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Mathematical Modeling of Landfill Gas (MSW)—Production of Gas with Methane Gas Content from Landfills (MSW)

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Abstract

The municipal solid waste (msw) is a source of landfill gas (msw)—with methane gas content. Preoccupations for landfill gas (msw) management date back since 1976 when, at a landfill (msw) in California (USA), it turned out practically that the landfill gas (msw) with methane gas content contains a gas with high caloric value that can be collected and used for economic purposes. The landfill gas (msw) contains methane gas (30% - 60% volume), carbon dioxide (45% - 50% volume), hydrogen sulfide and other gases. Methane gas, carbon dioxide, nitrous oxide and other gases are listed in Kyoto Protocol as high greenhouse gases. Their ecological-rational management is both a national and global preoccupation. In terms of greenhouse gases, especially methane gas, the landfill (msw) is held responsible for 3.5% - 5% of the total global greenhouse gases. Practically, the quantitative estimation of the methane gas in a municipal solid waste landfill can be done by measuring the landfill gas (msw) flow in an extraction-collection well. In Romania, a quantitative estimation relationship of methane gas from deposits (msw) was made, approaching the problem in a different way. This paper presents the calculation formula, the working algorithm, the municipal waste landfill equation and the NOMOGRAMA of a municipal solid waste landfill (msw). The NOMOGRAMA allows us to define the values for parameter -m- (number of months needed for an amount of municipal solid waste (msw) to degrade, starting with the year from which the landfill gas (msw) emission with methane gas content is calculated). Taking into account the environmental conditions for each location of municipal solid waste landfill, the calculation uses various indexes and approximations, while the fundamental parameter remains -m- defined by the NOMOGRAMA of the municipal solid waste landfill (msw). A municipal solid waste landfill (msw) is a conglomerate of waste with various biodegradation periods between 2 - 3 years and 5 - 10 - 30 years. Degradation of waste (msw) in to dissolved organic carbon will take place in a number of months defined -m- starting with the year from which the methane gas emission with the NOMOGRAMA of the municipal solid waste landfill (msw) is calculated. The -m- values for the year of the quantitative emission of methane gas can be also done analytically, which requires good experience in the ecologic-rational management of the municipal solid waste (msw).

Keywords

Municipal Solid Waste (MSW), NOMOGRAMA, Calculation Formula, Parameter -m-, Quantitative Estimation of Methane Gas

1. Introduction

In terms of environmental conditions, Romania is considered to have an European wet continental-temperate climate with slight influence from the mountains, so that [Romania's Climate Wikipedia, 2008] summers are dry (20 May-20 September), with temperatures between 30˚C - 40˚C, precipitations between 637 mm - 400 mm/year. In the mountains, precipitations are between 1000 - 1400 mm/year. In the spring time, 20 February-20 May, and in autumn, 20 September-20 November, temperatures are between 10˚C - 30˚C, and moderate precipitations. During winter, 20 November-20 February, temperatures are between −5˚C and −25˚C. Snow alternates with freezing-refreezing periods. Romania, as an European country has a climate distribution as shown in **Figure 1**.

Figure 1. Climate division in Europe. (*Source*: literature review: methane from landfills methods to quantify generation, oxidation and emission, 2010) [Oonk, 2010].

Within the map, you can see [Romania's Climate Wikipedia, 2008] the alpine climate, the cold continental climate, the wet continental climate, and the oceanic climate.

Romania's location on the globe is: latitude between 43˚37'7" North, with the far most point at Zimnicea and 48˚15'06" North on Prut river at Hodoriștea, and longitude—20˚15'44" East at the Western side of Beba Vecheand 29˚41'24" East on the Black Sea coast, at Sulina. **Figure 2** shows the classification (distribution) of the climate on the Romanian territory. In **Figure 3**, there are presented the precipitation areas in Romania Territory, zones marked with letter A, B and C.

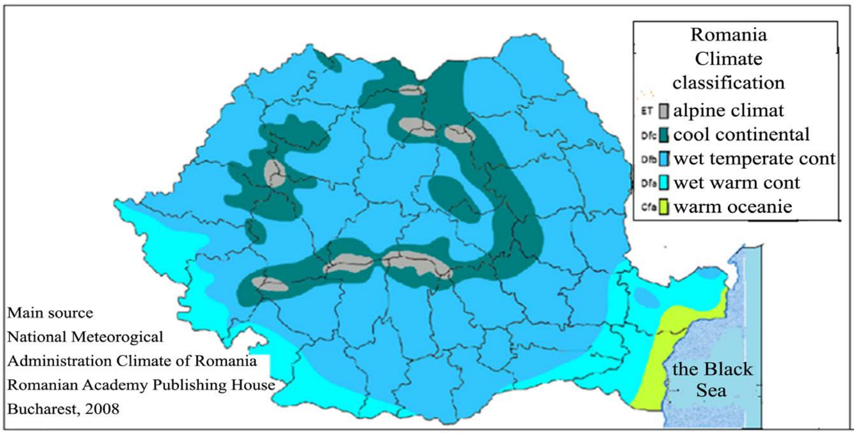

Figure 2. Climate map of Romania.

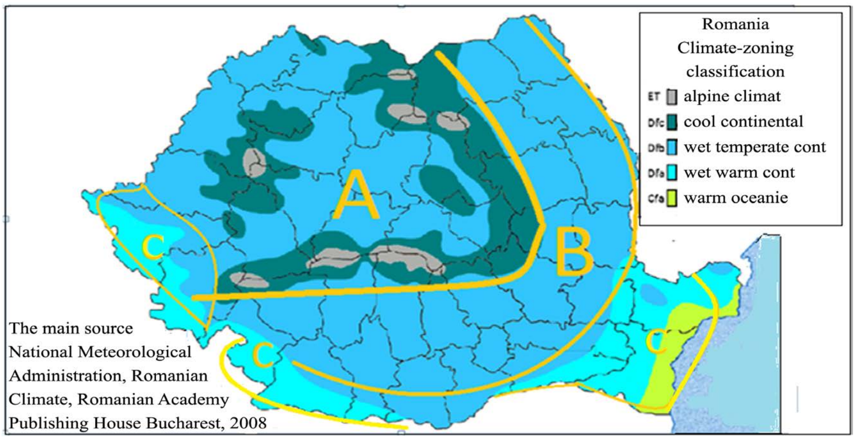

Figure 3. Map of the Precipitation areas in Romania. Zone A, precipitations of 1000 mm ÷ 1400 mm/year. For Zone A, $K_1 = 0.4$, $K_2 = 0.39$ [Hosseini et al., 2018]; Zone B, precipitations of 600 mm ÷ 637 mm/year. For Zone B, $K_3 = K_4 = 0.37$ [Hosseini et al., 2018]; Zone C, precipitations of 400 mm ÷ 500 mm/year. For Zone C, $K_5 = K_6 = 0.36$ [Hosseini et al., 2018] where K_1, K_2, K_3, K_4, K_5, K_6 is the degradation potential of the municipal solid waste (msw) as against the dissolved organic carbon, depending on the precipitations in the area of the municipal solid waste (msw). Calculation formula for Zone A: $K_1 = 2.79 * (10^{-4}(x)) + 0.01$, $K_2 = 3.8 * (10^{-4}(x)) + 0.01$, (x) = precipitations in Zone A. Calculation formula for Zone B: $K_3 = 6.00015 * (10^{-4}(x)) + 0.01$, $K_4 = 5.6515 * (10^{-4}(x)) + 0.01$, (x) = precipitationsin Zone B. Calculation formula for Zone C: $K_5 = 8.75 * (10^{-4}(x)) + 0.01$, $K_6 = 7.0 * (10^{-4}(x)) + 0.01$, (x) = precipitations in Zone C. K can change depending on the environmental conditions (precipitations) in the area [Hosseini et al., 2018].

2. Management of the Municipal Solid Waste (MSW) in Romania

The source of the municipal solid waste (msw) in Romania's Population by Locality on January 1, 2016 [www.insse.ro/cms/ro/content/populaţiaRomâniei-pe-localitati-la-1-ianuarie-2016] is:

1) The population, divided into:

- Urban—11,350,620 inhabitants. Supposing that 1.7 kg municipal solid waste (msw) is generated per inhabitant per day, the total annual amount is 7043 Gg/year;
- Rural—8,771,021 inhabitants. Supposing that 1.1 kg municipal solid waste (msw) is generated per inhabitant per day, the total annual amount is 3522 Gg/year.

2) Industrial [Voicu, 2016] (similar waste to household waste + trade + offices + agriculture and animal husbandry (agricultural processing and animal husbandry processing) + fish farming (fish processing) + human medicine and veterinary medicine that generate non-hazardous municipal solid waste (msw) that can be quantified annually. The annual amount generated is about 3120 Gg (600,000 × 30 kg/day × 260 days/year/1000/1000) where:

- 600,000 number of economic operators;
- 30 kg/day—minimal amount of municipal solid waste (msw) generated by the economic operator;
- 260—number of days/year of activity;
- 1000 transformation, in tons, and Gg.

To the amount of 4680 Gg municipal solid waste (msw) (similar to household waste) [generated by industrial + trade + offices + agriculture and fish farming (agricultural processing and animal husbandry processing) + fish farming (fish processing) + human medicine and veterinary medicine that generate non-hazardous municipal solid waste (msw)] we must add amounts of municipal solid waste such as: sewage sludge from towns, street sweeping, slit (that cannot be used in agriculture) from industrial and household sewage treatment plants. Estimated amount is 1500 Gg/year.

The total amount of municipal solid waste (msw) that must be managed in an ecological-rational manner in Romania, [Voicu, 2016] is 16,745 Gg municipal solid waste (msw) (7043 + 3522 + 4680 + 1500)/ year).

