POLYTECHNIC UNIVERSITY OF TURIN, ITALY
Department of Environment, Land and Infrastructure Engineering (DIATI)

PHD THESIS SUMMARY

STUDIES AND RESEARCH REGARDING THE EVALUATION OF TECHNOLOGICAL ASPECTS FOR THE POST-CLOSURE ACTIVITY OF LANDFILLS FOR MUNICIPAL SOLID WASTE

Scientific tutors:
Prof. dr. Silvia FOIREE
Prof. dr. Giuseppe GENON
Prof. dr. Eng. Dr. h. c. Valentin NEDEFF

Polytechnic University of Turin, Italy
Polytechnic University of Turin, Italy
„Vasile Alecsandri” University of Bacău, Romania

Eng. Mihai-Cosmin BELCIU

Bacău
2016
CONTENTS

INTRODUCTION .............................................................................................................................. 9

CHAPTER 1. THE CURRENT STATE OF WASTE MANAGEMENT AND TREATMENT ......................................................... 12

1.1. Waste and waste management - ways of approaching ........................................ 12
1.2. Legislative issues concerning waste management ........................................... 13
   1.2.1. International legislation .................................................................................. 13
   1.2.2. European legislation ....................................................................................... 13
   1.2.3. Legislation in Italy .......................................................................................... 14
   1.2.4. Legislation in Romania .................................................................................. 14
1.3. Issues regarding the dynamics of municipal solid waste ............................ 15
1.4. Municipal waste generation and the waste management ........................... 17
   1.4.1. Municipal solid waste generated in Europe .................................................... 17
   1.4.2. Municipal waste treatment in Europe ............................................................ 19
   1.4.3. Waste treatment by country .......................................................................... 21
   1.4.4. Strategies and tendencies .............................................................................. 23

CHAPTER 2 THEORETICAL ASPECTS CONCERNING WASTE AND WASTE MANAGEMENT ....................................................... 24

2.1. Waste - general characterization .......................................................... 24
   2.1.1. The physical properties of the waste ............................................................... 25
   2.1.2. The chemical properties of the waste ............................................................. 27
   2.1.3. The biological properties of the waste ............................................................ 27
2.2. Landfills .......................................................................................................... 28
   2.2.1. Landfill design and construction ................................................................. 31
      2.2.1.1. Waterproofing landfill bottom and sidewalls ........................................ 31
   2.2.2. The drainage system of water from precipitations ....................................... 32
   2.2.3. Leachate and biogas collection systems .......................................................... 32
   2.2.4. The monitoring system .................................................................................. 35
   2.2.5. Waste compaction .......................................................................................... 35
   2.2.6. Landfill lifecycle ............................................................................................. 37
2.3. Characteristics of landfills products ......................................................... 39
   2.3.1. Leachate ......................................................................................................... 39
      2.3.1.1. Leachate lifecycle ...................................................................................... 39
CHAPTER 3. ESTIMATIVE MATHEMATICAL MODELS DESCRIBING LEACHATE AND BIOGAS QUANTITATIVE, QUALITATIVE AND KINETIC ASPECTS .......................................................... 55/12

3.1. Mathematical modelling of leachate flow and transport prediction 56/12

3.1.1. HELP Model ........................................................................... 57
3.1.2. Serial Water Balance Method .................................................... 58
3.1.3. Hydrological Mass Balance ......................................................... 59
  3.1.3.1. Precipitation ........................................................................ 60
  3.1.3.2. Run-off(R or R*) ................................................................. 60
  3.1.3.3. Evapotranspiration ............................................................... 61
  3.1.3.4. Evaporation ........................................................................ 65
  3.1.3.5. Water infiltration through landfill surface ............................... 66
  3.1.3.6. Moisture content variation (ΔU) ........................................... 67
3.1.4. MODFLOW SURFACT Model .................................................... 68
3.1.5. PITTLEACH-2 Model ............................................................... 69
3.1.6. Mathematical model used to simulate leachate generation and transport ............................................................................. 70

3.2. Mathematical model used to estimate biogas generation ........... 71/13

3.2.1. Empirical models ..................................................................... 73
3.2.2. Stoichiometric models .............................................................. 76
3.2.3. Biochemical models ................................................................. 78
3.2.4. Zero-order Models ................................................................. 79
3.2.5. First-order Models ............................................................... 79
3.2.6. Second Order Models ......................................................... 80
3.2.7. Multiphase Models ............................................................. 80
3.2.8. Scholl Canyon Model ......................................................... 81
3.2.9. Palos Verdes Model ............................................................ 83
3.2.10. U.S. EPA LandGEM Model ................................................ 84

CHAPTER 4. CASE STUDIES: LANDFILLS ANALYSED IN ITALY AND ROMANIA ........................................ 87/15

4.1. Turin Landfill, Italy ................................................................. 88/16
   4.1.1. Description, construction and management ......................... 88
   4.1.2. Landfill structure ............................................................ 89
   4.1.3. Types of waste stored in landfill ....................................... 90
   4.1.4. Leachate collection system .............................................. 91
   4.1.5. Biogas collection system .................................................. 91
4.2. Potenza Landfill, Italia ......................................................... 92/18
   4.2.1. Description, construction and management ......................... 92
   4.2.2. Landfill structure ............................................................ 93
   4.2.3. Types of waste stored in landfill ....................................... 93
   4.2.4. Leachate collection system .............................................. 93
   4.2.5. Biogas collection system .................................................. 93
4.3. Cozzo Vulturo Landfill in Enna, Italia .................................. 93/18
   4.3.1. Description, construction and management ......................... 93
   4.3.2. Landfill structure ............................................................ 94
   4.3.3. Types of waste stored in landfill ....................................... 95
   4.3.4. Leachate collection system .............................................. 95
   4.3.5. Biogas collection system .................................................. 95
4.4. Bacău Landfill, Romania ...................................................... 95/19
   4.4.1. Description, construction and management ......................... 95
   4.4.2. Landfill structure ............................................................ 97
   4.4.3. Types of waste stored in landfill ....................................... 98
   4.4.4. Leachate collection system .............................................. 99
   4.4.5. Biogas collection system .................................................. 99
6.1. Data used to verify and assess mathematical models to calculate the estimated production of leachate and biogas ................................................. 191/97
6.2. Evaluation of mathematical models used to calculate the estimated production of leachate ................................................................. 195
   6.2.2. Calibration of Serial Water Balance Method for analyzed case studies. Comparative analysis ................................................................. 198
   6.2.3. Results and discussions ................................................................ 199
6.3. Evaluation of mathematical models used to calculate the estimated production of biogas ........................................................................... 201/99
   6.3.1. Calibration of Stoichiometric Model for analyzed case studies. Comparative analysis ................................................................. 201
   6.3.2. Calibration of U.S. EPA LandGEM Model for analyzed case studies. Comparative analysis ................................................................. 203
   6.3.3. Results and discussions ................................................................ 204

CHAPTER 7. MATHEMATICAL MODELS DEVELOPED TO DESCRIBE QUANTITATIVE, QUALITATIVE AND KINETICS ASPECTS APPLIED FOR DIFFERENT CASE STUDIES .......... 206/101

7.1. The elaboration of mathematical model to estimate production capacity of leachate and biogas from landfills in Italy and Romania .......... 206/101
   7.1.1. The elaboration of mathematical model for the production of leachate that can be collected from landfills ................................. 206/101
   7.1.2. The elaboration of mathematical model for the production of biogas that can be collected from landfills ...................................................... 211/106
7.2. Mathematical model evaluation ........................................................... 215/110
   7.2.1. The evaluation of mathematical model generated by TableCurve 3D software ...................................................................................... 216/111

CHAPTER 8. FACTORS THAT CAN LEAD TO LARGE DISCREPANCIES BETWEEN ACTUAL VALUES AND THE VALUES CALCULATED USING MATHEMATICAL MODELS USED FOR DIFFERENT CASE STUDIES FOR LEACHATE AND BIOGAS232/125

CHAPTER 9. ENVIRONMENTAL IMPACT ASSESSMENT GENERATED BY LANDFILLS FROM ITALY AND FROM ROMANIA ......................................................... 236/128

CHAPTER 10. TECHNICAL, ECONOMICAL AND ECOLOGICAL ASPECTS OF LANDFILLS FOR MUNICIPAL SOLID WASTE. ................................................................. 242/131
CHAPTER 11 GENERAL CONCLUSIONS ........................................248/136
CHAPTER 12 RECOMMENDATIONS BASED ON RESEARCH AND
COMPARATIVE ANALYSIS CONCERNING LANDFILLS FOR
MUNICIPAL SOLID WASTE FROM ITALY AND ROMANIA .266/153
BIBLIOGRAPHY .................................................................................267/156
LIST OF FIGURES ..................................................................................279
LIST OF TABLES .....................................................................................288

Note: The numbering of chapters, Figures, mathematical relations,
Tables, and references used are those corresponding with thesis.
CHAPTER 1
THE CURRENT STATE OF WASTE MANAGEMENT AND TREATMENT

1.2. Legislative issues concerning waste management

Waste management is a current issue worldwide, related to the fact that, in the last few years, there has been identified an increase and also a diversification of activities in all economic and social sectors, leading to an ascending dynamics of the amount of generated waste [116].

A policy of waste recycling and reuse has been developed in the European Union states in the recent decades, which determined, in the EU-27, an average decrease about 20 % weight/weight from the total quantity of municipal solid waste disposed in landfills between 2002 ÷ 2012. However, in 2012 an amount of 32% weight/weight from the total quantity of generated waste was disposed in landfills. As far as the situations in Italy and Romania are concerned, the amounts of disposed waste were 38% and 78% respectively [59].

In Italy, waste management activity is based on the Italian Legislative Decree 36/2003 [82]. This decree implements Directive 1999/31/EC on the waste landfills. This document encourages the practice of selecting biodegradable in landfill [46, 55, 82, 91].

Fig. 1. The hierarchy of waste management [57, 80].

In Romania, Law 211/2011 implements several EU directives on waste and waste management [80].
The primary objective of waste management is to reduce the amount of generated waste. The necessary options to reduce the amount of waste refer to (Figure 1) [57, 80]:

- source reduction: applying modern technologies in waste generating activities;
- reduction of waste flow amounts: implementing the best available practices in all the waste generators fields;
- Waste recovery: reuse, recycling and energy recovery;
- Waste disposal: standardized methods of incineration and storage in landfills.

Figure 5 presents a comparative analysis of the amounts of waste deposited in landfills in Romania and Italy. In Italy, this method of waste disposal presents a decreasing tendency, in accord with the European tendency to reduce the amount of waste deposited in landfills. [58, 61, 62, 64-66].

![Graph showing waste stored in landfills in Italy and Romania]

**Fig. 5.** The amount of waste stored in landfills in Italy and Romania during 1995 ÷ 2013 [58, 61, 62, 64-66].

**CHAPTER 2**
THEORETICAL ASPECTS CONCERNING WASTE AND WASTE MANAGEMENT

2.1. Waste - general characterization

The main factors influencing the composition and waste generation rate are [99]:
- Climate and seasonal variations;
- Financial resources available for municipalities and for landfill operators;
- Region’s economy;
- Physical characteristics of cities;
- Social and religious customs;
- Awareness of public health;
- Quality management and technical capacity;
- Desired environmental standards.

### 2.2. Landfills

In compliance with the current international laws, landfills can be classify in three classes, as shown in Figure 8 [55-57, 99]:

![Landfills Diagram](image)

**Fig. 8. Classes of landfill [55-57, 99].**

#### 2.2.6. Landfill lifecycle

A landfill presents an evolution over time in terms of planning, management and economic development. Figure 18 presents a landfill lifecycle [82, 91].
2.3. Characteristics of landfills products

2.3.1. Leachate

2.3.1.1. Leachate lifecycle

The leachate is the result of the decomposition of the organic matter by bacteria and the extract ion of organic contaminants from the waste using the solvent effect of water. The leachate takes the form of a dark-coloured liquid with a pungent smell, specific to the anaerobic degradation process that occurs in the body of the landfill. The organic waste materials present in the landfill are „colonized” by various microorganisms which grow at rates that depend on a series of factors such as the type of waste, moisture content, temperature, pH etc. [18].

