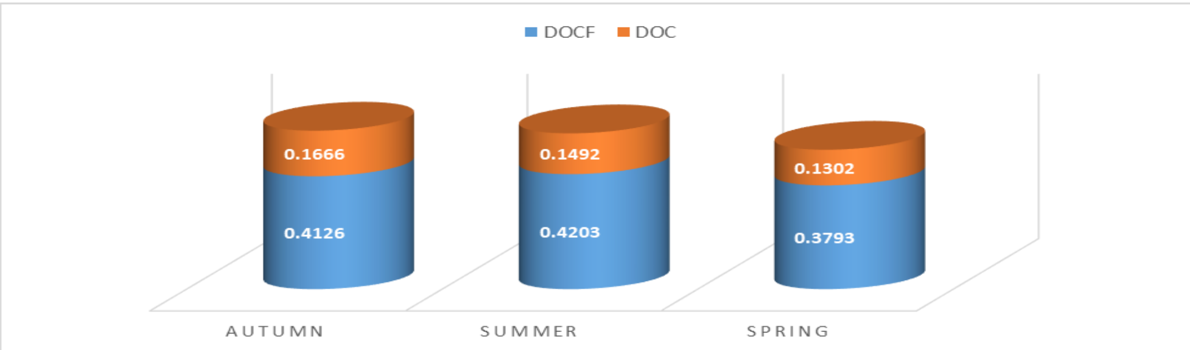

Fig. 4. Variation of DOC and DOC$_f$ in spring, summer and autumn, 2023

The results of the Extended Buswell Equation are presented in the tables Table 7, 8 and 9 below.

Table 7. Calculated molar proportion of mass fraction and variables needed for estimation of chemical composition $C_{\alpha}H_{\beta}O_{\gamma}N_{\delta}S_{\sigma}$, summer season, 2023

a	b	g	d	s	A_1	A_2	A_3	A_4	A_5
15.490	24.705	5.573	227	12	6703.5	9351.75	6138.25	227	12

Table 8. Calculated content of C, H, O, N and S, g/mg wet waste

Component	C	H	O	N	S
Food wastes	25,194	3,357	22,361	1,093	160
Paper	5,231	680	5,287	17	8
Cardboard	20,924	2,718	21,146	68	32
Plastics	93,305	13,140	11,959	400	57
Textiles	19,148	2,172	9,696	479	30
Rubber	655	84	0	17	0
Leather	504	67	97	84	3
Yard wastes	20,779	2,645	18,360	1,018	98
Wood	314	37	254	3	0
Total	186,054	24,900	89,159	3,181	389

Table 9. Results of estimated biogas composition

Carbon content in CH_4 and in CO_2	%
C --> CH_4	60.373
C --> CO_2	39.627
C total	100.0

The seasonal variation of fraction of CH_4 is presented in the figure 5 and is showing an increase of the fraction of methane in autumn season, due to higher share of organic fraction.

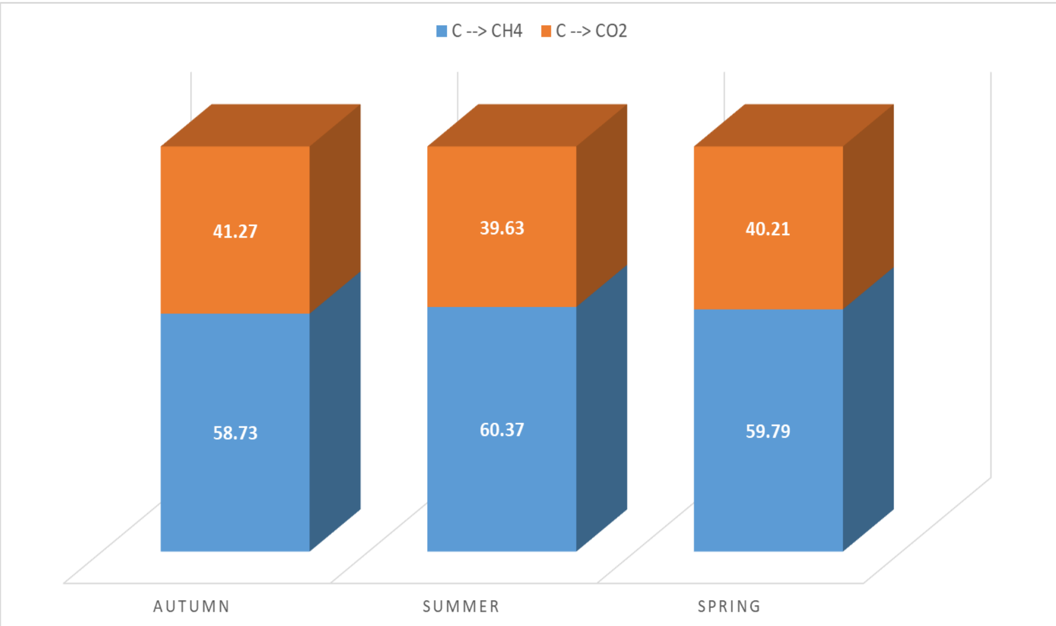

Fig. 5. Variation of values on biogas composition in landfill gas in the Republic of Moldova in spring, summer and autumn season, based on Extended Buswell Equation, %

CONCLUSIONS

The main conclusion and findings related to the consolidating data from municipal solid waste composition and estimation of country specific DOC, DOC_f and fraction of methane are presented below.

In this research study, the composition of MSW samples from low, medium, and high-income level areas for three seasons were determined. Results on composition of municipal solid waste over the 3 seasons show a clear variation of the organic fraction, with a considerable increase in autumn season up to 65%, comparing to summer with 55 %. The plastic fraction is similar in autumn and spring and is circa 9%, while in summer it increases up to 13 %. A similar trend is to be assigned to glass fraction, which also is similar in autumn and spring (3÷4 %), and is increasing in summer season up to 7 %. This can be explained by the intensive use of beverage in summer season.
Data on composition of municipal solid waste and humidity have been used for the estimation of DOC, DOC_f and fraction of CH_4 based on IPCC methodology and the Extended Buswell Equation for three seasons – spring, summer and autumn. Higher values of these parameters are referred to autumn season, due to a higher share of organic fraction in waste.
The obtained results revealed the fact that landfill gas composition was relatively constant during the seasons, with a slight increase in autumn, also due to higher organic fraction in waste.
The obtained results offer the opportunity to update the IPCC EFs for CH_4 emissions from landfills for the Republic of Moldova, by using the country specific emission factors for the whole time series. These leads to increasing of GHG emissions from SWDS, which can be an advantage in promoting emissions reduction projects under Kyoto Protocol.
To be mentioned that the results obtained by following FOD method are preferred, to be included into the Biannual Transparency Report 1 of the Republic of Moldova to the UNFCCC.

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