Since 15%/year represents recycling + recuperation + reutilization, it means that an amount of 14,233 Gg/year of municipal solid waste (msw) must be managed in an ecological-rational manner.

3. Disposal of the Municipal Solid Waste (MSW) in Romania

- Incineration, in authorized plants, to remove hazardous and potentially infectious municipal solid waste (msw). In case of non-hazardous municipal solid waste (msw), incineration is about 4%, 516 Gg/year;
- Energy recovery by economic operators in the cement industry and elec-

tro-thermal plants. The amount used (used oil, used tires, plastic, non-recyclable paper, non-recyclable textile, non-recyclable wood) is about 900 Gg/year;

- Landfills [Voicu, 2016] are the method most used across the world and in Romania. In 2019, there are 43 municipal solid waste landfills (MSW) authorized with Integrated Environmental Authorization out of which 3 in Bucharest-Ilfov area. The 3 ones in Bucharest-Ilfov receive 1200 Gg per year. The rest of 11,617 Gg/year of municipal solid waste (msw) need to be disposed of in 47 municipal solid waste landfills, 247 Gg/year, authorized with Integrated Environmental Authorization or 52 municipal solid waste landfills, 223 Gg/year, authorized with Integrated Environmental Authorization. 43 municipal solid waste landfills are not enough. 223 Gg/year municipal solid waste (msw) disposed of in municipal solid waste landfills is a reasonable figure that ensures safe management of the LFG with CH_4 content.

Overview of other countries:

- France [Meres, 2005] generated about 33,000 Gg municipal solid waste (msw) in 2011, out of which about 61% disposed of in landfills compliant with EU norms, about 25% recycled, recovered and reused, and about 14% incinerated;
- USA [Fei et al., 2015] generated about 251,000 Gg in 2014, out of which about 56% disposed of, about 28% recycled and reused, and about 16% + incinerated.

4. Generation of the Landfill Gas (LFG)

The municipal solid waste (msw) is disposed of in landfills. Under the influence of the environment (temperature, freezing/defreezing periods, precipitations, snow, variation of the air pressure), physical factors (compaction of the municipal solid waste (msw), coverage with inert material inert and soil, coverage with geotextile material and geomembranes), the landfill biodegrades and generates landfill gas (LFG).

Figure 4 presents the biodegradation of the municipal solid waste (msw), in stages [Meres, 2005], [Bellenoue et al., 2007].

4.1. LFG Production Mechanisms and Its Evolution

- At the beginning, the aerobic stage; the oxygen in the air retained by the municipal solid waste (msw) is consumed. The organic material decomposes into carbon dioxide [Bentley et al., 2002] [Scharff et al., 2017].
- When the oxygen is consumed, the anaerobic biodegradation begins (after covering the municipal solid waste (msw) with soil and inert material). Practically, the methanogenesis starts through cytogenesis. The CH_4 content in the LFG starts increasing, but the methanogenesis is unstable [Bellenoue et al., 2007], [Prud'homme, 2001].
- The ratio CH_4/CO_2 remains stable. This stage lasts for a few decades. Then the production of LFG with CH_4 content starts decreasing.

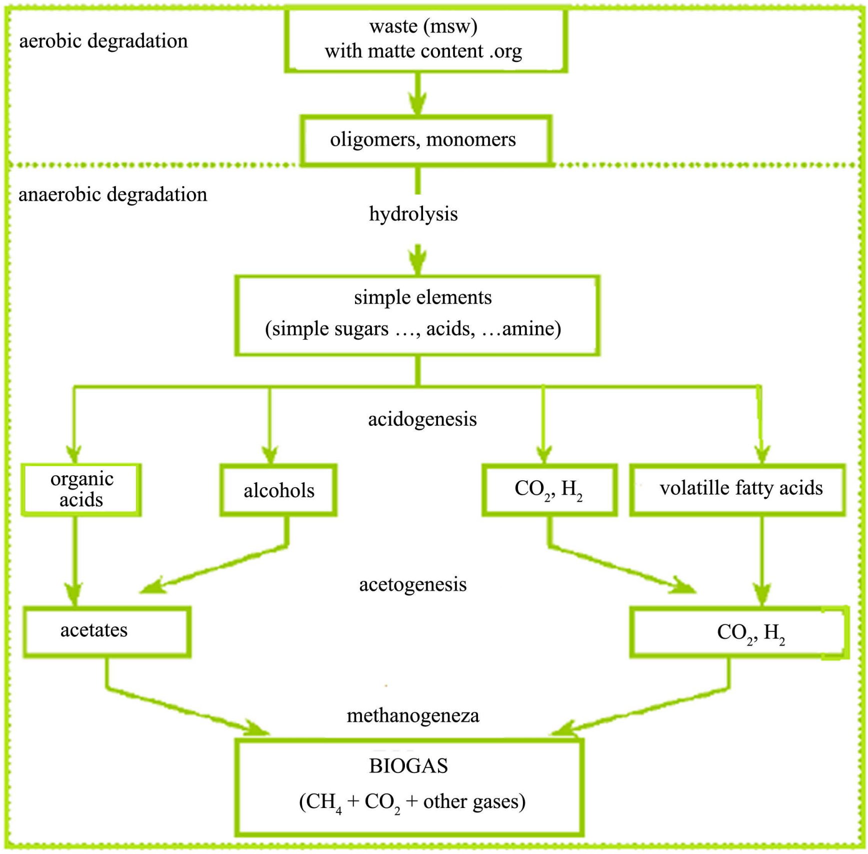

Figure 4. Biodegradation of municipal solid waste (msw) in stages: hydrolysis-acidogenesis, acetogenesis, methanogenesis. Source: Meres, 2005.

- When the LFG production becomes very low, the air starts penetrating again the landfill. If there is biodegradable material left, carbon dioxide will be generated.

The composition of the biogas varies in time. During the stable stage of methanogenesis, the CH_4 content is 30% - 60% and the CO_2 content 40% - 50%, the CH_4/CO_2 ratio is therefore 1.2 - 1.5, typical for this stage. Before, this ratio can reach 2. At the end of biodegradation, this ratio decreases.

4.2. Evolution of Methanogenesis

4.2.1. Initiation Stage

It lasts from a few months to a few years. After the first aerobic stage when the oxygen retained by the municipal solid waste (msw) in the landfill is consumed, the temperature increases and carbon dioxide is produced; the methanogenesis emerges gradually. The CH_4/CO_2 ratio varies and the amount of LFG with CH_4 content has a maximal value.

4.2.2. Production Stage

For decades, the methane production is stable. The C/N ratio does not change too much. The LFG flow gradually decreases [Meres, 2005], [Bellenoue et al., 2007], [Prud'homme, 2001].

4.2.3. Extinction Stage

The LFG produced tends to zero. It is replaced by air. Methanogenesis stops. Residual biodegradation generates mainly carbon dioxide.

The main characteristics of the LFG components and the physical parameters for a mix of 60% CH_4 and 40% CQ_2 are presented in **Figure 5** [Meres, 2005], [Bellenoue et al., 2007], [Prud'homme, 2001] [Guidance on the Management of Landfill Gas, 2004].

The LFG density in Romania is 0.72 kg/m^3.

5. Factors That Influence the Biodegradation of the Municipal Solid Waste (MSW) in the Landfill

5.1. Quantity and Quality of Municipal Solid Waste (MSW) with Organic Material Content

The LFG with CH_4 content is generated as a result of physical, chemical and microbial processes that develop in the landfill of the municipal solid waste (msw).

	Symbol	Unit	CH_4	CO_2	O_2	N_2	Air	H_2O	H_2S	Mixture containing CH_4		
										20%	40%	60%
molecular mass	M	g/mol	456.00	44.01	32.00	28.01	28.96	18.02	34.08	28.25	27.98	26.42
volumic mass	r	kg/Nm^3	0.72	1.98	1.43	1.25	1.29	0.86	1.54	1.27	1.25	1.19
density	d	"	0.56	1.53	1.11	0.97	1.00	0.67	1.19	0.98	0.97	0.92
mass thermal capacity	Cp at 0˚C	kJ/kg.K	2.15	0.82	0.91	1.04	1.00	1.89	1.00	1.23	1.43	1.65
kinemticvascosity at 20˚C	20˚C	µ Pa.s	11.19	15.34	19.92	16.95	17.08	9.01	12.4	15.70	14.08	12.66
compresibility factor	Z		1.00	0.99	1.00	1.00	1.00	0.93	0.99	1.00	0.99	0.99
critical pressure	Pc	bar	46.00	73.90	50.40	33.90	37.70	220.60	89.40	50.15	57.39	61.53
critical temperature	Tc	K	190.50	304.50	154.60	126.20	132.45	647.10	373.20	185.52	223.19	246.23
politropic index	gamma		1.31	1.31	1.40	1.40	1.40	1.40	1.30	1.37	1.34	1.31
high caloric value	PCSm	MJ/kg	55.66						16.52	11.15	22.28	33.41
volumetric calorific value	PCSv	MJ/m^3 (n) $^{(1)}$	39.82						25.37	7.99	15.95	23.92
lower caloric value	PClm	MJ/kg	50.04						15.19	10.02	20.03	30.04
lower caloric value by volume	PClv	MJ/m^3 (n)	35.88						23.33	7.20	14.38	21.55
Wobbe index	W	MJ/m^3 (n)	153.41						23.28	10.71	21.39	32.07
commercial $^{(2)}$ potential	Lmin	m^3(n)/m^3 (n)	9.57						7.23	1.22	3.43	5.71
the volume of $^{(3)}$ wet smoke	Vgb.h	m^3(n)/m^3 (n)	10.52						7.70	1.91	3.58	5.75

(1) m^3 (n) m^3 normal at 1 atm. and 0˚C;

(2) commercial potential m^3 combustion air/m^3 of combustible gas in stoichiometric conditions;

(3) volume of wet smoke m^3 of smoke/m^3 combustible gasin stoichiometric conditions;

(Source: to help workers in the 1990 ATG gas in industry (for pure gas) normal at 1 atm. and 20˚C).