2.3.2. Biogas

2.3.2.1. Biogas lifecycle

The decomposition of organic waste during the methanogenic phase produces a micelle composed of methane and carbon dioxide, but it also contains low levels of nitrogen, oxygen, sulphurs, hydrogen and carbon monoxide. There are also present traces of chemical compounds (about 0.1%) such as: dichloromethane, trichloromethane, benzene, toluene etc. Biogas looks like a ‘dirty’ heterogeneous micelle whose most significant constituent is methane and which can be energetically recovered. [18].

Fig. 18. The lifecycle of a landfill [82, 91].

Fig. 19. The process of leachate formation [18].
CHAPTER 3
ESTIMATIVE MATHEMATICAL MODELS DESCRIBING LEACHATE AND BIOGAS QUANTITATIVE, QUALITATIVE AND KINETIC ASPECTS

The collection of landfill products (leachate and biogas) is a major topical issue that should be the main concern of landfill operators for several reasons [22]:

1. the potential environmental impact of the matrix of water, soil, groundwater and surface water;
2. the unpleasant smell in the neighbourhood of landfills, and the potential negative consequences the greenhouse gas might have at a global level

3.1. Mathematical modelling of leachate flow and transport prediction

The first models used to estimate the behaviour of landfill products were empirical and semi-empiric.

On the basis of experimental data, there have been tried different formulas and approximate functions of the generated leachate. The disadvantage of these methods consists in their limited applicability to the analysed landfills, because there is no requirement to understand the phenomena and variables physically involved, the research being performed only by using the empirical correlations between input and output data. [22].

In order to estimate the amount of generated leachate, researchers have developed several mathematical models, trying to describe the numerous and complex phenomena that influence the leachate production [22].

The estimation of the amount of generated leachate varies depending on the complexity of the model, taking into account the quantitative and qualitative data concerning the disposed waste, the management operations, the meteorological aspects of the warehouse area and the physical, chemical, biological, and, kinetic parameters. The models that can be used for different estimations are briefly described in Table 4.
Table 4. Examples of mathematical models proposed to estimate leachate flow and transport [22].

<table>
<thead>
<tr>
<th>Name/type of model</th>
<th>Main features</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>HELP Model (Hydrologic Evaluation of landfill Performance)</td>
<td>- three-dimensional, multi-phase,variably saturated model;</td>
<td>[53, 104-106]</td>
</tr>
<tr>
<td></td>
<td>- estimates leachate amount and potential percolation in the subsurface of the landfill.</td>
<td></td>
</tr>
<tr>
<td>Serial Water Balance Method</td>
<td>- accuracy depends essentially on the input data on the solid waste physical characteristics and on the information about cells structure;</td>
<td>[90]</td>
</tr>
<tr>
<td></td>
<td>- the amount of leachate generated by a single cell using water balance.</td>
<td></td>
</tr>
<tr>
<td>Hydrological Mass Balance Model</td>
<td>- takes into account trade sectors, the construction and management models of the system, surface runoff, and evapotranspiration;</td>
<td>[30, 42, 43]</td>
</tr>
<tr>
<td></td>
<td>- estimates leachate quantity in both active and passive phases.</td>
<td></td>
</tr>
<tr>
<td>MODFLOW-SURFACT Model</td>
<td>- estimates leachate amount and the consequences of the transportation of contaminants within the landfill.</td>
<td>[26, 28, 39]</td>
</tr>
<tr>
<td>PITTLLEACH-2</td>
<td>- simulates leachate quantity and quality, as well as biogas generation</td>
<td>[7, 19, 20]</td>
</tr>
<tr>
<td>Mathematical models to simulate leachate generation and transport</td>
<td>- the curve representing the leachate concentration is derived from column/lysimetric studies;</td>
<td>[47-51]</td>
</tr>
<tr>
<td></td>
<td>- refers to the biological analysis of leachate.</td>
<td></td>
</tr>
</tbody>
</table>

3.2. Mathematical models used to estimate biogas generation

In the last few years, in specialized literature, there have been proposed different models to estimate the maximum extractable amount of biogas and to study the evolution of gas production in time. On the basis of the available data and of the level of knowledge about the system, a classification and description of mathematical models has been realised – summarized in Table 8.
Table 8. Examples of mathematical models proposed to estimate biogas/methane generation.

<table>
<thead>
<tr>
<th>Name/ type of model</th>
<th>Main features</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirical models</td>
<td>These models describe the tendency of available data, considering the landfill to be like a „black box“. This model is represented by a function that creates various correlations between the input data, namely the bio-classifiable organic fraction, and the output data, namely the biogas production.</td>
<td>[30, 42]</td>
</tr>
<tr>
<td>Stoichiometric Models</td>
<td>These models are based on a global stoichiometric reaction, in which the left-hand side represents the chemical composition of the waste, and the right-hand side the reaction products, namely methane and carbon dioxide. They are useful for the estimation of the biogas flow produced by a landfill.</td>
<td>[111]</td>
</tr>
<tr>
<td>Biochemical Models</td>
<td>These models are influenced by the biodegradability of organic matrix and describe the bio-gasification mechanisms using the biological kinetics characteristics.</td>
<td>[89]</td>
</tr>
<tr>
<td>Zero-order Models</td>
<td>The biogas production is considered constant over time.</td>
<td>[109]</td>
</tr>
<tr>
<td>First-order Models</td>
<td>An important parameter utilised in mathematical calculation refers to the effect of age of waste in biogas production</td>
<td>[109]</td>
</tr>
<tr>
<td>Second Order Models</td>
<td>The model is based on the complex reactions which occur during degradation of waste.</td>
<td>[120]</td>
</tr>
<tr>
<td>Multiphase Models</td>
<td>The model is based on the first order exponential equation. The differentiated fractions of the waste composition refer to the biodegradation rate.</td>
<td>[108, 109]</td>
</tr>
<tr>
<td>Scholl Canyon Models</td>
<td>For this model, the lag phase is negligible. The maximum methane generation rate is reached quickly. The main factor is the moisture content.</td>
<td>[54]</td>
</tr>
<tr>
<td>Palos Verdes Model</td>
<td>It is a first order kinetics model. The first phase represents the exponential growth of the biogas generating rate. The second phase shows the exponential decrease of the biogas generating rate.</td>
<td>[54, 108]</td>
</tr>
<tr>
<td>U.S. EPA LandGEM Model</td>
<td>It is based on the first-order equation. Methane generation rate can be annually estimated for the active phase, and for a post-closure phase of at least 30 years. The period is calculated according to the landfill storage capacity and waste acceptance rate.</td>
<td>[17, 21, 23, 78, 95, 112]</td>
</tr>
<tr>
<td>Ecological Models</td>
<td>These type of models are more stringent and highly detailed. They describe the controlled landfills as complex ecosystems and assess the connections between microbial populations, from hydrolysis to methanogenic phase. These models are not frequently used due to their complexity.</td>
<td>[77]</td>
</tr>
</tbody>
</table>
This study analyses three landfills from Italy (Figure 29) and four landfills from Romania (Figure 30).

The analysed landfills in Italy and Romania are:
- „Basse di Stura” landfill – located in Turin area, in the North of Italy;
- „Montegrosso” landfill – located in Montegrosso, in Potenza area, in the South of Italy;
- „Cozzo Vulturo” landfill – located in Enna area, Sicily, Italy;
- Bacau landfill, Romania – situated at the southern boundary of Bacău city, near Nicolae Bălcescu village, ensuring a minimum distance of 1000 m to human settlements;
- Bihor landfill, located in Oradea city, Bihor county;
- Piatra Neamț landfill, Romania – located in Piatra Neamț city, Neamț county;
- Ghizela landfill, Romania – located outside Ghizela village, in the eastern part of Șanovița village, Timiș county.
4.1. Turin landfill – Italy

„Basse di Stura” non-hazardous landfill (Figure 31) is located in the Piedmont Region, near Turin, at Borgaro city limit, and is managed by Spa AMIAT Company [10].

Turin landfill development progresses vertically, starting from a depth of three meters below ground level and reaching a height of 32 m. A free surface of the aquifer can be identified below the landfill bottom, at a depth between 6 and 10 m below ground level [32, 85].

2009 was the last year of activity. On January 1st 2010, the landfill entered the post-closure phase; in this period, attempts were made to reconstruct the vegetation cover and the surrounding environment. [9, 10, 32, 85].

During the post-closure period, of about 30 years, maintenance work will be performed in compliance with the environmental safety and security standards.
According to the Italian law DPR 915/1982, three categories of waste have been deposited in the Turin landfill [32, 85]:

- Municipal Solid Waste: non-voluminous waste derived from domestic or residential activities, voluminous waste, such as durable goods and furniture parts, external waste from public areas or roads;
- Waste analogous to Municipal Solid Waste: waste resulting from production activities, which can be assimilated, with regard to its toxicity characteristics, quality, and composition, to municipal waste;
- Sewage sludge: sludge from sewage treatment of household water, mostly transported from the waste water treatment plant SMAT.

The leachate collection from the bottom of the landfill is mandatory and essential to limit, as much as possible, the contact time with the waste mass, thus avoiding excessive increase in pollutant charges and, consequently, limiting the leachate chemical aggressiveness. The leachate is taken from special wells, transported to the plant for wastewater homogenization, and then discharged to the waste water treatment plant SMAT - mentioned above.[9, 10, 32, 85].

The biogas collection operation is continuously carried out after the landfill had been filled up, the final coating layer had been added, and the methanogenic phase had become stable. [9, 10, 32, 85].

During the period in which biogas production is limited (in winter), when the energy recovery treatment is not profitable, the biogas is burned in torch, thus ensuring its elimination [10, 32, 76, 85].
4.2. Potenza landfill, Italy

The Italian landfill of Potenza was operational from 1989 to 2004 and is now managed by ACTA-Power, which takes care of municipal waste collection [8].

![Figure 32. The structure of Potenza landfill, Italy [8].](image)

The landfill is located in Montegrosso town, Potenza Region (Figure 32), and is structured in seven cells. The site is located at 800 m altitude above sea level and covers an area of 10 ha. Cells were filled in different years with municipal solid waste [8].

The total capacity of Potenza landfill is 63,000 m$^3$ of municipal solid waste collected from Potenza Region. The main categories of the disposed waste are paper, cardboard, plastic and rubber, metals, glass and inert, biodegradable organic substances, wood and leather [8].

The landfill is equipped with a biogas collection system with wells in each cell. It is equipped with a leachate drainage and runoff collection system at the bottom [8].

4.3. Cozzo Vulturo landfill in Enna, Italy

Cozzo Vulturo landfill is located in a weak anthropic area unaffected by urban agglomeration, near Enna town, in a site that extends over a 4.5 ha area (Figure 33) [84]:
The landfill, which is divided into several cells, began its activity in July 2007. It is equipped with a leachate collection system. There is a higher level of contribution of the infiltrated rainfall during four months of the year, the amount of the recorded leachate flow being above average. Due to the delay generated by the heavy water infiltration in the coating clay, and due to the waste compaction, there is constancy in the attenuation of these leachate production peaks [84].

The landfill is also equipped with a biogas collection system. All the biogas transportation lines have condensate separators placed at the potential accumulation points, where the condensed water is separated by biogas. The heated biogas is sent through pipes to the burning systems where it is ignited by an electrode and torch combustion takes place. For this case study, there are no data about the biogas amount collected during the landfill active phase. [84].

4.4. Bacău landfill, România

Bacău landfill (Figure 35) is 32.4 ha in area, of which 25.3 ha represents the main deposit (4 cells). The landfill also contains [4]:
- Sorting station;
- Composting station;
- Administrative spaces;
- Facilities.
Fig. 35. Bacău landfill, România [68].

For this type of landfill there is a separate collection of green waste, waste from markets and biodegradable waste from cafeterias and markets, as well as a separate collection of organic waste for 80% of the houses in the following neighbouring towns: Comănești, Moinești, Onești, Slănic Moldova, Tg. Ocna and Dârmănești [4].

The leachate drainage and collection system is composed of seven lines of absorbent drains in the eastern sub-cell and seven lines in the western sub-cell. The drain lines are equidistantly placed at 30 m from one another. At 15 m on both sides of the drain, ridges are modelled. The leachate reaches the 700 m³ storage tank and then the reverse osmosis plant. Waste water treatment plant is dimensioned for a maximum flow of 120 m³/day [4].

In order to collect the biogas, a collection system is used. It consists of:

[4]:
 - Biogas extraction wells;
 - Biogas collection and transport system including pipelines, dehydration and gas substation systems;
 - Biogas torch combustion system.

4.5. Bihor landfill, România

Bihor landfill is located in Oradea city (Figure 36) and is divided into two cells. Cell 1 covers an area of 3.8 ha and was designed for a total capacity of 756,436.8 tonnes of waste deposited between August 2005 and May 2011.
Cell 2 occupies an area of 3.8 ha and was designed for the same capacity for the waste deposited between June 2011 and December 2014 [37].

During the active phase, the following waste categories were deposited in the landfill [37]:
- Non-hazardous industrial waste;
- Non-hazardous waste resulted from constructions/demolitions – used to build and reinforce the access road on the waste stream;
- Non-hazardous municipal waste;
- Stripped excavated soil – used to build the embankment.

The leachate produced in the landfill is drained at the bottom of the deposit. In the gravel layer there are perforated pipes that take over the leachate and carry it to the waste treatment plant through drainage pipes at a slope of 1.5% [37].

The leachate treatment is carried out through the reverse osmosis process, which consists of [37]:
- Pre-filtering;
- Proper treatment, using reverse osmosis.

The generated biogas is collected through extraction wells 10-17 m deep. The gas extraction is realised using suction gas collection wells. The wells are connected to the main collection pipe through biogas control stations. After filtration and condensate separation, the biogas is neutralized by burning or used to generate heat [37].
4.6. Piatra Neamț landfill, România

The Romanian landfill of Piatra Neamț (Figure 39) is located in Piatra Neamț city, General N. Dăscălescu street. The city lies in the major meadow area of the Bistrița river [3, 5, 100, 101].

The landfill development progresses horizontally, in daily storage cells. The waste is distributed in one meter compacted layers, with a compaction degree of 0.8 t/m$^3$. Industrial waste is accepted in landfill only mixed with municipal solid waste. The deposited and compacted waste are daily covered, using solid waste (soil and gravel), constructions and demolitions waste. It is thus ensured a minimum thickness of 10 cm of the coating layer [3, 5, 100, 101].

The landfill is composed of two cells [3, 5, 100, 101]:
- Cell 1 with an area of 2 ha and a volume of 125,000 m$^3$, closed in 2010;
- Cell 2 with an area of 2.8 ha and a total storage capacity of 300,000 m$^3$. Cell 2 follows Cell 1, on its western side.

The collected waste is processed as follows [3, 5, 100, 101]:
- Recyclable waste, paper/cardboard, glass, plastic and aluminium beverage doses are processed in the sorting station for submission to subsequent recovery;
- Biodegradable and recyclable waste, and the waste resulting from constructions and demolitions are processed in composting or crushing stations and turned into compost/crushing aprons;
- Voluminous household waste is collected in waste categories;
- Non-hazardous municipal solid waste is collected from the waste generators, transported and delivered for final storage to the landfill.

Because the landfill site benefits from the existence in the area of a sewage network connected to the municipal sewage treatment plant, the leachate will be pre-treated on-site to allow a subsequent treatment at the municipal plant and to fall below the limits imposed by the Romanian legislation. Leachate is collected from the landfill cells through four points and then pumped into a tank by an electrically driven pump [3, 5, 100, 101].

Leachate treatment is performed in a reverse osmosis plant, fully automated, located in three containers. The station is for a maximum flow rate of waste water of 40 m$^3$/day [3, 5, 100, 101].

Piatra Neamț non-hazardous waste landfill is not equipped with a biogas collection system. Biogas is naturally released into the atmosphere, without any collection or torch combustion system.

4.7. Timiş landfill, România

Timiş non-hazardous waste landfill (Figure 40) is located outside Ghizela village, in Timiş county, the eastern part of Șanovița village, at about 1540 m from the built-up area [1].

In order to monitor the parameters of the surrounding environment of the landfill, in the administrative building there is a weather station having the following technical and functional parameters [1]:
- temperature, humidity and wind measurement (average, maximum and minimum values);
- parameters are measured for at least one year;
- digital interface;
- high precision measurement sensors.

Timiş landfill is divided into five cells and occupies a total area of 35.14 ha, and a total capacity of 5,131,300 m$^3$ [1].

Timiş landfill is classified as a non-hazardous landfill. The following types of waste have been deposited in the landfill [1]:
- Municipal solid waste collected from the population;
- Waste from parks and streets and crowded markets;
- Waste from institutions and industry similar to household waste.
The treatment plant capacity to process the leachate from cell 1 is 39 m$^3$/day [1].
Leachate treatment is performed in two stages [1]:
- Mechanical stage, in which a pH reduction and a pre-filtration take place;
- Biological stage, in which the actual treatment takes place, through reverse osmosis and nano-filtration.

Timiș landfill for non-hazardous waste is not equipped with a biogas collection system, the biogas being naturally realised into the atmosphere. There is no biogas recovery system or torch combustion system, and there is no information about a monitoring system of the emission of methane or some other gasses contained in the biogas that can be released into atmosphere.

**CHAPTER 5**
**LANDFILLS CHARACTERIZATION: CASE STUDIES: PRESENTATION OF EXPERIMENTAL DATA**

**5.1. Experimental data and characteristics used in comparative analysis**

**5.1.1. Turin Landfill, Italy**

The total amount of waste deposited in Turin landfill, in its active phase, can be observed in Figure 43. In compliance with the Italian and
European legislation, three categories of waste were stored in Turin landfill. The amount of each category is expressed in Figure 44.

Fig. 43. The total quantity of waste deposited in Turin landfill, Italy [9].

Fig. 44. The quantities of different categories of stored waste in Turin landfill, Italy: municipal solid waste, analogous municipal solid waste and sludge [9].
Fig. 45. Percentage representation of the composition of municipal solid waste stored in Turin landfill between 2000 and 2009 [9].

In order to create and apply different mathematical models, it is necessary to know the structure of the deposited waste. Waste fractions have their own characteristics that can influence the amount of generated leachate, and consequently the amount of generated biogas. Figure 45 represents the structure of the deposited waste in Turin landfill between 2000 and 2009 [9].
Starting from the period for which there exists a waste structure, (Figure 45), it was calculated an average of the values of each fraction of the municipal solid waste deposited in Turin landfill (Figure 46).

Figure 47 represents the fraction structure of the whole amount of municipal solid waste deposited in Turin landfill. It was observed that the largest fraction of stored waste was represented by the paper and cardboard waste fractions and the organic waste fraction. Analysing the average percentage representation of the structure of the municipal solid waste stored in Turin landfill, it was seen that the amount of wood and metal fractions were the lowest. The biogas production capacity and the leachate production capacity are influenced by the high percentage of organic waste fraction and also by the high percentage of waste paper and cardboard, which increase the carbon content, thus favouring the methane production capacity and the carbon dioxide production capacity, that is the biogas production capacity.
The mathematical model used to calculate the leachate and biogas production takes into account the weather/climatic parameters. Turin landfill has its own stations to monitor weather parameters which favour leachate and biogas production capacity. There have been identified average monthly values for the following parameters: (Figure 48):
- precipitations;
- temperature;
- solar radiation.

Calculations use different parameters that may influence the leachate and biogas production. Thus, using equations 17 and 18, there have been calculated the monthly averages for the following parameters:
- run-off (Figure 49);
- evaporation or evapotranspiration (Figure 50).
Fig. 48. Variation of average monthly weather-climatic conditions in the Turin landfill area [9, 10, 14, 32].

The liquid content determined by the meteorological conditions represents an important part of the leachate amount – in the active phase, rainwater is a significant part of the whole amount of leachate.
Fig. 49. Variation of average monthly runoff for Turin landfill.

Fig. 50. Variation of average monthly evapo-transpiration for Turin landfill.
Fig. 51. The percentage of moisture content for each fraction of waste deposited in landfills [92].

Figure 51 shows the percentage of moisture content of each fraction contained in the waste composition. This percentage will be used to calculate the municipal solid waste and similar wastes. The standard value of the moisture content of sludge used in calculations is 70% [92].

Fig. 52. Waste density [75].

Figure 52 represents the density of each fraction of waste deposited in landfills, used in calculations [75].
Fig. 53. The estimation of the moisture content related to the paper and cardboard fraction of the municipal solid waste deposited in Turin landfill.

For each fraction of the municipal solid waste deposited in Turin landfill, the total amount of liquid produced in the landfill can be estimated (Figures 53 ÷ 61).

Fig. 54. The estimation of moisture content related to the leather fraction of the municipal solid waste deposited in Turin landfill, Italy.
Fig. 55. The estimation of moisture content related to the wood fraction of municipal solid waste deposited in Turin landfill, Italy.

Fig. 56. The estimation of moisture content related to the glass fraction of municipal solid waste deposited in Turin landfill, Italy.
Fig. 57. The estimation of moisture content related to the metal fraction of municipal solid waste deposited in Turin landfill, Italy.

Fig. 58. The estimation of moisture content related to the plastic fraction of municipal solid waste deposited in Turin landfill, Italy.
Fig. 59. The estimation of moisture content related to the organic fraction of municipal solid waste deposited in Turin landfill, Italy.

Fig. 60. The estimation of moisture content related to the fine particles fraction of municipal solid waste deposited in Turin landfill, Italy.
Fig. 61. The estimation of moisture content related to other type of waste fraction of municipal solid waste deposited in Turin landfill, Italy.

For each fraction of the analogous municipal solid waste disposed in Turin landfill, the total amount of liquid produced in the landfill can be estimated (Figures 62 ÷ 70).

Fig. 62. The estimation of moisture content related to the paper fraction of the analogous municipal solid waste disposed in Turin landfill, Italy.
Fig. 63. The estimation of moisture content related to the leather fraction of the analogous municipal solid waste deposited in Turin landfill, Italy.

Fig. 64. The estimation of moisture content related to the wood fraction of the analogous municipal solid waste deposited in Turin landfill, Italy.
Fig. 65. The estimation of moisture content related to the glass fraction of the analogous municipal solid waste deposited in Turin landfill, Italy.

Fig. 66. The estimation of moisture content related to the metal fraction of the analogous municipal solid waste deposited in Turin landfill, Italy.
Fig. 67. The estimation of moisture content related to the plastic fraction of the analogous municipal solid waste deposited in Turin landfill, Italy.

Fig. 68. The estimation of moisture content related to the organic fraction of the analogous municipal solid waste deposited in Turin landfill, Italy.
Fig. 69. The estimation of moisture content related to the fine particles fraction of the analogous municipal solid waste deposited in Turin landfill, Italy.

Fig. 70. The estimation of moisture content related to the other types of waste fraction of the analogous municipal solid waste deposited in Turin landfill, Italy.
Fig. 71. The estimation of moisture content related to the sewage sludge deposited in Turin landfill, Italy.

Figure 71 presents the estimation of the moisture content related to the total quantity of sewage sludge deposited in Turin landfill during the active phase.

Fig. 72. The estimation of liquid amount was formed during the active phase due to the weather-climatic conditions in Turin landfill, Italy.
Figure 72 presents an estimation of the total amount of liquid that was formed during the active phase due to the meteorological conditions that contributed to leachate generation in Turin landfill. The estimation was mainly based on the amounts of liquid resulting from: precipitations, runoff, evaporation and evapo-transpiration – influenced by solar radiation and temperature.

Figure 73 presents a comparative analysis between the estimation of the total amount of liquid that can be formed of the Turin landfill body, the total amount of leachate collected during active phase and the total amount of leachate that will be collected during the post-closure phase.

The result of estimations and calculations was a total amount of liquid of 6,392,568.97 m$^3$ which represents the leachate production capacity of Turin landfill, Italy. It is known that between 2000 and 2012 a total amount of leachate of 2,740,167 m$^3$. This amount was collected during the active phase and, for a short period, during the post-closure phase. It can be concluded
that, in the post-closure phase, a total amount of leachate of 3,652,401.97 m³ can be collected.

The total amount of leachate in the Turin is obtained by adding the following:

- the estimation of moisture content of the mixture of all the fractions of the municipal solid waste deposited in landfill;
- the estimation of moisture content of the mixture of all the fractions of the analogous municipal solid waste deposited in landfill;
- the estimation of moisture content related to the total quantity of sewage sludge deposited in landfill (Figure 71);
- the estimation of the liquid amount was formed during the active phase due to the weather-climatic conditions (Figure 72).

For post-closure phase, it is considered that the amount of leachate that can be collected from landfill tends to decrease towards the end of the post-closure period. In order to determine the amount of leachate that can be collected during the post-closure phase, the estimative equation 72 will be used, which describes both the post-closure phase of Turin landfill, and the post-closure phase of any landfill:

\[
L = \frac{x}{i} \cdot \frac{1}{j} \quad \text{(m}^3/\text{year)}
\]  

(72)

where:

- \(L\) is the total amount of leachate that can be collected in \(j\) years, (m³/year);
- \(x\) – post-closure period, at least 30 years under current legislation, (year);
- \(j\) – the period of time from the moment when post-closure starts, (year).