Figure 5. Physical characteristics and energy characteristics of the LFG components for a mix of 60% CH_4 and 40% CO_2. Source: Gerer le gaz de decharge Techniques et recommendations, 2001.

Due to the organic nature of most municipal solid waste (msw), the microbial process generates gas-LFG. [Guidance on the Management of Landfill Gas, 2004], [Conestoga-Rovers & Associates, 2010], [Isin, 2013] [International Best Practices Guide for LFGE Projects, 2012]. This process is sensitive to its environment, therefore certain natural and artificial conditions will affect the microbial population and the flow of the LFG generated. The short term research on the big municipal solid waste landfills using data from LFG extraction tests indicate LFG generation flows between 0.05 - 0.40 m^3 LFG/kg municipal solid waste (msw) in landfills. The amount of the municipal solid waste (msw) is the solid material (75% - 80%), and humidity (25% - 20%). This range is a function of the organic content of the municipal solid waste (msw) in the landfill.

The LFG generation takes place in anaerobic conditions and all natural or artificial conditions that turn the process into anaerobic will affect the LFG generation. To note that the LFG generation is not instantaneous; all amounts of municipal solid waste (msw) brought to a landfill will be subject to the processes presented in **Figure 4** and **Figure 6**.

As **Figure 4** shows, the first stage, the aerobic biodegradation, takes place right after the disposal of the municipal solid waste (msw) due to the oxygen in the municipal solid waste (msw). Anaerobic biodegradation produces carbon dioxide, water and heat until the oxygen in the waste is consumed. The next stage is the anoxic, non-methanogenous stage, when acid chemical components and hydrogen are formed, while carbon dioxide is being generated; in general, this is a hydrolysis and cytogenesis process.

The environmental factors, during this stage of fragmentation of big molecules into small molecules such as ammonia, carbon dioxide, hydrogen, water and heat, consumes the residual oxygen and the nitrogen resulted from the municipal solid waste (msw) [Guidance on the Management of Landfill Gas, 2004], [Conestoga-Rovers & Associates, 2010], [Isin, 2013].

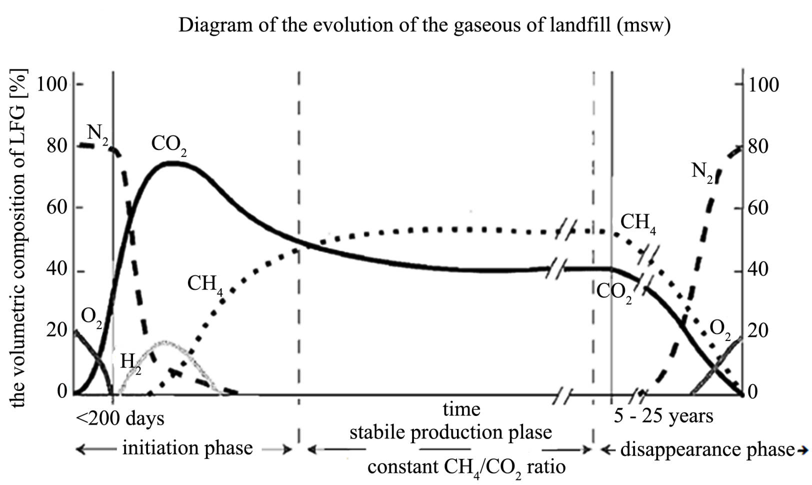

Figure 6. Graph of the evolution of gas composition per stages of biodegradation in a municipal solid waste landfill. Source: Gerer le gaz de decharge Techniques et recommandations, 2001.

The third stage is the unsafe methanogenic stage. The generation of carbon dioxide decreases, because the biodegradation of the municipal solid waste (msw) turns from aerobic stage into anaerobic stage. The anaerobic biodegradation results in heat and water, and, unlike the anaerobic process of decomposing, results in methane, too.

The methanogenic bacteria are active during this stage, and they use the secondary products of the previous stage, the methane production.

During the fourth stage, methane is generated with a concentration between 35% - 65% out of the total volume [Guidance on the Management of Landfill Gas, 2004], [Conestoga-Rovers & Associates, 2010], [Isin, 2013]; the processes responsible for methane generation are generally stable. The biodegradation of the municipal solid waste (msw), in most landfills, reaches the stable stage in less than 2 years from the disposal of the municipal solid waste (msw). To note, however, the importance of the local environmental conditions (temperature and humidity, precipitations, air pressure variation, air movement above the landfill).

5.2. Composition of the Municipal Solid Waste (MSW)

The composition of the municipal solid waste (msw) is the major factor to estimate the potential to generate LFG and the total yield of the municipal solid waste landfill. The maximal potential volume of LFG depends on the amount and on the type of organic material in the municipal solid waste (msw) [Guidance on the Management of Landfill Gas, 2004], [Conestoga-Rovers & Associates, 2010], [Isin, 2013], since the organic material in the municipal solid waste (msw) that decomposes is the main source of LFG with CH_4 content.

Inorganic and inert material will produce less or zero LFG with CH_4 content; more municipal solid waste (msw) with organic content will produce more LFG with CH_4 content on kilo. The municipal solid waste (msw) with high content of organic material, such as food waste, and sludge generate high amounts of LFG, but they contain water fractions that do not produce LFG but increase the LFG flow. In terms of humidity, there is a threshold above which the LFG generation decreases [Guidance on the Management of Landfill Gas, 2004], [Conestoga-Rovers & Associates, 2010], [Isin, 2013].

5.3. Humidity Content

The percentage of moisture in the landfill (msw) is considered to be one of the most important parameters that control the flow rate of LFG; moisture provides the aqueous environment needed to generate LFG and also serves as a mean of transport for the nutrients and bacteria.

In Romania, the annual average of precipitations, [Romania's Climate Wikipedia, 2008] following the gradual decrease of oceanic and Mediterranean influences, decreases slightly from west to east. The annual average of precipitations (calculated throughout the territory) is of 637 mm per year, with significantly higher values in the mountain areas (1000 - 1400 mm/year, (Stâna de Vale resort is considered the "rain pole in Romania")) and progressively lower towards the east, in Bărăgan being below 500 mm/year, in Dobrogea and the Danube Delta falling below 400 mm/year [Romania's Climate Wikipedia, 2008].

6. New Calculation Method to Estimate the CH_4 Emission in the Municipal Solid Waste Landfill in Romania, Author: Danila Vieru Msc., Chemistry

Figure 7 presents the biodegradationof the municipal solid waste (msw) at an active landfill and at a landfill where the disposal of the municipal solid waste (msw) has ended.

If one type of municipal solid waste does not reach the landfill, it can be removed from the calculation program.

Annually, part of the municipal solid waste (msw) at a landfill is biodegraded down to dissolved organic carbon and part of it remains non-biodegraded. Biodegradationtakes place in a number of months -*m*- between 2 successive disposals at the landfill according to NOMOGRAMAVieru® (see **Figure 7**).

Clarification: biodegradation of the municipal solid waste (msw) in the landfill takes place during the lifetime of the landfill and until exhaustion of the organic material contained in the municipal solid waste (msw) [Atabi et al., 2014].

The disposal of the municipal solid waste (msw) is based upon few principles:

- The municipal solid waste (msw) is disposed of, after sorting, in the random landfill, so all kinds of waste come in contact with each other [Scharff, Jacobs et al., 2006] [Hosseini et al., 2018] [Jacobs et al., 2001];

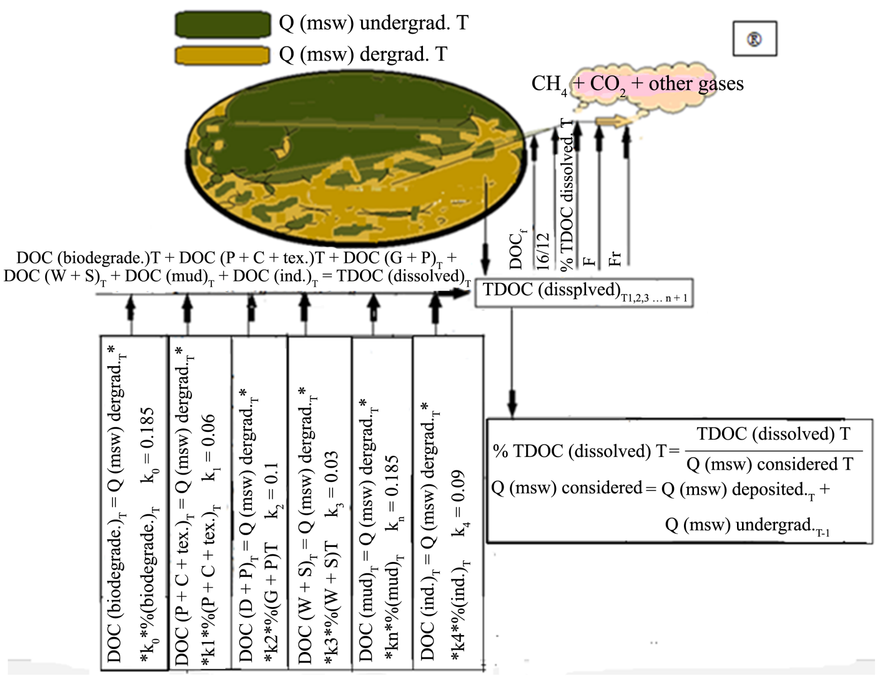

Figure 7. The working algorithm® to estimate the CH_4 emission in the LFG, at an active landfill of municipal solid waste (msw), given the 7 types of municipal solid waste (msw) that can penetrate the landfill of municipal solid waste.