In order to estimate the leachate amount that can be collected in post-closure phase, presented in Figure 73, it has been established the date of post-closure phase completion, in 2042, after 33 years of post-closure. Thus, the active phase was estimated to be 26 years, and the post-closure period 33 years.

Figure 74 presents a comparative analysis between the leachate amount collected from Turin landfill during its active phase (2000÷2009) and a part of post-closure period (2010÷2012), the estimation of the leachate quantity in its the post-closure phase – using equation 73, and the estimation of the leachate quantity that can be collected in its active phase and in its post-closure phase (33 years) for Turin landfill, Italy.
Fig. 74. Comparative analysis between the amount of leachate collected during the active phase and the estimation of the leachate amount using the estimative mathematical model for the Turin landfill, Italy.

In order to make the estimation, a mathematical model for leachate, based on the Gaussian equation, is used (equation 73):

$$y = y_0 + \left[ \frac{A}{w \cdot \sqrt{\frac{\pi}{2}}} \cdot \exp \left( -2 \cdot \left( \frac{x - xc}{w} \right)^2 \right) \right] \text{ (m}^3\text{/year)}$$  

(73)

where:

- $y$ is the annually estimated leachate amount;
- $y_0$, $w$, $xc$, $x$ and $A$ – terms of the equation.

The terms in the equation are specific to each landfill and to each study. The estimative mathematical model describes the leachate production capacity that can be collected from a landfill during its active and its post-closure phases.

For the Turin landfill, in Italy, the terms of the equation 73 are shown in Table 10.
Table 10.
The terms of the Gaussian equation used to estimate the leachate amount that can be collected from the Italian landfill in Turin.

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_0$</td>
<td>3.664.80551</td>
</tr>
<tr>
<td>$x_c$</td>
<td>5.92523</td>
</tr>
<tr>
<td>$w$</td>
<td>12.74896</td>
</tr>
<tr>
<td>$A$</td>
<td>$3.82243 \cdot 10^6$</td>
</tr>
</tbody>
</table>

For the estimative mathematical model used to estimate the leachate quantity that can be collected in from the Turin landfill, it was considered that the truth degree is equal to 0.91155 ($r^2 = 0.91155$). The mathematical model was generated using the Origin Pro 8.5 software.

Regarding the period for which the mathematical model was applied, in calculations, the zero year, representing the first year of leachate collection, was considered to be the year 2000. The closure year was considered to be the tenth year – 2009. The year 2010 was the first year of the Turin landfill post-closure phase. The estimation using the mathematical model was realised for a period of 43 years (2000-2042).

The comparative analysis presents the fact that the leachate quantity variation maintains the trend of the actual leachate quantity collected from the Turin landfill.

In order to estimate the biogas amount, a first order mathematical model was used. Parameters that influence the biogas production capacity from a landfill refer to the total amount of waste deposited in a landfill during its active phase, to the period of time the waste was deposited in the landfill, and to the post-closure period. The reason for using and applying a first order mathematical order was the lack of complex data and the insufficient data about all the landfills considered as case studies. The identification of the main issues that may influence the biogas production capacity and the possible amounts that may collect in the post-closure period is also very important.

The amount of biogas was estimated using an estimative mathematical model, which is based on the equation 74:

$$Q = \sum_{i=1}^{n} kL_0 \left( \frac{m_i}{10} \right) e^{-k_i} \quad \text{(m}^3/\text{year})$$

where:

$Q$ represents the biogas quantity, annually estimated for $i$ year, (m$^3$/year);
The mathematical models for biogas production capacity that are based on the first order exponential equations are described and discussed by SWANA and by Thorneloe [109, 112].

The mathematical model described by equation 74 was developed to identify the main aspects of the analysed case-studies. Thus, in specialized literature, different values are used for the biogas production rate and for potential capacity of biogas generation.

![Graph](image)

**Fig. 75.** The statistical comparative analysis for the identification of the terms of the equation used to calculate the biogas production capacity for the Turin landfill, Italy.

In order to identify the most accurate values, it was performed a statistical comparative analysis between the biogas amounts collected from the Turin landfill for both active post-closure phases, and the estimations of the biogas quantities considering different values for $k$ and $L_0$ parameters.
The conventional standard values used in specialized literature have different values, as follows:
- 0.02 ÷ 0.7 year\(^{-1}\): for the biogas production rate;
- 100 ÷ 170 m\(^3\)/tonnes: for the potential capacity of biogas generation.

From Figure 75, it appears that the most accurate estimation of the biogas amount that can be collected from the Turin landfill, using the estimative mathematical model, is realised for a biogas production rate 0.3 year\(^{-1}\), and a biogas generation potential capacity of 100 m\(^3\)/t.

For all analysed case studies, the standard values have been considered – those from Figure 75, because, for the other landfills, it was not possible to compare the values obtained using the mathematical model with the real values of the collected biogas.

![Graph](image)

**Fig. 76. Analysis of the amount of collected biogas and the estimation of biogas amount using the estimative mathematical model, for the Turin landfill.**

Figure 76 presents a comparative analysis of the amount of collected biogas reported by the landfill operator and the estimation of the biogas quantity using the estimative mathematical model for biogas production capacity of the Turin landfill, Italy.

The estimation was carried out for the active phase of the landfill (1984 – 2009) and for a period of 31 years in the post-closure period (2010 – 2040). The estimation maintains the trend of the real curve, and shows a tendency to overestimate the real values of the collected biogas in active phase.
The analysis shows that the mathematical model tends to overestimate the biogas production capacity, but maintains the production increasing and decreasing tendency throughout the entire collection period.

5.1.2. Potenza landfill, Italy

The total waste quantity deposited in Potenza landfill during its active phase can be observed in Figure 77.

![The total amount of waste](image)

**Fig. 77. The total quantity of waste deposited in Potenza landfill, Italy [8].**

The waste quantity was deposited between 1989 and 2004; in February 2004, the landfill entered the post-closure phase.

Two categories of waste were stored in the Potenza landfill - each category is expressed in Figure 78. The figure also shows that between 1990 and 1998, there were also deposited different amounts of sludge, thus favouring the leachate and biogas production capacities.
Fig. 78. The categories of stored waste in Potenza landfill, Italy: municipal solid waste and sewage sludge [8].

Fig. 79. The average percentage representation of the composition of the municipal solid waste deposited in Potenza landfill, Italy [8].

The percentage composition of the waste deposited in the Potenza landfill, presented in Figure 79 [8], was taken from the specialized literature. It can be observed that the fractions of wood, plastic and other types of waste
are not found in the structure of the waste stored in this landfill. The highest percentages are those of organic fraction, and of paper and cardboard fractions of waste, which favours high leachate and biogas production capacities.

**Fig. 80.** The quantitative representation of composition of the municipal solid waste deposited in Potenza landfill, Italy.

Figure 80 presents the structure of the entire municipal solid waste deposited in the Potenza landfill, Italy.

There is no information about the existence of weather stations in the Potenza landfill area. In calculations, there were used the average monthly values of the following weather-climatic parameters (Figure 81):

- precipitations;
- temperature.

Using the recorded data, the average monthly values for every parameter were calculated, and were used for the entire active phase of the Potenza landfill.
Fig. 81. The monthly average variations of the meteorological and climatological parameters (temperature/precipitations) in Potenza landfill area [15, 16].

Fig. 82. The variation of monthly average of runoff, calculated for the Potenza landfill area.
To validate the mathematical mode, it is necessary to estimate the total liquid amount that can be formed due to meteorological and climatological parameters. Besides the liquid amounts resulted from precipitations, using equations 17 and 18, there were calculated the monthly average variations for the following parameters used in modelling:

- runoff (Figure 82);
- evaporation/evapotranspiration (Figure 83).

![The variation of monthly average calculated for evapotranspiration](image)

**Fig. 83. The variation of monthly average of evapotranspiration, calculated for Potenza landfill area.**

In calculations, there were used the moisture content percentages of each fraction of waste deposited in the Turin landfill, as shown in Figure 51. The use of these values is explained by the fact that, for the Potenza landfill, there was not carried out any study on the moisture content of deposited waste, and by the fact that in this landfill there were stored waste quantities for a period of 26 years, this facilitating the accuracy and truthfulness of the moisture content of each waste fraction.

The density values presented in Figure 52 were used in calculations. The same values of density for each waste fraction were considered, because the waste presents the same structural characteristics for all the fields.

It was calculated the moisture content of each fraction of the deposited municipal solid waste, for each year of the period in which the Potenza landfill was active (Figures 84 ÷ 88).
It was calculated the moisture content related to each fraction from municipal solid waste deposited, for each year of activity of Potenza landfill, Italy.

**Fig. 84.** The estimation of moisture content related to the paper fraction of the municipal solid waste deposited in Potenza landfill, Italy.

**Fig. 85.** The estimation of moisture content related to the leather fraction of the municipal solid waste deposited in Potenza landfill, Italy.
Fig. 86. The estimation of moisture content related to the glass fraction of the municipal solid waste deposited in Potenza landfill, Italy.

Fig. 87. The estimation of moisture content related to the organic fraction of the municipal solid waste deposited in Potenza landfill, Italy.
Fig. 88. The estimation of moisture content related to the fine particles fraction of the municipal solid waste deposited in Potenza landfill, Italy.

Fig. 89. The estimation of the amount of liquid resulted from the total amount of municipal solid waste deposited in Potenza landfill, Italy.
Fig. 90. The estimation of moisture content related to the sludge amount stored in Potenza landfill, Italy.

Figure 89 presents an estimation of the total amount of liquid resulted from the municipal solid waste deposited in the Potenza landfill. The amounts of liquid of each fraction of the waste deposited in the landfill were added.

Figure 90 presents an estimation of the moisture content of the total amount of sewage sludge deposited in the Potenza landfill during its active phase.

The amount of liquid that can be generated in the Potenza landfill due to weather and climatologic conditions is 987.719 m³/year, and for the whole period of its activity it is 15,803.504 m³/year.

The total quantity that can be formed in Potenza landfill is 168,162.3 m³.

The total amount of leachate that can be formed in the Potenza landfill body can be obtained by adding the following parameters:
- The estimation of the moisture content of the mixture of all the waste fractions of municipal solid waste deposited in the landfill (Figure 89);
- The estimation of the moisture content of the total quantity of sewage sludge deposited in the landfill (Figure 90);
- The estimation of the amounts of liquid that can be formed due to weather and climatologic parameters.
**Fig. 91.** A comparative analysis of the leachate amount determined by using the moisture content calculation and the estimation of leachate amount determined by using the estimative mathematical model for leachate for the Potenza landfill, Italy.

The post-closure period was considered to have started in 2004, 16 years after the landfill was opened. 1989 was considered to the 1\textsuperscript{st} year, and 2004, the 16\textsuperscript{th} year; The 1\textsuperscript{st} year of leachate collection was 1994, the 5\textsuperscript{th} year, and, considering the mathematical model, the first year of collection was 1996, the 7\textsuperscript{th} year.

Figure 91 presents a comparative analysis of the leachate quantity determined by using the moisture content calculation, and the estimation of the leachate production capacity determined by using the estimative mathematical model for leachate for the Potenza landfill, Italy. For the estimation, it was used the mathematical model described by equation 73, the Gaussian estimative equation.

**Table 11.** The terms of Gaussian equation used to estimate the leachate amount that can be collected from the Italian landfill of Potenza.

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_0$</td>
<td>771.35302</td>
</tr>
<tr>
<td>$xc$</td>
<td>16.75531</td>
</tr>
<tr>
<td>$w$</td>
<td>17.43747</td>
</tr>
<tr>
<td>$A$</td>
<td>151,152.12769</td>
</tr>
</tbody>
</table>
For the Potenza landfill, the terms of Gaussian equation were presented in Table 11.

In order to verify and validate the equation, the truth degree was considered to be $r^2 = 0.92003$. The mathematical model was elaborated using the Origin Pro 8.5 software, used by the Windows operating system.

In the specialized literature only the amount of leachate collected in 2003 can be found. Using mathematical models, the amount of leachate for 2003 was obtained, having the same value as in reality, namely 7,543.78 m$^3$.