- Based on the recommendations of the IPCC experts, 7 kinds of waste have been identified with a certain degradation rate expressed by factor k [Word Press.com, 2014], [Pipatti & Svardal, 2006], [Godlove et al., 2018] [Peer et al., 1992].
- The LFG emission with CH_4 content, for the reference year, is due to the amount of municipal solid waste (msw) biodegraded down to dissolved organic carbon [Ludwig et al., 2010].
- The amount of biodegraded waste for the reference year includes the pre-established percentage of municipal solid waste (msw) in the landfill. **Table 1** presents the pre-established percentages of the types of municipal solid waste (msw) in the landfill. This composition is retained in the amount of municipal solid waste (msw) degraded in the reference year.
- With data collected from stakeholders involved in the management of the municipal solid waste (msw), we can establish the percentages in the municipal solid waste landfill [Voicu, Vieru et al., 2019]. The composition can be maintained up to 5 years or it can be changed annually, depending on socio-economic circumstances. The statistics of the municipal solid waste (msw) plays major role in establishing the percentages in the municipal solid waste landfill (see **Table 1**).
- The disposal of the municipal solid waste (msw) is done for the 12-month calendar year when they are leveled and compacted [Word Press.com, 2014].

Table 1. Chitila-Rudeni-Iridex municipal solid waste landfill–pre-established percentages of municipal solid waste (msw) in the landfill.

Municipal solid waste (msw) in the landfill, for the reference year, Between 2000-2011, (%)					
51.2	16	16.8	3	1	12
Biodegradable municipal solid waste (msw) (food, animal farming, agriculture, street sweeping etc.)	Municipal solid waste (msw) (P + G)**	Municipal solid waste (msw) (P + C + tex)***	Municipal solid waste (msw) (wood + straw)	Sludge (sewage cleansing, Sludge from treatment plants)	Industrial municipal solid waste (similar to household + sterile medical waste)
Municipal solid waste (msw) in the landfill in the reference year, For 2012, (%)					
58	13.8	10.7	3	1.5	13
Biodegradable municipal solid waste (msw) (food, animal farming, agriculture, street sweeping etc.)	Municipal solid waste (msw)(P + G)**	Municipal solid waste (msw) (P + C + tex)***	Municipal solid waste (msw) (wood + straw)	Sludge (street sweeping, sewage cleansing, sludge from treatment plants)	Industrial municipal solid waste (similar to household + Sterile medical municipal solid waste)
Municipal solid waste (msw) in the landfill in the reference year, Between 2013-2016, (%)					
60	14.4	14.2	3	1.4	7
Biodegradable municipal solid waste(msw) (food, animal farming, agriculture, street sweeping etc.)	Municipal solid waste (msw) (P + G)**	Municipal solid waste (msw) (P + C + tex)***	Municipal solid waste (msw) (wood + straw)	Sludge (street sweeping, sewage cleansing, sludge from treatment plants)	Industrial municipal solid waste (similar to household + Sterile medical municipal solid waste)

(P + G) municipal solid wastefrom parks and gardens; *(P + C + tex) municipal solid waste from paper + cardboard + textile.

- Vertical-A_C—is the calendar year when the disposal is done, practically the height-(h) of the municipal solid waste landfill on the vertical that includes coverage with low permeability material.
- Vertical-A_T—is the year when the amount of municipal solid waste (msw) biodegraded to DOC (dissolved organic carbon) lower with 6 months than the calendar year.
- Estimation of the amount f municipal solid waste (msw) degraded down to DOC (dissolved organic carbon), in the reference year, that generates CH_4 emissions annually starts with the 2nd calendar year after the municipal solid waste (msw) is disposed of; the first year of calculation—A_T-1 is the first 6 months after the beginning of the disposal [Barlaz et al., 2012].
- Each year, there is an amount of non-degraded municipal solid waste (msw) in the municipal solid waste landfill that is taken into account for calculation in the following year.
- The LFG with CH_4 content, on its way to the cover of the municipal solid waste landfill or to the extraction-collection well, will collect all incipient gases.
- A NOMOGRAMA Vieru®can be allocated to each municipal solid waste landfill, as seen in **Figure 8**.

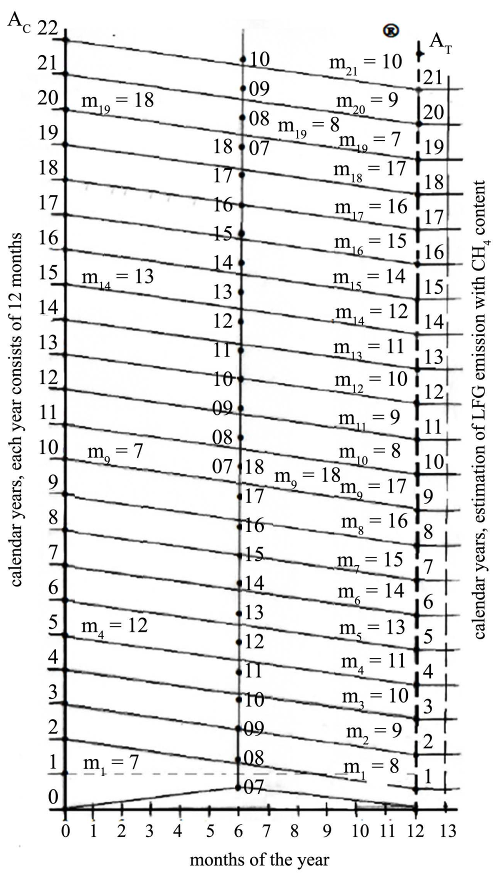

Figure 8. NOMOGRAMA Vieru® of a municipal solid waste landfill. NOMOGRAMA Vieru®.

- Landfills that collect LFG with CH_4 content shall send the information to the environmental authority.
- Landfills that do not collect LFG should know when they introduce the extraction-collection system as they needn't pay environmental taxes.

6.1. NOMOGRAMA Vieru® of a Municipal Solid Waste Landfill

Aspects of NOMOGRAMA Vieru® of a municipal solid waste landfill (see **Figure 8**):

- A_C, to the left, is the number of calendar years of the municipal solid waste landfill. A calendar year has 12 months. As a rule, the life time of a municipal solid waste landfill is 20 - 30 years, but we can also have municipal solid waste landfills of 40 - 50 years. A_C-1 is the year when the disposal of the municipal solid waste (msw) begins.
- A_T, to the right, is the number of years of calculation regarding the estimation of CH_4 emission. Due to the practical observations according to which the beginning of the LFG emission with CH_4 content is delayed with approx. 6 months since the beginning of the disposal and to the fact that it has been agreed that: municipal solid waste(msw) disposed of between 01.07 - 31.12. remained non-degraded, for the 6th month, there have been given, on the vertical, solutions for the equation of a municipal solid waste landfill $3m + 7 = 13 - m$, $m \in$ N, $7 \le m \le 12$ [Mihoc et al., 1980] or after the first year of disposal but after the end of the 2nd calendar year $\left[(3+8n)m+7=(12n+13)-m\right]$, $m \in$ N, $7 \le m \le 18$.
- By connecting the points on A_T with the points on A_C, at the intersection of the line of the solutions of the equation $(3+8n)m+7=(12n+13)-m$ ®*, $7 \le m \le 18$, [Vieru, 2017a: pp. 436-454], [Vieru, 2017b: pp. 191-209] we find the number of months during which the degradation of an amount of municipal solid waste (msw) for the reference year takes place. The use of NOMOGRAMA Vieru® requires a lot of expertise.
- Horizontal, the calendar year has 12 months, the municipal solid waste landfills are leveled, compacted and covered with inert material. Month 13 appears because, after the end of the calendar year, 1 more month is needed to collect information about the municipal solid waste landfill analyzed. The information consists of: the amount of municipal solid waste disposed of in the landfill in the calendar year that has ended, the amount of LFG with CH_4—content (m^3 or Gg.)—collected in the calendar year that has ended, whether a LFG extraction-collection system has been implemented, the CH_4 (%) concentration, the number of vertical wells to collect LFG, the existence of a horizontal LFG extraction-collection system, the management of the leach ate, the pressure (mbar) of the LFG extraction-collection system, the variation of the air pressure (mm Hg), the temperature in the area of the municipal solid waste landfill, the precipitation periods, the amounts of sludge from treatment plants, [Gg] + amounts of sludge from sewage cleansing [Gg], the amounts of municipal solid waste from parks and gardens (P + G) including cemeteries [Gg], the amounts of industrial municipal solid

waste (similar to household municipal solid waste) [Gg], amounts of sterile-ground medical municipal solid waste [Gg], amounts of straw and wood municipal solid waste [Gg]).

6.2. Regarding the Equation® of a Municipal Solid Waste Landfill

The equation of a municipal solid waste landfill after replacing x with t is $3t+7=13-t$ ® [Mihoc et al., 1980], which is $(3+8n)\cdot t+7=(12n+13)-t$ ®* [Vieru, 2017a: pp. 436-454], [Vieru, 2017b: pp. 191-209] after the first year, where t is the biodegradation time of the municipal solid waste (msw) in the landfill and can be replaced with m because t can only be expressed in number of months-m; it cannot be expressed in seconds, minutes, days, years.

The equation $[3+(n*8)]*t+7=[(n*12)+13]-t$, ® [Vieru, 2017a: pp. 436-454; Vieru, 2017b: pp. 191-209] or $[3+(n*8)]*t+7=[(n*12)+(12+1)-t]$ ®* [Vieru, 2017a: pp. 436-454], [Vieru, 2017b: pp. 191-209] expresses: if we add 7 to 3 times the time t, expressed by a number of months -m- of stationary municipal solid waste (msw) at a location in the landfill—is the same with deducting a time t (expressed by a number of months -m-) from 25.

In the above equation:

n is the number of the calendar year of disposal;

12—number of the calendar months of the year of disposal;

1 in (12 + 1) is 1 month needed to collect information regarding the municipal solid waste landfill analyzed;

t—time during which the municipal solid waste was stationary at the location in the landfill, expressed by the number of months -m-.

For each year of disposal, starting with the 2nd year, the equation changed its terms but mathematically it will always have a unique solution 3/2.

The number of month's -m- is defined for each reference year when it shall fulfill the condition:

1) $7 \le m \le 18$, $m \in$ N, [Vieru, 2017a: pp. 436-454], [Vieru, 2017b: pp. 191-209]

2) $\sum(m_1+m_2+m_3+\cdots+m_{n+1}) \le [(n*12)+13]-7$, ® [Vieru, 2017a: pp. 436-454]

Based on NOMOGRAMAVieru®, presented in **Figure 7**, for the reference year, we can establish the number of month's -m- (during which a certain amount of municipal solid waste (msw) degraded down to DOC (dissolved organic carbon).

6.3. Definition of Parameter *m*

m is the number of months during which maximum 45% of the municipal solid waste (msw) disposed or taken into account degrades at the landfill.

6.4. NOMOGRAMA of a Municipal Solid Waste Landfill

The calendar years and the years of calculation result from replacing 1, 2, 3, ..., 20, ..., 30 with the years 1992, 1993, 1994, 2011, 2012, 2013, ..., 2025, ..., 2030.

®* means that, in Romania, the calculation kit to estimate the CH_4emission from municipal solid waste landfills, the equation of a municipal solid waste landfill, NOMOGRAMA of a municipal solid waste landfill-NOMOGRAMA Vieru®-, and the working algorithm to estimate the emission of the CH_4 contained in the LFG are registered with ORDA (the Romanian Office for Intellectual Rights) on the name of Danila Vieru. Any other concerns or questions may be submitted via e-mail to danila.vieru@gmail.com. The calculation formula to estimate the CH_4 emission in the municipal solid wasteland fills in Romania can be applied to other countries with similar environmental conditions.

6.5. Equation of a Municipal Solid Waste Landfill

1) For a municipal solid waste landfill where the disposal of the municipal solid waste has ended, we can write the equation:

$$3t + 7 = 13 - t \tag{1}$$

where t is the time (expressed in number of months -m-) during which, for the reference year-T-of the emission of LFG with CH_4 content a certain amount of municipal solid waste (msw) degrades—$Q_{\text{mswdegradat},T}$-down to DOC which generates LFG with CH_4 content. The calculation range for the amount of municipal solid waste $Q_{\text{mswdegradat},T}$ is m = 6. Annually, for each m = 6, the $Q_{\text{msw},T}$ degraded down to DOC will be calculated. The reason of this calculation is: the municipal solid waste (msw) disposed of degrades down to DOC depending on the environmental conditions at the location of the landfill and there is no other municipal solid waste (msw) disposed to influence the LFG emission. For m = 6, the repetitive calculation will lead to zero emission at the landfill analyzed and implicitly the entire amount of municipal solid waste (msw) degraded down to DOC. The amounts of municipal solid waste consisting of plastic material with very long degradation time that form carbon deposits are not taken into account in this calculation.

2) For an operational municipal solid waste landfill (receiving, annually, a certain amount of municipal solid waste (msw)), the following equation shall be written:

$$(3 + 8n)t + 7 = (12n + (12 + 1)) - t \tag{2}$$

where t is the time (expressed by a number of months -m-) during which, in the reference year -T-, a certain amount of municipal solid waste (msw) degrades—$Q_{\text{mswdegradat},T}$-down to DOC (dissolved organic carbon) which will generate LFG with CH_4 content. For the reference year -T- of the emission of LFG with CH_4 content, it remains an amount of non-degraded municipal solid waste (msw) disposed of during the last 6 months (01.07 - 31.12) of the year when it was disposed of. The municipal solid waste that remains non-degraded in the reference year -T- shall be taken into account for the next year (see the working algorithm **Figure 7**).

The mathematical equation and the other equations that clarify the estimation of the CH_4 emission at the municipal solid waste landfills in Romania can be written as follows [Vieru, 2017a: pp. 436-454], [Vieru, 2017b: pp. 191-209]:

$$\mathrm{CH_4}\left(\mathrm{Gg/year}\right)_T = Q_{\mathrm{mswdegrad},T} * \%\mathrm{TDOC}_{\mathrm{dissolved},T} * \mathrm{DOC_f} * 16/12 * F * F_r, \quad ^{®*} \tag{1}$$

$$Q_{\mathrm{mswdegrad},T} = \left(Q_{\mathrm{msw},T} + Q_{\mathrm{msw},T-1}\right) * \left[1 - \exp\left(-Kt\right)\right]^{®*} \ [\mathrm{Gg}] \tag{2}$$

$$Q_{\mathrm{mswdegrad},T} = \left(Q_{\mathrm{msw},T} + Q_{\mathrm{mswundegra},T-1}\right) * \left[1 - \exp\left(-Kt\right)\right]^{®*} \ [\mathrm{Gg}] \tag{3}$$

$$Q_{\mathrm{mswundegrad},T} = \left(Q_{\mathrm{msw},T} + Q_{\mathrm{msw},T-1}\right) - Q_{\mathrm{mswdegrad},T} \quad ^{®*} \ [\mathrm{Gg}] \tag{4}$$

$$\mathrm{TDOC}_{\mathrm{dissolved},T} = \sum\left[A + B + C + D + E + G\right]^{®*} \ [\mathrm{Gg}] \tag{5}$$

$$A = Q_{\mathrm{mswdegrad},T} * \%Q_{\mathrm{mswbiodegrad},T} * k_0, \quad ^{®*} \ [\mathrm{Gg}] \tag{6}$$

$$B = Q_{\mathrm{mswdegrad},T} * \%Q_{\mathrm{msw(G+P)degrad},T} * k_1, \quad ^{®*} \ [\mathrm{Gg}] \tag{7}$$

$$C = Q_{\mathrm{mswdegrad},T} * \%Q_{\mathrm{msw(H+C+text.)degrad},T} * k_2, \quad ^{®*} \ [\mathrm{Gg}] \tag{8}$$

$$D = Q_{\mathrm{mswdegrad},T} * \%\mathrm{Msw}_{\mathrm{(wood+straw)degrad},T} * k_3, \quad ^{®} \ [\mathrm{Gg}] \tag{9}$$

$$E = Q_{\mathrm{mswdegrad},T} * \%\mathrm{msw}_{\mathrm{sludg.degrad},T} * k_n, \quad ^{®*} \ [\mathrm{Gg}] \tag{10}$$

$$G = Q_{\mathrm{mswdegrad},T} * \%Q_{\mathrm{mswind.degrad},T} * k_4, \quad ^{®*} \ [\mathrm{Gg}] \tag{11}$$

$$\%\mathrm{TDOC}_{\mathrm{dissolved},T} = \left(\mathrm{TDOC}_{\mathrm{dissolved},T}\right) / \left(Q_{\mathrm{mswtakenintoconsid},T}\right)^{®*} \ [\mathrm{Gg}] \tag{12}$$

$$Q_{\mathrm{mswtakenintoconsid},T} = Q_{\mathrm{msw},T} + Q_{\mathrm{mswundergrad},T-1}, \quad ^{®*} \ [\mathrm{Gg}] \tag{13}$$

where:

$Q_{\mathrm{msw},T}$—amount of municipal solid waste (msw) disposed of in the year T, [Gg];

$Q_{\mathrm{msw},T\text{-}1}$—amount of municipal solid waste (msw) disposed of in the year T_1, [Gg];

$Q_{\mathrm{mswdegrad.}T}$—amount of municipal solid waste (msw) degraded in the reference year regarding the estimation of the CH_4 emission [Gg];

$Q_{\mathrm{mswundegrad.}T}$—amount of municipal solid waste (msw) remained non-degraded in the year of calculation, [Gg];

$Q_{\mathrm{mswundegrad},T\text{-}1}$—amount de municipal solid waste (msw) remained non-degraded in the year T-1, taken into account to calculate %TDOC, [Gg];

K-degradation rate of the municipal solid waste (msw) disposed of that contain types of municipal solid waste (msw) in the landfill, in percentages [Vieru, 2017a: pp. 436-454], [Vieru, 2017b: pp. 191-209]; value of K for Romaniais defined depending on the rain water in the area if the landfill as well as other environmental conditions.

T-time expressed by the number of month's -m-. It can be expressed by the formulas: [$\frac{13-m}{12}$] or [$\frac{25-m}{12}$];

$Q_{\mathrm{mswbiodegrad.}}$—% of biodegraded municipal solid waste (msw) from the amount of municipal solid waste (msw) degraded in the year T;

$Q_{\mathrm{msw(G+P)}}$—% of municipal solid waste of (G + P) from the amount of municipal solid waste (msw) degraded in the year T;

$Q_{msw(P+C+tex)}$—% of municipal solid waste (P + C + tex) from the amount of municipal solid waste (msw) degraded in the year T;

$Q_{msw(wood+straw)}$—% of municipal solid waste (wood + straw) from the amount of municipal solid waste (msw) degraded in the year T;

$Q_{mswsludg.}$—% of sludge from the amount of municipal solid waste (msw) degraded in the year T;

$Q_{mswind.}$—% of industrial municipal solid waste (similar to household municipal solid waste) + sterile medical municipal solid from the amount of municipal solid waste (msw) degraded in the year T;

k_0—degradation rate of the biodegradable municipal solid waste, with CH_4 emission, 0.185 [-];

k_1—degradation rate of the municipal solid waste (G + P), with CH_4 emission, 0.1 [-];

k_2—degradation rate of the municipal solid waste (P + C + tex), with CH_4 emission, 0.06 [-];

k_3—degradation rate of the municipal solid waste (wood + straw), with CH_4 emission, 0.03 [-];

k_n—degradation rate of the municipal solid waste (sludge or mud), with CH_4 emission, 0.185 [-];

k_4—degradation rate of the municipal solid waste (industrial, similar to household municipal solid waste), with CH_4 emission, 0.09 [-];

$$\mathrm{TDOC}_{\mathrm{disoved}} = \sum \left(A + B + C + D + E + G \right)_T \text{ , [Gg]}$$

where: A, B, C, D, E, G amounts of DOC generated by the types of municipal solid waste (msw) that reached the landfill;

$Q_{mswtekenintoconsid.}$—amount of municipal solid waste (msw) disposed of in the year T ($Q_{msw,T}$) + amount of municipal solid waste (msw) remained non-degraded in the year $T-1$($Q_{mswundegrad,T-1}$), [Gg].