**Fig. 92. The estimation of the biogas amount using the estimative mathematical model for the biogas amount which can be collected from the Potenza landfill, Italy.**

Figure 92 presents the estimation of the biogas amount from the Potenza landfill. The estimation was calculated using the mathematical model described by equation 74.

The estimation was carried out for the active phase (1989 – 2004) and for a period of 32 years of the post-closure phase of the Potenza landfill.

As far as Potenza landfill is concerned, there are no data referring to the collected biogas amount for either active or post-closure phase. Consequently, a comparative analysis to validate the mathematical model used for estimation cannot be carried out. This study can be considered a good method of checking the monitored values of the biogas production capacity.
5.1.3. Enna Landfill, Italia

The total amount of waste deposited in the Enna landfill during its active phase is shown in Figure 93. It appears, considering the specialized literature, that there are no data referring to this landfill. The only known data refer to the quantity of municipal solid waste [84].

![Figure 93. The amount of municipal solid waste deposited in Enna landfill, Italy [84].](image)

![Figure 94. The variation of monthly average of precipitation of the Enna landfill, Italy [84].](image)
Fig. 95 The variation of monthly average of temperature of the Enna landfill, Italy [84].

Fig. 96. The variation of monthly average of runoff calculated for the Enna landfill, Italy.
Similar to Potenza landfill, there is no information about any weather station to monitor the weather and climatologic conditions.

The weather and the climatology of the area is described by the monthly average variation of the following parameters:

- precipitations (Figure 94);
- temperature (Figure 95).

For mathematical modelling, there were calculated the monthly average variations of runoff (Figure 96), using equation 17, and of evaporation/evapotranspiration (Figure 97), using equation 18.

In order to calculate the leachate production, considering that there is no public data the waste structure, it was used the waste structure of municipal solid waste deposited in Turin landfill, presented in Figure 46. The reason for the use of this structure was the annual analysis carried out at this landfill for the identification of the waste composition. Moreover, having been a landfill in its active phase for 26 years, and being one of the oldest landfills in Italy, it was subjected to various studies and research whose results can be found in the specialized literature.

Figure 98 presents the quantitative composition of the waste deposited in the Enna landfill.
Because there is no structure of the waste stored in the Enna landfill, and it was used, in calculations, the Turin landfill waste structure, it will also be used the percentage of the moisture content fractions of the waste deposited in the Turin landfill, described in Figure 51. The Turin landfill is considered to be representative for Italy, as far as the waste structure analysis is concerned. The default values for the waste density for each fraction of deposited waste were described in Figure 52. There were used the same values, taking into consideration that each waste fraction has the same structure.

For the estimation of the total amount of liquid that can be generated by the deposited waste, it is necessary to calculate the moisture content of each waste fraction of the waste structure.

Figures 99 ÷ 107 present the estimations of the moisture content of each waste fraction of the municipal solid waste deposited in the Enna landfill, Italy. In the Enna landfill it was deposited only municipal solid waste, therefore, neither the moisture content of the wastes analogous to municipal solid waste, nor the moisture content of the deposited sewage sludge can be calculated.
Fig. 99. The estimation of moisture content related to the paper and cardboard fraction of municipal solid waste deposited in Enna landfill, Italy.

Fig. 100. The estimation of moisture content related to leather and textile fraction of municipal solid waste deposited in Enna landfill, Italy.
Fig. 101. The estimation of moisture content related to the wood fraction of municipal solid waste deposited in Enna landfill, Italy.

Fig. 102. The estimation of moisture content related to the glass fraction of municipal solid waste deposited in Enna landfill, Italy.
Fig. 103. The estimation of moisture content related to metal fraction of municipal solid waste deposited in Enna landfill, Italy.

Fig. 104. The estimation of moisture content related to the plastic fraction of municipal solid waste deposited in Enna landfill, Italy.
Fig. 105. The estimation of moisture content related to the organic fraction of municipal solid waste deposited in Enna landfill, Italy.

Fig. 106. The estimation of moisture content related to the fine particles fraction of municipal solid waste deposited in Enna landfill, Italy.
Fig. 107. The estimation of moisture content related to other types of waste fraction of municipal solid waste deposited in Enna landfill, Italy.

Fig. 108. The estimation of moisture content related to the total municipal waste quantity deposited in Enna landfill, Italy.
By summing the moisture content for each fraction from annually deposited waste, it can be estimated the total amount of liquid that can be formed in the landfill body, annually, in active phase. Considering Enna landfill, Figure 108 presents the estimation of liquid quantity for period 2007÷2013.

Considering meteorological and climatological parameters, using monthly average variation of each parameter, it can be obtained the estimation of liquid quantity that it can be formed in Enna landfill with value $444.3678 \text{ m}^3$/year. Because the landfill has been working for seven years, it was estimated the total amount of liquid related to the entire activity period with value $3,110.5746 \text{ m}^3$.

The total amount of liquid that it can be formed inside of Enna landfill, Italy is $145,833.59 \text{ m}^3$. The total leachate amount that it can be formed in Enna landfill consist of summing the following parameters:
- the estimation of moisture content resulted from all fraction of municipal solid waste deposited in landfill (Figure 108);
- the estimation of liquid quantities which it can be formed from meteorological and climatological parameters.

![Graph](image)

**Fig. 109.** Comparative analysis between the leachate quantity determined through mathematical calculation and the estimation of leachate quantity determined with the estimative mathematical model for leachate for Enna landfill, Italy.
It is considered that the post-closure phase begins in 2013, after seven years from landfill opening. It was considered in the calculations the first year – 2007 and the seventh year – 2013. The first year of leachate collection is considered the fourth year (2011) and from mathematical model results the first year of leachate collection the fourth year (2011). The post-closure phase has a duration of 30 years.

Figure 109 presents a comparative analysis between the calculated leachate quantity and the estimation of leachate quantity determined with estimative mathematical model for leachate for Enna landfill, Italy, which is based on the equation 73, estimative Gaussian equation.

Considering Enna landfill, Italy, the terms of the equation 73 are presented in Table 12.

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>y₀</td>
<td>1,616.43857</td>
</tr>
<tr>
<td>xc</td>
<td>5.68525</td>
</tr>
<tr>
<td>w</td>
<td>4.53011</td>
</tr>
<tr>
<td>A</td>
<td>108,369.58139</td>
</tr>
</tbody>
</table>

For the equation, it is considered the truth degree \( r^2 = 0.96841 \). Mathematical model was elaborated using Origin Pro 8.5 software utilised for operating system Windows 10.

Given that doesn’t exist no data from monitoring concerning the real quantity of collected leachate, it cannot realise a model validation. In this sense, the obtained values for post-closure phase may be used to estimate the final date of definitively landfill closure.

The estimation performed using the mathematical model has values close to the values obtained by the method of relative moisture content calculations for each fraction of waste deposited in Enna landfill.

Figure 110 presents an estimation of biogas quantity. The estimation was calculated using an estimative mathematical model to determine the biogas production capacity from a municipal solid waste landfill. The mathematical model is based in equation 74, a first-order exponential equation.
The estimation was realised for the active phase (2007-2013) and for a period of 31 years in post-closure phase of Enna landfill, Italy.

For Enna landfill, Italy, doesn’t exist any data concerning biogas quantity collected for active phase or for post-closure phase. In this regard, it cannot be achieved a comparative analysis for the accuracy of the used model. Considering specialized literature, it is known that only a part of collected biogas is used for co-generation and some is burned in torch.

5.1.4. Bacău landfill, România

Regarding Bacău landfill, it can be said that aren’t any information’s concerning the amount of deposited waste. There is no system control and no monitor parameters, considering the closure of the landfill when it reaches the maximum capacity of opened cell.

For this landfill there are different plants for waste sorting and treatment, but aren’t functional. Therefore it cannot be identified a waste structure.

Given that the waste quantities aren’t monitored, nor isn’t a structure of deposited waste, it cannot be applied an estimative mathematical model either for moisture content calculations, neither for estimation of leachate or biogas quantities.

For this landfill, it will consider only climatological and meteorological calculations.
Bacău landfill doesn’t have its own weather station, so all data concerning meteorological and climatological parameters (precipitations and temperature) were collected from Department of Climatology from Weather Romania, being calculated the monthly average for the period 1961 – 2013 (Figure 111 and Figure 112).

Considering that in some months the monthly average calculated temperatures were negative, it was not considered the evapotranspiration value for the month.

Fig. 111. The variation of monthly average of precipitation for Bacău landfill, România [86].

Monthly average variations for runoff (Figure 113) and for evaporation/ evapotranspiration (Figure 114) were calculated using equation 17, respectively, 18.
Fig. 112. The variation of monthly average of temperature for Bacău landfill, România [86].

Fig. 113. The variation of monthly average of runoff calculated for Bacău landfill, România.
5.1.5. Bihor landfill, România

The total amount of waste deposited in Bihor landfill, during active phase (2005 \(\div\) 2014) is presented in Figure 115.

Fig. 115. The total quantity of waste deposited in Bihor landfill, România [37].
Fig. 116. The representation as an average percentage of composition of municipal solid waste deposited in Bihor landfill, România [37].

The average values of the main fraction of waste stored in Bihor landfill are presented in Figure 116. For an overview of municipal waste composition, it can be observed, in Figure 117, the structure of each fraction for the whole waste quantity stored in Bihor landfill, România.

Fig. 117. The quantitative representation of composition of municipal solid waste deposited in Bihor landfill, România.
Monthly average variation of precipitation (Figure 118) and Monthly average variation of temperature (Figure 119) were calculated using meteorological and climatological data for the period 2005 – 2013. These data were collected from the Department of Climatology from Weather Romania. Bihor landfill does not have a weather station to monitor weather-related parameters.

Fig. 118. The variation of monthly average of precipitation for Bihor landfill, România [86].

Fig. 119. The variation of monthly average of temperature for Bihor landfill, România [86].
Monthly average variation of runoff for Bihor landfill, România, presented in Figure 120 was calculated using equation 17. Monthly average variation of evapotranspiration for Bihor landfill, România (Figure 120) was calculated using equation 18.

![The variation of monthly average calculated for runoff](image1)

**Fig. 120.** The variation of monthly average of runoff calculated for Bihor landfill, România.

![The variation of monthly average calculated for evapotranspiration](image2)

**Fig. 121.** The variation of monthly average of evapotranspiration calculated for Bihor landfill, România.
The total amount of liquid that can be formed in Bihor landfill it can be estimated using the moisture content related to each fraction from municipal solid waste composition, presented in Figures 122 ÷ 129.

![Graph showing moisture content related to paper and cardboard fraction](image)

Fig. 122. The estimation of moisture content related to the paper and cardboard fraction of municipal solid waste deposited in Bihor landfill, România.

![Graph showing moisture content related to leather fraction](image)

Fig. 123. The estimation of moisture content related to the leather fraction of municipal solid waste deposited in Bihor landfill, România.
Fig. 124. The estimation of moisture content related to the wood fraction of municipal solid waste deposited in Bihor landfill, România.

Fig. 125. The estimation of moisture content related to the glass fraction of municipal solid waste deposited in Bihor landfill, România.
Fig. 126. The estimation of moisture content related to the metal fraction of municipal solid waste deposited in Bihor landfill, România.

Fig. 127. The estimation of moisture content related to the plastic fraction of municipal solid waste deposited in Bihor landfill, România.
Fig. 128. The estimation of moisture content related to the organic fraction of municipal solid waste deposited in Bihor landfill, Romania.

Fig. 129. The estimation of moisture content related to the fine particles fraction of municipal solid waste deposited in Bihor landfill, Romania.
To calculate the liquid amount, were used moisture content percentages shown in Figure 51. For Bihor landfill doesn’t exist any study concerning the weight of moisture content, for each fraction from waste structure. It were used the values calculated for Turin landfill, this landfill being representative for all analysed case studies and because of complexity of monitored parameters. For mathematical calculation, it were used the density values described in Figure 52, taking into consideration the fact that the waste present the same fraction density in the deposited waste structure.

Weather parameters, specific for Bihor landfill, for the active phase gave a total annual liquid quantity of 395.394 m$^3$/yr. It is considered the fact that the Bihor landfill enters in post-closure phase starting with 2015, so, the total amount of liquid that it can be formed due to weather and climatological conditions, during the active phase is 3,953.94 m$^3$.