DOC_f-fraction of the municipal solid waste (msw) that biodegrade in the landfill due to the environmental conditions [%]. As a rule, it is pre-defined with values [0.5 - 0.77] according to the recommendations of the IPCC for CEECs. The empirical calculation, by using Tabarasan formula, [$0.014T + 0.28$] where $-T$ is the annual average temperature, in ˚C, for the environmental areas in Romania, yielded the values: 45%, 55%, 70%, 80%. There is a close relation between the outside temperature in the area of the municipal solid waste landfill (msw) and the inside of the municipal solid waste landfill.

1.3333, that is (16/12), is the conversion factor of the carbon in CH_4.

F—the correction factor of the emission of LFG with CH_4 content; it depends on the management of the municipal solid waste (msw) at the landfill; this factor involved the level of compaction of the municipal solid waste (msw) in the landfill and its values are:

1) if the municipal solid waste is not compacted, (0.40);

2) if the municipal solid waste is compacted by using a compactor and a bull-

dozer (0.6);

3) if the municipal solid waste is compacted with two bulldozers and two compactors (0.8 - 0.9). To note that there is no value of 1 because there is no perfect management of the municipal solid waste (msw).

F_r is a correction factor of the fraction of CH_4 in the LFG. According to the recommendations of the IPCC experts, these values are between 40% - 60% (Pipatti & Svardal, 2006).

7. Case Study

For this study, we have used information received from the manager of the landfill about the amounts of municipal solid waste (msw) disposed of volumes of LFG with CH_4 content collected in 2011 and 2012, as follows:

- 2011-7,500,000 m^3, 5640 [Gg], for the amount of municipal solid waste (msw) (see below);
- 2012-7,470,000 m^3, 5363 [Gg], for the amount of municipal solid waste (msw) (see below);

For 2011 and 2012, the emission of CH_4 is calculated as the difference between the amounts of CH_4 generated [Gg], calculated and collected.

To calculate that Equation (1) has been used, as follows:

$$\mathrm{CH_4}\left(\mathrm{Gg/year}\right) = \left(\mathrm{Q}_{\mathrm{mswdegrad},T}\right)*\left(\%\mathrm{TDOC}_{\mathrm{disolved},T}\right)*\left(\mathrm{DOC_f}\right)*\left(16/12\right)*\left(F\right)*\left(F_r\right)^{®*}, \text{[Gg]} \quad (1)$$

[Vieru, 2017a: pp. 436-454], [Vieru, 2017b: pp. 191-209]

where:

$Q_{\mathrm{mswdegrad},T}$, is the amount of municipal solid waste (msw) degraded in the reference year A_T, based on the value -m-, according to the methodology previously presented. For the estimation, Equation (3) has been used:

$$Q_{\mathrm{mswdegrad},T} = \left(Q_{\mathrm{msw},T} + Q_{\mathrm{mswundegrad},T-1}\right)*\left[1-\exp\left(-Kt\right)\right]^{®*} \ \text{[Gg]}, \quad (3)$$

$$Q_{\mathrm{mswdegrad},2011} = \left(Q_{\mathrm{msw},2011} + Q_{\mathrm{mswundegrad},2010}\right)*\left[1-\exp\left(-Kt\right)\right] \ \text{[Gg]}$$

where:

$Q_{\mathrm{msw},2011} = 361.000$ [Gg], amount of municipal solid waste (msw) disposed of in the landfill in 2011;

$Q_{\mathrm{mswundegrad},2010} = 496.989$ [Gg], amount of municipal solid waste (msw) remained non-degraded, in the landfill in 2010, $\left(1-\exp\left(-Kt\right)\right)$ expressed $\left(1-\mathrm{e}^{-K\left(\frac{25-m}{12}\right)}\right)$, m = 7 (m-value for the year of calculation A_T = 11; it shall fulfill 2 conditions:

1) $7 \le m \le 18$,

2) $\sum 0 + m_1 + m_2 + m_3 + m_4 + m_5 + m_6 + m_7 + m_8 + m_9 + m_{10} + m_{11} \le \left(145-7\right)$.

The equation: $\sum 0+9+7+14+13+12+11+9+8+7+10+7 \le 13$, yield 107 ≤ 138 [Vieru, 2017a: pp. 436-454], [Vieru, 2017b: pp. 191-209].

Consequently:

$$Q_{\text{mswdegrad},2011} = (361.000 + 496.989) * \left(1 - e^{-K\left(\frac{25-m}{12}\right)}\right) \quad [\text{Gg}],$$

For $K = 0.4$ and $m = 7$, the equation becomes:

$$Q_{\text{mswdegrad},2011} = (361.000 + 496.989) * \left(1 - e^{-K\left(\frac{25-7}{12}\right)}\right) \quad [\text{Gg}],$$

$$Q_{\text{mswdegrad},2011} = 387.125 \quad [\text{Gg}].$$

$$Q_{\text{mswundegrad},2011} = (361.000 + 496.989) - 387.125 \quad [\text{Gg}]$$

$$Q_{\text{mswundegrad},2011} = 470.864 \quad [\text{Gg}]$$

Equation (12) calculated $\%\text{TDOC}_{\text{dissolved},T}$:

$$\%\text{TDOC}_{\text{dissolved},T} = \left(\text{TDOC}_{\text{dissolved},T}\right) / \left(Q_{\text{msw taken in to consid},T}\right), [\%], ^{®*} \tag{12}$$

$\text{TDOC}_{\text{dissolved},T}$ *is the Total DOC in the year T*, [Gg].

It has been defined by using Equation (5):

$$\text{TDOC}_{\text{dissolved},2011} = \sum \left[A + B + C + D + E + G\right] \quad [\text{Gg}], ^{®*} \tag{5}$$

A, *B*, *C*, *D*, *E*, *G* are calculated for 2011, by using appropriate equations:

$$A = Q_{\text{mswdegrad},T} * \%\text{MSW}_{\text{biodegrad},T} * k_0 \quad [\text{Gg}], ^{®*} \tag{6}$$

$$A_{2011} = Q_{\text{mswdegrad},2011} * \%\text{MSW}_{\text{biodegrad},2011} * k_0, [\text{Gg}]$$

$k_0 = 0.185$ -Degradation rate down to DOC of the biodegradable municipal solid waste (msw) according to chapter V—Municipal solid waste (recommended by IPCC).

$$Q_{\text{mswdegrad},2011} = 387.125 \quad [\text{Gg}];$$

$\%\text{MSW}_{\text{biodegrad},2011} = 51.2$, percentage pre-defined for 2011 (see Table 1);

$$A_{2011} = 387.125 * 0.512 * 0.185 = 36.668 \quad [\text{Gg}]$$

$$B = Q_{\text{mswdegrad},T} * \%\text{MSW}_{(\text{G+P})\text{degrad},T} * k_1 \quad [\text{Gg}], ^{®*} \tag{7}$$

$$B_{2011} = Q_{\text{mswdegrad},2011} * \%\text{MSW}_{(\text{G+P})\text{degrad},2011} * k_1, [\text{Gg}]$$

$k_1 = 0.1$ -degradation rate down to DOC of the municipal solid waste (P + G) according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{(G+P)\text{degrad},2011} = 16$, percentage pre-defined for 2011 (see Table 1);

$$B_{2011} = 387.125 * 0.16 * 0.1 = 6.194, [\text{Gg}]$$

$$C = Q_{\text{mswdegrad},T} * \%\text{MSW}_{(\text{P+C+tex.})\text{degrad},T} * k_2 \quad [\text{Gg}] ^{®*} \tag{8}$$

$$C_{2011} = Q_{\text{mswdegrad},2011} * \%\text{MSW}_{(\text{P+C+text.})\text{degrad},2011} * k_2 \quad [\text{Gg}]$$

$k_2 = 0.06$ -degradation rate down to DOC of the municipal solid waste (P + C + tex) according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{(\text{P+C+text.})\text{degrad},2011} = 16.8$ percentage predefined for 2011 (see Table 1);

$$C_{2011} = 387.125 * 0.168 * 0.06 = 3.902 \quad [\text{Gg}]$$

$$D = Q_{\text{mswdegrad},T} * \%\text{MSW}_{(\text{Wood+straw})\text{degrad},T} * k_3, \quad [\text{Gg}] ^{®*} \tag{9}$$

$$D_{2011} = Q_{\text{mswdegrad},2011} * \%\text{MSW}_{(\text{Wood+straw})\text{degrad},2011} * k_3 \text{, [Gg]}$$

$k_3 = 0.03$ -degradation rate down to DOC of the municipal solid waste (wood + straw) according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{(\text{wood+straw})\text{degrad},2011} = 3$, percentage predefined for 2011 (see Table 1);

$$D_{2011} = 387.125 * 0.03 * 0.03 = 0.348 \text{, [Gg]}$$

$$E = Q_{\text{mswdegrad},T} * \%\text{MSW}_{\text{sludg,degrad},T} * k_n \text{, [Gg]} \quad ^{®*} \tag{10}$$

$$E_{2011} = Q_{\text{mswdegrad},2011} * \%\text{MSW}_{\text{sludg,degrad},2011} * k_n \text{, [Gg]}$$

$k_n = 0.185$ -Degradation rate down to DOC of thesludge according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{\text{sludg,degrad},2011} = 1$, percentage predefined for 2011 (see Table 1);

$$E_{2011} = 387.125 * 0.01 * 0.185 = 0.716 \text{, [Gg]}$$

$$G = Q_{\text{mswdegrad},T} * \%\text{MSW}_{\text{ind,degrad},T} * k_4 \text{, [Gg]} \quad ^{®*} \tag{11}$$

$$G_{2011} = Q_{\text{mswdegrad},2011} * \%\text{MSW}_{\text{ind,degrad},2011} * k_4 \text{, [Gg]}$$

$k_4 = 0.09$ -Degradation rate down to DOC of the industrial municipal solid waste (msw) according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{\text{ind,degrad},2011} = 12$, percentage predefined for 2011(see Table 1);

$$G_{2011} = 387.125 * 0.12 * 0.09 = 4.181 \text{, [Gg]}$$

$$\text{TDOC}_{\text{dissolved},2011} = 36.668 + 6.194 + 3.902 + 0.348 + 0.716 + 4.181 = 52.01 \text{, [Gg]}$$

$$\%\text{TDOC}_{\text{dissolved},T} = \left(\text{TDOC}_{\text{dissolved},T}\right) / \left(Q_{\text{msw taken in to consid},T}\right) \text{, [\%]} \quad ^{®*} \tag{12}$$

$$\%\text{TDOC}_{\text{dissolved},2011} = \left(\text{TDOC}_{\text{dissolved},2011}\right) / \left(Q_{\text{msw taken in to consid},2011}\right) \text{ [\%]}$$

$$Q_{\text{msw taken in to consid},T} = Q_{\text{msw},T} + Q_{\text{msw undegrad},T-1} \text{, [Gg]} \quad ^{®*} \tag{13}$$

$$Q_{\text{msw taken in to consid},2011} = Q_{\text{msw},2011} + Q_{\text{mswundegrad},2010} \text{, [Gg]}$$

$$Q_{\text{msw taken in to consid},2011} = 361.000 + 496.989 = 857.989 \text{, [Gg]}$$

$\%\text{TDOC}_{2011} = 52.01/857.989 = 0.06062$; that is 6.062 %.

The amount of CH_4 generated for 2011 is calculated with Equation (1), as follows:

$$(\text{CH}_4)_{\text{generated}/2011} = 387.125 * 0.06062 * 1.3333 * 0.5 * 0.8 * 0.5 = 6.25785 \text{, [Gg]}$$

where:

- 385.125 [Gg] is the amount of municipal solid waste (msw) degraded in 2011 that generated DOC and further on CH_4;
- 6.062 is %TDOC in the landfill;
- 0.5 is the DOC_f implicit value that takes into account the environmental conditions of the location of the municipal solid waste landfill;
- 1.3333 (16/12) is C in CH_4;
- 0.8 is the management of the municipal solid waste landfill in the reference year;

- 0.5 is the content % CH_4 in the LFG, [%].

To note that the CH_4 emission increasing gradually, not suddenly, according to the environmental conditions at the location of the landfill. A certain amount of municipal solid waste will remain non-degraded and will be taken into account for the next year, so that the degradation of the municipal solid waste (msw) will generate, again, DOC and CH_4.

In 2011, the economic operator collected 5640 [Gg] CH_4, which was used for green energy production.

At the same time, the operatore mitted the difference in the atmosphere:

$$(\mathrm{CH}_4)_{\text{generated},2011} - (\mathrm{CH}_4)_{\text{collected},2011} = 6.25785 - 5.640 = 0.61785 \quad [\mathrm{Gg}]$$

The equivalent CO_2 is:

$$(\mathrm{CO}_2)_{\text{equivalent},2011} = (\mathrm{CH}_4)_{\text{emitted},2011} * 21 = 0.61785 * 21 = 12.97485, \ [\mathrm{Gg}]$$

In 2012, for the same municipal solid waste landfill located in Chitila-Rudeni-Iridex, the amount of municipal solid waste (msw) disposed of was:

$Q_{\text{msw},2012} = 371.568$, [Gg] municipal solid waste (msw) disposed of at the landfill.

$Q_{\text{mswundegrad},2011} = 470.864$ [Gg]amount of municipal solid waste (msw) remained non-degraded since 2011;

$$Q_{\text{msw taken in to consid},T} = Q_{\text{msw},T} + Q_{\text{mswundegrad},T-1}, \ [\mathrm{Gg}] \tag{13}$$

$$Q_{\text{mswtaken in to consid},2012} = 371.568 + 470.864 = 842.432 \quad [\mathrm{Gg}]$$

To calculate the amount of municipal solid waste (msw) degraded in 2012, we used Equation (3):

$$Q_{\text{mswdegrad},T} = \left(Q_{\text{msw},T} + Q_{\text{mswundegrad},T-1}\right) * \left[1 - \exp(-Kt)\right] \quad [\mathrm{Gg}] \tag{3}$$

K = 0.4 and m = 9, according to the NOMOGRAMA of the landfill, (see **Figure 7**).

$$Q_{\text{mswdegrad},2012} = 350.452 \quad [\mathrm{Gg}],$$

For the amount of municipal solid waste (msw) remained non-degraded at the end of 2012, we used Equation (4):

$$Q_{\text{mswundegrad},2012} = \left(Q_{\text{msw},2012} + Q_{\text{mswundegrad},2011}\right) - Q_{\text{degrad},2012} \tag{4}$$

$$Q_{\text{mswundegrad},2012} = (371.568 + 470.864) - 350.452 = 491.980 \quad [\mathrm{Gg}]$$

By using Equation (12), we calculated $\%\mathrm{TDOC}_{\text{dissolved},T}$:

$$\%\mathrm{TDOC}_{\text{dissolved},T} = \left(\mathrm{TDOC}_{\text{dissolved},T}\right) / \left(Q_{\text{msw taken in to consid},T}\right) \quad [\%] \tag{12}$$

$\mathrm{TDOC}_{\text{dissolved},T}$—*Total DOC(Organic Dissolved Carbon)*, was established by using Equation (5):

$$\mathrm{TDOC}_{\text{dissolved},2012} = \sum \left[A + B + C + D + E + G\right] \quad [\mathrm{Gg}] \tag{5}$$

A, *B*, *C*, *D*, *E*, *G* are calculated for 2012, by using appropriate equations:

$$A_{2012} = Q_{\text{mswdegrad},2012} * \%\text{MSW}_{\text{biodegrad},2012} * k_0, \ [\text{Gg}] \tag{6}$$

$k_0 = 0.185$ degradation rate down to DOC of the biodegradable municipal solid waste, according to chapter V—Municipal solid waste (recommended by IPCC);

$$Q_{\text{mswdegrad},2012} = 350.452 \ \ [\text{Gg}]$$

$\%Q_{\text{mswbidegrad},2012} = 58$, percentage predefined for 2012 (see Table 1);

$$A_{2012} = 350.452 * 0.58 * 0.185 = 37.603 \ \ [\text{Gg}]$$

$$B = Q_{\text{mswdegrad},T} * \%\text{MSW}_{(\text{G+P})\text{degrad},T} * k_1, \ [\text{Gg}] \tag{7}$$

$$B_{2012} = Q_{\text{mswdegrad},2012} * \%\text{MSW}_{(G+\text{P})\text{degrad},2012} * k_1, [\text{Gg}]$$

$k_1 = 0.1$ -Degradation rate down to DOC of the municipal solid waste (P + G) according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{(\text{G+P})\text{degrad},2012} = 13.8$, percentage predefined for 2012 (see Table 1);

$$B_{2012} = 350.452 * 0.138 * 0.1 = 4.836, [\text{Gg}]$$

$$C = Q_{\text{mswdegrad},T} * \%\text{MSW}_{(\text{P+C+text.})\text{degrad},T} * k_2, \ [\text{Gg}] \tag{8}$$

$$C_{2012} = Q_{\text{mswdegrad},2012} * \%\text{MSW}_{(\text{P+C+text.})\text{degrad},2012} * k_2, [\text{Gg}]$$

$k_2 = 0.06$ -Degradation rate down to DOC of the municipal solid waste (P + C + tex) according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{(\text{P+C+text.})\text{degrad},2012} = 10.7$, percentage predefined for 2012 (see Table 1);

$$C_{2012} = 350.452 * 0.107 * 0.06 = 2.249, [\text{Gg}]$$

$$D = Q_{\text{mswdegrad},T} * \%\text{MSW}_{(\text{wood+straw})\text{degrad},T} * k_3, [\text{Gg}] \tag{9}$$

$$D_{2012} = Q_{\text{mswdegrad},2012} * \%\text{MSW}_{(\text{wood+straw})\text{degrad},2012} * k_3, [\text{Gg}]$$

$k_3 = 0.03$ -Degradation rate down to DOC of the municipal solid waste (wood + straw) according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{(\text{wood+straw})2012} = 3$, percentage predefined for 2012 (see Table 1);

$$D_{2012} = 350.452 * 0.03 * 0.03 = 0.315 \ \ [\text{Gg}]$$

$$E = Q_{\text{mswdegrad},T} * \%\text{MSW}_{\text{sludg,degrad},T} * k_n, [\text{Gg}] \tag{10}$$

$$E_{2012} = Q_{\text{mswdegrad},2012} * \%\text{MSW}_{\text{sludg,degrad},2012} * k_n, [\text{Gg}]$$