![The amount of liquid resulted from municipal solid waste](image)

**Fig. 130. The estimation of moisture content resulted from total quantity of municipal solid waste deposited in Bihor landfill, România.**

The total amount of liquid resulted from deposited waste is presented in Figure 130. This quantity was calculated by summing the estimations of each moisture content related to each waste fraction of municipal solid waste deposited in Bihor landfill, România.

By summing the annual estimation of the moisture content from the mixture of all fraction from waste structure, resulted from deposited amount of waste (Figure 130) and the estimation of liquid which was formed from meteorological and climatological parameters, it can be obtained the total
quantity of leachate that it can be formed inside of Bihor landfill. The total leachate production capacity has the value 458,485.6 m$^3$.

For Bihor landfill, is considered first year of post closure phase 2015, after ten years of activity. In calculation, it was considered first year 2005 and tenth year – 2014. First year of leachate collection was considered fourth year (2009) and from the mathematical model elaboration for leachate production capacity resulted the same year when leachate collection started (2009).

![Fig. 131](image)

**Fig. 131. Comparative analysis between calculated leachate quantity and the estimation of leachate quantity determined using estimative mathematical model for leachate production capacity for Bihor landfill, România.**

Figure 131 presents a comparative analysis between the amount of leachate determined by calculation and the estimation of leachate quantity determined using estimative mathematical model for leachate production capacity for Bihor landfill, România. For the estimation it was utilised an estimative mathematical model based on equation 73, estimative Gaussian equation. The truth degree of the equation is $r^2 = 0.95516$.

For Bihor landfill, România, the terms of equation 73 are presented in Table 13.
Table 13

The terms of Gaussian equation used to estimate the leachate amount that can be collected from Romanian Bihor landfill.

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_0$</td>
<td>3,953.91212</td>
</tr>
<tr>
<td>$xc$</td>
<td>6.81093</td>
</tr>
<tr>
<td>$w$</td>
<td>9.41047</td>
</tr>
<tr>
<td>$A$</td>
<td>409,667,90769</td>
</tr>
</tbody>
</table>

Considering specialized literature, it is considered the amount of leachate collected only for year 2014. Using the method of moisture content calculation for each waste fraction, it was identified the fact that for year 2014, the leachate quantity was the same as in reality, namely $30,315.6 \text{ m}^3$.

![Amount of biogas estimated](image)

**Fig. 132. The estimation of biogas quantity using estimative mathematical model for biogas production capacity for Bihor landfill, România.**

Figure 132 presents an estimation of biogas quantity that can be collected from Bihor landfill, România. The estimation was calculated using an estimative mathematical model for biogas given by equation 74.

The estimation was realised for active phase and for a period of 32 years in the post-closure phase of Bihor landfill, România.

For Bihor landfill, România, the estimation of leachate quantity using own mathematical model has the tendency to overestimate the real values in
active phase, but keeping the variation gave by the calculated leachate quantity using moisture content values.

Considering Bihor landfill, biogas quantity collected is much smaller than the calculated quantity of biogas. In this sense, it can be said that the mathematical model overestimates the real quantities of collected biogas. This assumption is justified by the fact that in Romania is not achieved the estimations of biogas quantities, therefore, there isn’t a clear evidence about the correct amount that can be collected from the landfill.

5.1.6. Piatra Neamţ landfill, România

The total waste quantity stored in Piatra Neamţ landfill, during active phase can be observed in Figure 133.

Fig. 133. The total waste quantity deposited in Piatra Neamţ landfill, România [3, 5, 100, 101].

Opposed to analysed Italian landfills, in Piatra Neamţ landfill are stored different types of waste, which have a different structure that municipal solid waste or analogous municipal solid waste, but were not considered in calculations. The average values of waste fractions from municipal solid waste stored in Piatra Neamţ landfill are presented in Figure 134.
Fig. 134. The representation as an average percentage of composition of municipal solid waste deposited Piatra Neamț landfill, România [3, 5, 100, 101].

Fig. 135. The quantitative representation of composition of municipal solid waste deposited in Piatra Neamț landfill, România.
It can be observed the fact that the fraction percentage of glass, metal and plastic are non-existent. This can be explained by the existence of pre-sorting station before final disposal. For an overview of the composition of municipal solid waste, it can be observed, in Figure 135, the fraction structure for the entire waste quantity stored in Piatra Neamț landfill, România.

Using data about meteorological and climatological parameters (temperature and precipitation) collected from the Department of Climatology from Weather Romania were calculated
- monthly average variation for precipitations for Piatra Neamț landfill, România for period 2004-2013 (Figure 136);
- monthly average variation for temperature for Piatra Neamț landfill, România for period 2004-2013 (Figure 137).

For Piatra Neamț landfill, România, it was calculated the monthly average variation for runoff using equation 17 and is represented in Figure 138

Monthly average variation for evapotranspiration was calculated for Piatra Neamț landfill, România using equation 18 (Figure 139).

Meteorological and climatological parameters were used to estimate the liquid content which it can be formed in Piatra Neamț landfill, România considering the values of monthly average variations thereof.
Fig. 137. The variation of monthly average of temperature for Piatra Neamț landfill, România [86].

Fig. 138. The variation of monthly average of runoff calculated for Piatra Neamț landfill, România.
Considering that in some months, the monthly average temperatures are negative, is were not considered the values of evapotranspiration for those months.

Fig. 139. The variation of monthly average calculated for evapotranspiration calculated for Piatra Neamț landfill, România

As in other analysed case studies, in calculations it was used the moisture content percentage for waste structure stored in Turin landfill, presented in Figure 51. At the same time, for mathematical calculations, it were used the density values described in Figure 52.

Taking into consideration the Figure 134, which presents the deposited waste structure, it can be estimated the moisture content for each fraction from waste stored in Piatra Neamț landfill and by summing the liquid related to each fraction, it can be estimated the total quantity of liquid that is formed in landfill.

It were realised the estimations of moisture content related to waste fraction of paper and cardboard, leather and textile, wood, organic waste and fine particles of waste (Figures 140 ÷ 144).

In Piatra Neamț landfill were stored several types of waste, but in calculations were considered only municipal waste quantities. Industrial and construction waste were neglected and it were considered as a substitute for periodically soil cover layers for landfill.
Fig. 140. The estimation of moisture content related to the paper and cardboard fraction of municipal solid waste deposited in Piatra Neamț landfill, România.

Fig. 141. The estimation of moisture content related to the leather fraction of municipal solid waste deposited in Piatra Neamț landfill, România.
Fig. 142. The estimation of moisture content related to the wood fraction of municipal solid waste deposited in Piatra Neamț landfill, România.

Fig. 143. The estimation of moisture content related to the organic fraction of municipal solid waste deposited in Piatra Neamț landfill, România.
Fig. 144. The estimation of moisture content related to the fine particles fraction of municipal solid waste deposited in Piatra Neamț landfill, România.

Fig. 145. The estimation of moisture content resulted from total quantity of municipal solid waste deposited in Piatra Neamț landfill, România.
Concluding the mathematical calculations, it was realised an estimation of the amount of liquid resulted from the quantity of municipal solid waste deposited in Piatra Neamț landfill, presented in Figure 145.

Considering the monthly average variations of meteorological and climatological parameters, it was estimated the amount of liquid that it can be formed in Piatra Neamț landfill with value 746.58144 m³/year. The landfill was active for a period of ten year, so, it can be said that the amount of liquid resulted from meteorological and climatological parameters is 7,465.8144 m³.

![Graph](image)

**Fig. 146. Comparative analysis between calculated leachate quantity and the estimation of leachate quantity determined using estimative mathematical model for leachate production capacity of Piatra Neamț landfill, România.**

It was considered that the post-closure period begins in 2013, after ten years after the landfill opening. In mathematical calculation were considered first year – 2004 and tenth year 2013. The first collection year for leachate is considered the fifth year (2008), and from mathematical model results the same value, first collection year in 2008. The total amount of liquid that can be formed in Piatra Neamț landfill is 214,702.12 m³. The total amount of leachate that it can be formed in landfill is represented by summing the following parameters:

- the estimation of moisture content of all fraction from structure of deposited municipal solid waste (Figure 145);
- the estimation of liquid quantities that it can be formed from meteorological and climatological parameters.

Figure 146 presents a comparative analysis between:
- the leachate quantity determined using moisture content calculation related to each fraction from deposited municipal solid waste;
- the estimation of leachate quantity determined using estimative mathematical model for leachate production capacity of Piatra Neamț landfill, România. The estimative mathematical model use the equation 73, being generated with Origin Pro 8.5 software. The truth degree for the equation is $r^2 = 0.96029$.

Considering Piatra Neamț landfill, România, the terms of equation 73 are presented in Table 14.

### Table 14.
The terms of Gaussian equation used to estimate the leachate amount that can be collected from Romanian Piatra Neamț landfill.

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_0$</td>
<td>901.63992</td>
</tr>
<tr>
<td>$x_c$</td>
<td>9.85911</td>
</tr>
<tr>
<td>$w$</td>
<td>12.5949</td>
</tr>
<tr>
<td>$A$</td>
<td>226,143.71913</td>
</tr>
</tbody>
</table>

From specialized literature [3, 5] collected leachate amount is known only for year 2013. Using moisture content calculation method for each fraction, the leachate quantity for year 2013 had the value 14,313.47467, being more than the fair value, 990 m$^3$. This can be explained by the fact that the collected leachate amount isn’t monitored and doesn’t exist any estimation of leachate quantity that it can be formed in landfill body. Also is important to mention that, after a treatment, a part of leachate returns to the landfill using recirculation operations.

The estimation of biogas quantity that it can be collected from Piatra Neamț landfill, România is presented in Figure 147. The estimation was calculated using an estimative mathematical model for biogas production capacity which can be collected from landfill, described by equation 74.

The estimation was realised for active phase (2004 – 2013) and for a period of 30 years in post-closure phase of Piatra Neamț landfill, România.
94

Fig. 147. The estimation of biogas quantity using estimative mathematical model for biogas production capacity from Piatra Neamț landfill, România.

Considering Piatra Neamț landfill, it can be said that doesn’t exist any data about the amount of biogas collected in active phase or in post-closure phase. In this sense, it cannot be realised a comparison between the amount of leachate collected and the biogas estimation to verify the accuracy of model used.

5.1.7. Timiș landfill, România

Regarding the waste amount stored in Timiș landfill, it can be said that doesn’t exist any public information on this. Since aren’t any information on waste quantity or structure, it cannot be realized the structure of waste fraction.

In Timiș landfill area exist a weather station, but data about weather-climatic conditions (temperature and precipitation) were collected from the Department of Climatology from Weather Romania, and were calculated monthly average variations for precipitations and for temperature for the period 1961 - 2013 (Figure 148 and Figure 149). The monthly average variations for runoff (Figure 150) and for evapotranspiration (Figure 151) were calculated with equations 17 and 18.
Fig. 148. The variation of monthly average for precipitations for Timiş landfill, România [86].

Fig. 149. The variation of monthly average of temperature for Timiş landfill, România [86].
Fig. 150. The variation of monthly average of runoff calculated for Timiș landfill, România.

Fig. 151. The variation of monthly average of evapotranspiration calculated for Timiș landfill, România.
CHAPTER 6
THE ANALYSIS OF LEACHATE AND BIOGAS
QUANTITATIVE, QUALITATIVE AND KINETIC ASPECTS IDENTIFIED IN ITALIAN AND ROMANIAN LANDFILLS

6.1. Data used to verify and assess mathematical models to calculate the estimated production of leachate and biogas

Each country has specific legislation on the types of waste accepted in landfills. The categories of waste accepted in landfills is an important factor in landfill evaluation in terms of the products obtained.

Table 15.
The quantitative and the qualitative characteristics of the waste stored in landfills [1, 3-5, 8, 10, 32, 37, 76, 85, 100, 101].