$k_n = 0.185$ -degradation rate down to DOC of the sludge according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{\text{sludg,degrad},2012} = 1.5$, percentage predefined for 2012 (see Table 1);

$$E_{2012} = 350.452 * 0.015 * 0.185 = 0.973, [\text{Gg}]$$

$$G = Q_{\text{mswdegrad},T} * \%\text{MSW}_{\text{ind,degrad},T} * k_4, [\text{Gg}] \tag{11}$$

$$G_{2012} = Q_{\text{mswdegrad},2012} * \%\text{MSW}_{\text{ind,degrad},2012} * k_4, [\text{Gg}]$$

$k_4 = 0.09$, degradation rate down to DOC of the industrial municipal solid waste + sterile medical municipal solid waste according to chapter V—Municipal solid waste (recommended by IPCC);

$\%\text{MSW}_{\text{ind,degrad},2012} = 13$, percentage predefined for 2012 (see Table 1);

$$G_{2012} = 350.452 * 0.13 * 0.09 = 4.100 \text{ , [Gg]}$$

$$\text{TDOC}_{\text{dissolved,2012}} = 37.603 + 4.836 + 2.249 + 0.315 + 0.973 + 4.100 = 50.077 \quad \text{[Gg]}$$

$$\%\text{TDOC}_{\text{dissolved},T} = \left(\text{TDOC}_{\text{dissolved},T}\right) / \left(Q_{\text{msw taken in to consid},T}\right) \quad [\%] \tag{12}$$

$$\%\text{TDOC}_{\text{dissolved,2012}} = \left(\text{TDOC}_{\text{dissolved,2012}}\right) / \left(Q_{\text{msw taken in to consid,2012}}\right) \quad [\%]$$

$$Q_{\text{msw taken in to consid},T} = Q_{\text{msw},T} + Q_{\text{mswundegrad},T-1} \text{ , [Gg]} \tag{13}$$

$$Q_{\text{msw taken in to consid,2012}} = Q_{\text{msw,2012}} + Q_{\text{mswundegrad,2011}} \text{ , [Gg]}$$

$$Q_{\text{msw taken in to consid,2012}} = 371.568 + 470.864 = 842.432 \quad \text{[Gg]}$$

$\%\text{TDOC}_{2012} = 50.077/842.432 = 0.05944$; that is 5.944%.

The amount of CH_4 generated in 2012 is calculated by applying Equation (1), as follows:

$$\left(CH_4\right)_{\text{generated/2012}} = 350.452 * 0.05944 * 1.3333 * 0.5 * 0.9 * 0.5 = 6.24945 \quad \text{[Gg]}$$

where:

- 350,452 [Gg] is the amount of municipal solid waste (msw) degraded in 2012 that generated DOC and CH_4;
- 5.944 is %TDOC in the landfill;
- 0.5 is the DOC_f implicit value that takes into account the environmental conditions of the location of the municipal solid waste landfill;
- 1.3333 (16/12) is the C in CH_4;
- 0.9 is the management of the municipal solid waste landfill in the year of calculation;
- 0.5 is the content % CH_4 in the LFG, [%].

To note that the CH_4 emission increasing gradually, not suddenly, according to the environmental conditions of the location of the municipal solid waste landfill. A certain amount of municipal solid waste (msw) from the municipal solid waste landfill will remain non-degraded and shall be taken into account for the next year, so that the degradation process of the municipal solid waste (msw) will generate again DOC and CH_4.

For 2012, the economic operator collected 5363 [Gg] CH_4, amount used for green energy production.

At the same time, the operator emitted the difference in the atmosphere:

$$\left(CH_4\right)_{\text{generated,2012}} - \left(CH_4\right)_{\text{collected,2012}} = 6.24945 - 5.363 = 1.1315 \quad \text{[Gg]}$$

The equivalent CO_2 is:

$$\left(CO_2\right)_{\text{equivalent,2012}} = \left(CH_4\right)_{\text{emitted,2012}} * 21 = 1.1315 * 21 = 23.7615 \quad \text{[Gg]}$$

For the municipal solid waste landfill located in Chitila-Rudeni-Iridex, data (amounts of municipal solid waste (msw) disposed of/volume of CH_4 collected) has been received for 2013, 2014, 2015, 2016. The graph of the evolution of the greenhouse effect in Chitila-Rudeni-Iridex landfill for 2000-2016 is presented in **Figure 9**.

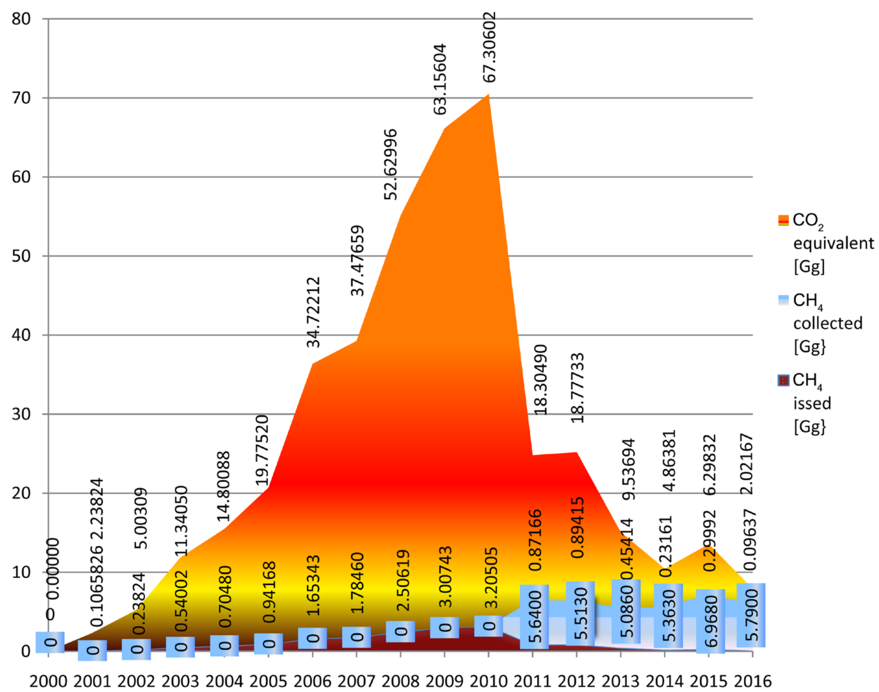

Figure 9. Graph of the evolution of the greenhouse effect in Chitila-Rudeni-Iridex municipal solid waste landfill between 2000-2016.

Starting with 2011, the greenhouse effect significantly decreased.

8. Conclusion

The estimation formula used to calculate the emission of CH_4 in the municipal solid waste landfills proposed by us is reproducible, credible and coherent. Due to its working methodology, it does not affect the achievements of other researchers interested in the estimation of the CH_4 emissions in municipal solid waste landfills, as it uses:

- The variation of the air pressure;
- The calculation of stoichiometric coefficients of the many reactions that take place in the municipal solid waste landfill;
- It establishes the LFG flow with CH4 content and the calculation of the LFG flow;
- It collects information about: environmental temperature and precipitations at the location of the landfill, the variation of the air pressure, the orientation and the speed of the wind, the thickness of the cover of the landfill, the permeability of the coverage material of the landfill and others;
- It determines the pressure of the LFG in the municipal solid wasteland fill, it correlates it with the air pressure and it calculates then the CH_4 flow.

All the findings of the researchers, all empirical and advanced calculation formulas can be used by the government or by the owner of the municipal solid wasteland fill.

Eventually, the decision to calculate by using a certain technology or a certain algorithm will be taken based on the costs involved, the duration and the accuracy of the results.

The formula proposed by us to calculate the estimation of the CH_4 emission does not imply the collection of lots of information [amount of municipal solid waste (msw), [Gg], disposed of per year, and the percentages of types of municipal solid waste (msw): rapidly biodegradable, moderately biodegradable, slowly biodegradable in the landfill], the environmental conditions at the location (wet periods of time with precipitations, dry periods without precipitations, alternation of freezing/de-freezing periods expressed by a number of months -*m*-), number of bulldozers and compactors that work at the landfill, all that is information of interest. The environmental conditions expressed by the number of months *m* lead to the biodegradation of the municipal solid waste with CH_4 emissions.

We believe that NOMOGRAMA®, typical of all municipal solid wasteland fills because it includes the year when the disposal of the municipal solid waste (msw) started, is extremely interesting because it allows calculation of the amount de municipal solid waste (msw) degraded in the reference year that, through the amount of DOC, allows the estimation of the CH_4 generated. More attention shall be given to the quality of the silty leachate that can be introduced in the landfill, if the air intrusion is properly controlled.

The working algorithm® allows removal from the calculation of the types of municipal solid waste (msw) that are not biodegradable but reach the municipal solid wasteland fill.

The realities of the 21st century reveal the need to manage the LFG in an ecological-rational manner in order to achieve the diminution of the greenhouse effect generated by the management of the municipal solid waste (msw). Definitely, the LFG with CH_4 content has an economic value that can be enhanced through proper treatment and brought to the quality of the natural CH_4.

9. Clarification

For clarifications regarding the working methodology and the approach of the New Method of calculating the emission of the LFG with CH4 content, the works from the bibliography, numbered [Vieru, 2017a: pp. 436-454] and [Vieru, 2017b: pp. 191-209], will be consulted. In the 2 articles, there is enough data leading to the clarification of possible ambiguities. For any other assumptions or positions I state: all models for calculating the emission of the LFG with CH_4 content from landfills (msw) presented by other researchers are valid. When implementing a model, the realization costs will make a difference. I also state that Danila Vieru's method of calculating the emission of LFG with CH_4 content does not lead to high costs. It requires only specifications regarding the percentage composition of the waste (msw) arrived in the landfill (msw); important: the amount of waste (msw) disposed of at the considered landfill (expressed in SI (international system of units)) is also a necessity, the percentage estimation of the types of waste arrived in the landfill. Any ambiguities or questions, raised when reading this document, can be resolved, in writing, to the email address danila.vieru@gmail.com, the author of the proposed working method.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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