<table>
<thead>
<tr>
<th>Landfill</th>
<th>Deposited waste amount (10^6 t)</th>
<th>Time</th>
<th>Type of waste (% w/w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turin, Italy</td>
<td>17.385</td>
<td>1984-2009</td>
<td>73% municipal solid waste (MSW), 14% analogous MSW, 13% sludge</td>
</tr>
<tr>
<td>Potenza, Italy</td>
<td>0.406</td>
<td>1989-2004</td>
<td>90% MSW, 10% sludge</td>
</tr>
<tr>
<td>Enna, Italy</td>
<td>0.448</td>
<td>2007-2013</td>
<td>73% MSW, 14% analogous MSW, 13% sludge</td>
</tr>
<tr>
<td>Bacău, România</td>
<td>n.a.</td>
<td>n.a.</td>
<td>MSW, industrial, construction*</td>
</tr>
<tr>
<td>Piatra Neamț, România</td>
<td>0.105</td>
<td>2004-2013</td>
<td>85% MSW, 5% analogous MSW, 1% sludge, 3% industrial, 6% construction</td>
</tr>
<tr>
<td>Bihor, România</td>
<td>1.422</td>
<td>2005-2015</td>
<td>55% MSW, 22% construction, 9% industrial, 14% sol</td>
</tr>
<tr>
<td>Timiș, România</td>
<td>n.a.</td>
<td>n.a.</td>
<td>MSW, industrial*</td>
</tr>
</tbody>
</table>

n.a.: not available;
* Relative abundances are not specified

According to actual Italian regulations, the landfills are classified in disposal plants for inert waste, for non-hazardous waste and for hazardous waste. This classification ensures, at least for inert and non-hazardous wastes, a rather predictable composition of the leachate originated in a certain category of landfill. [46, 81, 82].

The quality of wastes accepted in the considered plants is rather heterogeneous (see Table 15):

- the Italian plant accepted mostly MSW, MSW analogous (they have the same composition of MSW but derive from non-domestic sources) and
sewer sludge, that since 2003 is not admitted in Italian non-hazardous waste landfills on the grounds of its Dissolved Organic Carbon (DOC) content;

- the considered Romanian plants accept mixed types of waste, thus MSW are typically mixed with construction and industrial wastes. The amount of deposited waste and the relative abundances of their different types were not declared for all case studies.

To realise a comparative analyse between different landfills from Italy and Romania, it was used Hydrological Mass Balance model, based on the evaluation of mass balance of water inside of a landfill, which distinguishes between active phase and passive phase.

Serial Water balance was applied only for Turin landfill because of the multitude of available data.

To provide a clearer evidence of the difference in terms of leachate quantity for landfills, it was realised a suggestive comparison using available data for the best possible accuracy.

To calculate the leachate quantity was used Mass Balance model. The data concerning biogas production are available only for four landfills, two from Italy and two from Romania. To realize a pertinent comparative analyses the data were normalized on the mass unit of waste deposited in a single year (Table 20). In Italian landfills all leachate was extracted during the active phase, while in Bihor and Piatra Neamț plants a part of the leachate was left in the cells. The comparison of the data about leachate generated shows values having the same magnitude order, with differences that may be due to the types and amounts of the deposited wastes (see Table 2), to their composition (see Tables 3 and 4), to their field capacity (see Table 5), to their grade of compaction and to the nature of cultivation operations.

<table>
<thead>
<tr>
<th>Landfill</th>
<th>Year</th>
<th>Generated leachate</th>
<th>Treated leachate</th>
<th>Calculated leachate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m³/year</td>
<td>m³/tonnes</td>
<td>m³/year</td>
</tr>
<tr>
<td>Turin</td>
<td>2009</td>
<td>257,415</td>
<td>0.0148</td>
<td>257,415</td>
</tr>
<tr>
<td>Potenza</td>
<td>2003</td>
<td>7,543.78</td>
<td>0.263</td>
<td>7,543.78</td>
</tr>
<tr>
<td>Bihor</td>
<td>2014</td>
<td>30,316</td>
<td>0.0213</td>
<td>20,243</td>
</tr>
<tr>
<td>Piatra Neamț</td>
<td>2013</td>
<td>990</td>
<td>0.0094</td>
<td>919</td>
</tr>
</tbody>
</table>

Considering Table 20, it can be observed the following differences:
- it can be observed that exist some differences between leachate quantity for each landfill;
- only Bihor case study exhibits a good agreement,
- Hydrological Mass Balance model underestimated the real values for collected leachate for Turin landfill, respectively for Potenza landfill;
- for Piatra Neamț landfill, it may observe that the trend is opposite;
- collected leachate from Romanian landfills is partial treated, while the leachate collected from Italian landfills is entirely treated.

Considering the leachate quantity related to the waste quantity stored in landfill, it can be said that the most „productive” landfill is Potenza landfill and the landfill with the lowest productivity level is Piatra Neamț landfill.

Actually the model’s limitations are due to several issues: first of all approximated values of the required parameters were employed (i.e. average monthly meteorological data and simplified composition of waste), then some significant aspects of filtration were neglected (i.e. channelling in preferential paths), as well as the effect of the hydraulic load of leachate collected at the bottom of the landfill, and the heterogeneous features of waste as porous medium.

Even if there exist such limitations, mass balance model can be considered one of the best ways to estimated leachate quantity, especially used for evaluations longer in time (long periods of landfill active phase).

6.3. The valuation of mathematical models used to calculate the estimated production of biogas

For comparative analyses between biogas quantities from landfills considered as case studies, were used estimative mathematical models presented in the previous chapters:
- stoichiometric model – based on mass balance derived from elemental composition of the waste;
- US EPA LandGEM Model.

For a much clearer analysis between analysed landfills from two countries, it was considered an analysis between the values calculated using stoichiometric model and the real values of biogas, respectively methane. The analysis was performed for two of the case studies presented, because it doesn’t exist public data for all landfills concerning biogas production, respectively methane. More than that, two Romanian landfills doesn’t have a biogas collection system.

The comparison of the data about generated biogas showed values having different magnitude orders, because of the already underlined differences about the types and amounts of the deposited wastes and their composition.

Taking into account the biogas/methane quantities generated for two considered landfills, and real volumes (Table 21 and Table 22), it can be
realized different comparative analysis between real quantities and estimated values, but also between two landfills, considering the volume reported to the amount of deposited waste.

Table 21. Comparative analysis between the real values and estimated amounts of biogas production using Stoichiometric model.

<table>
<thead>
<tr>
<th>Landfill</th>
<th>Year</th>
<th>Generated biogas</th>
<th>Calculated biogas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m³/year</td>
<td>m³/tonnes</td>
</tr>
<tr>
<td>Bihor</td>
<td>2014</td>
<td>16,956.17</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Taking into account a comparison between real data and the values calculated by means of the Stoichiometric Model (see Table 8), it may be noticed that Turin case study exhibits an agreement about the magnitude order, while in Bihor case the model overestimated the real value by nearly 100 times.

Regarding the differences between the two landfills concerning biogas or methane production capacities related to the amount of waste deposited in landfill, it can be observed the fact that the gas generation rate is much higher for Italian landfills, comparing with Romanian cases. However, by applying the model, it can observed the difference between the magnitude order for two cases:

- for Turin landfill, calculated values doubles the real biogas values;
- for Bihor landfill, calculated values overestimate over 75 times the real values of generated biogas.

Table 22. Comparative analysis between the real values and estimated amounts of methane production using stoichiometric model.

<table>
<thead>
<tr>
<th>Landfill</th>
<th>Year</th>
<th>Generated methane</th>
<th>Calculated methane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m³/year</td>
<td>m³/tonnes</td>
</tr>
<tr>
<td>Turin</td>
<td>2009</td>
<td>35,379,360.62</td>
<td>2.035</td>
</tr>
<tr>
<td>Bihor</td>
<td>2014</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Taking into account arguments as referred and the truthful of applied model it can be enounced the following assumptions:

- given that the calculations were made for the last year of the landfill from Italy it may be justified the overestimation of the generated amount more than the actual value;
- considering Bihor landfill, it can be observed that exist extremely large differences between actual and calculated values. This can be justified
by the approximations made in the calculations. In practice, it is considered necessary extracting a major amount of biogas to avoid critical situations.

The main weaknesses of the model are this case: first of all the assumption that all the Carbon fraction of the waste may be biologically degraded, then the assumption of a simplified composition of waste, finally the amount of biogas generated in a specific year may be due not only to the waste deposited in that year, but also to slowly biodegradable fractions of waste previously landfilled.

CHAPTER 7
MATHEMATICAL MODELS DEVELOPED TO DESCRIBE QUANTITATIVE, QUALITATIVE AND KINETICS ASPECTS APPLIED FOR DIFFERENT CASE STUDIES

7.1. The elaboration of mathematical model to estimate production capacity of leachate and biogas from landfills in Italy and Romania

The results obtained from comparative analysis or from mathematical calculations used to estimate the leachate, respectively biogas quantities shows that the flows of leachate or of biogas that can be collected from landfills depends on the amount of waste that was stored in the active phase of landfill and also on the landfill life (both active and post-closure phases).

By employing the TableCurve 3D software for generating linear and non-linear equation the mathematical models for leachate flow and biogas flow that it can be collected from landfills were obtained for waste quantity that is deposited in landfill and on the activity period of landfill.

Mathematical model was elaborated for each case study from Italy and from Romania for leachate production and also for biogas production.

7.1.1. The elaboration of mathematical model for the production of leachate that can be collected from landfills

For each mathematical model elaborated for calculation of leachate production was considered the total waste quantity deposited and the time, as follow: year one - the first year in which were putted waste in landfill and the post-closure phase was considered for a period of 31 years for Turin, Enna and Bihor landfills and for a period of 30 years for the other landfills (Potenza and Piatra Neamț). Figure 166 presents the variation of leachate production which can be collected from Turin landfill for a period of 41 years. It was considered the first year of collection year 2000 (the 17th year utilised in mathematical model) and for permanent closure of landfill was considered year 2040 (the 57th year utilised in mathematical model).
Fig. 166. The variation of leachate production that can be collected from Turin landfill, Italy.

Fig. 167. The variation of leachate production that can be collected from Potenza landfill, Italy.

Considering Potenza landfill, it was calculated the variation of leachate production that it can be collected for a period of 42 years (Figure 167). For
model elaboration, it was considered first year of leachate collection year 1995 (the fifth year utilised in mathematical model) and the permanent closure of landfill was estimated to be in the year 2034 (the 46th year utilised in mathematical model).

Figure 168 describe the variation of leachate production that can be collected from Enna landfill, Italy. For this landfill, it was obtained a total leachate quantity that can be collected for a period of 35 years. First year for leachate collection utilized in calculation was considered year 2010 (the fourth year utilized in mathematical model) and the permanent closure of landfill was estimated to be in the year 2044 (the 38th year utilized in mathematical model).

![Figure 168](image)

**Fig. 168. The variation of leachate production that can be collected from Enna landfill, Italy.**

Regarding Bihor landfill from Romania, for a period of 38 years of collection it was calculated the variation of leachate production. It was considered the first year of leachate collection – 2008 (the fourth year utilised in mathematical model) and the final closure was estimated to be in 2045 (the 41st year utilised in mathematical model).
Fig. 169. The variation of leachate production that can be collected from Bihor landfill, Romania.

Fig. 170. The variation of leachate production that can be collected from Piatra Neamț landfill, Romania.

The variation of leachate production that can be collected from Piatra Neamț landfill, for a period of 36 years is represented in Figure 170. First year
of leachate collection was considered in 2008 (the fifth year utilised in mathematical model). The post-closure phase will finish in year 2043 (the 40th year utilised in mathematical model).

Table 23.
The values of equation constants that describe the mathematical model for leachate elaborated for landfills from Italy and from Romania.

<table>
<thead>
<tr>
<th>Landfill</th>
<th>Equation constants</th>
<th>Constant values</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turin, Italy</td>
<td>a, b, c, d, e, f</td>
<td>-40,034.1681392452, 271,356.794142747, -459,240.407702551, 213,761.721999775, -28.986.7891657603, 0.114012603520142</td>
<td>0.57</td>
</tr>
<tr>
<td>Potenza, Italy</td>
<td>a, b, c, d, e, f</td>
<td>1,188.9070651011, -11,005.6191751017, 14,526.2225421523, -4,699.76586857529, 424.988114170623, -0.0390491358105443</td>
<td>0.92</td>
</tr>
<tr>
<td>Enna, Italy</td>
<td>a, b, c, d, e, f</td>
<td>-7,139.71253842392, -52,180.8770947126, 72,052.5755587861, -28,587.5871175297, 3,560.3106118661, 0.235131280862251</td>
<td>0.83</td>
</tr>
<tr>
<td>Bihor, Romania</td>
<td>a, b, c, d, e, f</td>
<td>-2,022.50542621047, -77,821.010989026, 121,442.679510803, -50,981.6085053701, 6,494.18972518707, 0.081792082432437</td>
<td>0.93</td>
</tr>
<tr>
<td>Piatra Neamț, Romania</td>
<td>a, b, c, d, e, f</td>
<td>5,726.87695394837, -33,324.8630459427, 54,173.8307778669, -23,214.1710580887, 2,951.85869360293, -0.0852695871431864</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The surface obtained is characterized by the equation 76, with the following form:

105
\[ z = a + b \cdot \ln x + c \cdot (\ln x)^2 + d \cdot (\ln x)^3 + e \cdot (\ln x)^4 + f \cdot y \]  \hspace{1cm} (76)

where:

\( z \) is the leachate production that can be annually collected from landfill, (m\(^3\)/year);
\( x \) – activity year of landfill, (year);
\( y \) – waste quantity, annually deposited in landfill, (tonnes/year).

For each case study, the correlation coefficient which corresponds to the equation in between \( r^2 = 0.57 \div 0.93 \) (Table 23).

In Table 23 are presented the constant values from equation 76 corresponding to leachate production for each landfill from Italy and from Romania.

7.1.2. The elaboration of mathematical model for the production of biogas that can be collected from landfills

For each elaborated mathematical model used to calculate the biogas production was considered the waste quantity deposited in active phase and time when the waste quantities were stored in landfill, namely: year one – the first year when the waste was putted in landfill and the post-closure phase was considered for 31 years for Turin, Enna and Bihor landfills and for 30 year for the rest of analysed landfills (Potenza and Piatra Neamț).

Figure 171 presents the variation of biogas production that can be collected from Turin landfill, Italy for a period of 56 of years. It was considered the first year of collection – year 1985 (the second year utilised in mathematical model) and the final closure of landfill will be in 2040 (the 57\(^{th}\) year utilised in mathematical model).

As in the case of Turin landfill, the variation of biogas production it can be collected from Potenza landfill, Italy for a period of 45 years (Figure 172). The first year of biogas collection was considered year 1990 (the second year utilized in mathematical model) and the post-closure phase will finish in year 2034 (the 46\(^{th}\) year in mathematical model).

Concerning Enna landfill, Italy, the variation of biogas production that can be collected, in active phase and also in post-closure phase, is presented in Figure 173. The leachate was considered to be collected for a period of 35 years. The first collection year of biogas was considered year 2008 (the second year utilised in mathematical model) and the permanent closure of the landfill is estimated to be in year 2044 (the 38\(^{th}\) year utilised in mathematical model).
Fig. 171. The variation of biogas production that can be collected from Turin landfill, Italy.

Fig. 172. The variation of biogas production that can be collected from Potenza landfill, Italy.

The variation of biogas production that can be collected from Bihor landfill, Romania for a period of 38 years (active phase and post-closure period) is presented in Figure 174. It was considered first year of biogas collection year 2006 (the second year utilised in mathematical model) and the
final closure of landfill is estimated to be in 2045 (the 41\textsuperscript{st} year utilised in mathematical model).

**Fig. 173.** The variation of biogas production that can be collected from Enna landfill, Italy.

**Fig. 174.** The variation of biogas production that can be collected from Bihor landfill, Romania.
Figure 175 describes the variation of biogas production that can be collected from Piatra Neamț landfill, Romania. From mathematical model resulted the fact that the biogas it can be collected from a period of 36 years, first year of biogas collection being in 2005 (the second year utilised in mathematical model) and the final closure of landfill is considered to be in 2043 (the 40th year utilised in mathematical model).

The surface generated by mathematical model is characterized by the equation 77, with the following form:

\[
z = a + b \cdot x + c \cdot x^2 + d \cdot x^3 + e \cdot x^4 + f \cdot y
\]

where:
- \( z \) is the biogas production that can be annually collected from landfill, (m³/year);
- \( x \) – the activity year of landfill, (year);
- \( y \) – the waste quantity, annually deposited in landfill, (tonnes/year).

For each case study, it was considered the correlation coefficient which corresponds to the equation 77 and is between \( r^2 = 0.87 \div 0.96 \) (Table 24).

In Table 24 are presented the values of equations constants from equation 77 for leachate production from each landfill.
Table 24.
The values of equation constants that describe the mathematical model for biogas elaborated for landfills from Italy and from Romania.

<table>
<thead>
<tr>
<th>Landfill</th>
<th>Equation constant</th>
<th>Constant value</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turin, Italy</td>
<td>a</td>
<td>-49,700,711.0972997</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>23,375,337.6457672</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>-1,067,497.78592499</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>15,448,0313266982</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>-62,5431796804985</td>
<td></td>
</tr>
<tr>
<td></td>
<td>f</td>
<td>22,070355729551</td>
<td></td>
</tr>
<tr>
<td>Potenza, Italy</td>
<td>a</td>
<td>-2,186,612.28979817</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>1,516,594.71339108</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>-116,506.469700311</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>3,098,26313287352</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>-27,4337659310281</td>
<td></td>
</tr>
<tr>
<td></td>
<td>f</td>
<td>14.6323831647287</td>
<td></td>
</tr>
<tr>
<td>Enna, Italy</td>
<td>a</td>
<td>-4,481,160.45461195</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>3,416,424.20065106</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>-348,728.407915687</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>12,273.2538531001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>-142,232018248422</td>
<td></td>
</tr>
<tr>
<td></td>
<td>f</td>
<td>28.3911937177432</td>
<td></td>
</tr>
<tr>
<td>Bihor, Romania</td>
<td>a</td>
<td>-13,174,700.8917097</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>9,299,162.62971821</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>-856,279.9195162</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>27,284.6420583288</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>-287,444276459276</td>
<td></td>
</tr>
<tr>
<td></td>
<td>f</td>
<td>12.7207405135238</td>
<td></td>
</tr>
<tr>
<td>Piatra Neamț, Romania</td>
<td>a</td>
<td>-7,040,075.02515877</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>3,460,536.43762627</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>-311,483.71160825</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>10,021.4462969401</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>-107,6023782551</td>
<td></td>
</tr>
<tr>
<td></td>
<td>f</td>
<td>65,7702546205259</td>
<td></td>
</tr>
</tbody>
</table>

7.2. Mathematical model evaluation

It were evaluated the mathematical models obtained after employing TableCurve 3D program for generating linear and nonlinear equations was carried out for capacities of leachate production and also biogas production from Italian landfills (Turin, Potenza and Enna) and from Romanian landfills (Bihor and Piatra Neamț).

The accuracy of mathematical model is given by the fact that for analysed landfill from Italy exist much more monitored parameters, being in
post-closure phase, while Romania is at the beginning of waste management domain.

7.2.1. The evaluation of mathematical model generated by TableCurve 3D software

For mathematical model evaluation, it was chosen one equation for each studied method, namely:

- the variation of leachate production that can be collected from Turin landfill, Italy:

$$
P_{levigat} = -40034.1681392452 + 271356.794142747 \cdot \ln t_{To} - \\
-459240.407702551 \cdot (\ln t_{To})^2 + 213761.721999775 \cdot (\ln t_{To})^3 - \\
-28986.7891657603 \cdot (\ln t_{To})^4 + 0.11401260352 \cdot m_{To}
$$

(78)

- the variation of leachate production that can be collected from Potenza landfill, Italy:

$$
P_{levigat} = 1188.9070651011 - 1188.9070651011 \cdot \ln t_{Po} + \\
+ 14526.2225421523 \cdot (\ln t_{Po})^2 - 4699.76586857529 \cdot (\ln t_{Po})^3 + \\
+ 424.988114170623 \cdot (\ln t_{Po})^4 - 0.0390491358105443 \cdot m_{Po}
$$

(79)

- the variation of leachate production that can be collected from Enna landfill, Italy:

$$
P_{levigat} = -7139.71253842392 - 52180.8770947126 \cdot \ln t_{En} + \\
+ 72052.5755587861 \cdot (\ln t_{En})^2 - 28587.5871175297 \cdot (\ln t_{En})^3 + \\
+ 3560.3106118661 \cdot (\ln t_{En})^4 + 0.235131280862251 \cdot m_{En}
$$

(80)

- the variation of leachate production that can be collected from Bihor landfill, Romania:

$$
P_{levigat} = -2022.50542621047 - 77821.010989026 \cdot \ln t_{Bi} + \\
+ 121442.679510803 \cdot (\ln t_{Bi})^2 - 50981.6085053701 \cdot (\ln t_{Bi})^3 + \\
+ 6494.18972518707 \cdot (\ln t_{Bi})^4 + 0.081792082432437 \cdot m_{Bi}
$$

(81)
- the variation of leachate production that can be collected from Piatra Neamț landfill, Romania:

\[
P_{levigat} = 5726.87695394837 - 33324.8630459427 \cdot \ln t_{PN} + \\
+54173.8307778669 \cdot (\ln t_{PN})^2 - 23214.1710580887 \cdot (\ln t_{PN})^3 + \\
+2951.858695871431864 \cdot m_{PN}
\]  

(82)

- the variation of biogas production that can be collected from Turin landfill, Italy:

\[
P_{biogaz} = -49700711.0972997 + 23375337.6457672 \cdot t_{To} - \\
-1067497.78592499 \cdot t_{To}^2 + 15448.0313266982 \cdot t_{To}^3 - \\
-62.5431796804985 \cdot t_{To}^4 + 22.070357295551 \cdot m_{To}
\]  

(83)

- the variation of biogas production that can be collected from Potenza landfill, Italy:

\[
P_{biogaz} = -2186612.28979817 + 1516594.71339108 \cdot t_{Po} - \\
-116506.469700311 \cdot t_{Po}^2 + 3098.2631287352 \cdot t_{Po}^3 - \\
-27.4337659310281 \cdot t_{Po}^4 + 14.632381647287 \cdot m_{Po}
\]  

(84)

- the variation of biogas production that can be collected from Enna landfill, Italy:

\[
P_{biogaz} = -4481160.45461195 + 3416424.20065106 \cdot t_{En} - \\
-348728.407915687 \cdot t_{En}^2 + 12273.2538531001 \cdot t_{En}^3 - \\
-142.232018248422 \cdot t_{En}^4 + 28.3911937177432 \cdot m_{En}
\]  

(85)

- the variation of biogas production that can be collected from Bihor landfill, Romania:

\[
P_{biogaz} = -13174700.8917097 + 9299162.62971821 \cdot t_{Bi} - \\
-856279.9195162 \cdot t_{Bi}^2 + 27284.6420583288 \cdot t_{Bi}^3 - \\
-287.444276459276 \cdot t_{Bi}^4 + 12.707405135238 \cdot m_{Bi}
\]  

(86)

- the variation of biogas production that can be collected from Piatra Neamț landfill, Romania:
\[ P_{\text{biogas}} = -7040075.02515877 + 3460536.43762627 \cdot t_{PN} - \\
-311483.71160825 \cdot t_{PN}^2 + 10021.4462969401 \cdot t_{PN}^3 - \\
-107.60237825515 \cdot t_{PN}^4 + 65.7702546205259 \cdot m_{PN} \]  

(87)

The relative error was calculated using the equation 88:

\[
\varepsilon = \frac{p_e - p_m}{p_m} \cdot 100 \quad (\%) 
\]

(88)

where:
- \( \varepsilon \) is relative error;
- \( p_e \) – production capacity experimental obtained (collected) for leachate and for biogas;
- \( p_m \) – production capacity obtained using mathematical model for leachate, respectively for biogas.

Tables 25 ÷ 34 are presenting the values obtained using mathematical model and the values obtained from the estimation realised in chapter 5.

**Table 25.**

The variation of leachate production that can be collected from Turin landfill, Italy.

<table>
<thead>
<tr>
<th>Calendar year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Leachate production (m³/year)</th>
<th>Relative error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mathematical model</td>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>1</td>
<td>341,477</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1985</td>
<td>2</td>
<td>331,321</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1986</td>
<td>3</td>
<td>356,477</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1987</td>
<td>4</td>
<td>376,782</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1988</td>
<td>5</td>
<td>542,339</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1989</td>
<td>6</td>
<td>636,893</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1990</td>
<td>7</td>
<td>655,536</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1991</td>
<td>8</td>
<td>701,117</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1992</td>
<td>9</td>
<td>650,444</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1993</td>
<td>10</td>
<td>686,941</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1994</td>
<td>11</td>
<td>795,583</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1995</td>
<td>12</td>
<td>1,041,490</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1996</td>
<td>13</td>
<td>1,278,410</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1997</td>
<td>14</td>
<td>263,360</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1998</td>
<td>15</td>
<td>513,659</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1999</td>
<td>16</td>
<td>896,268</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2000</td>
<td>17</td>
<td>1,013,210</td>
<td>151,656.92</td>
<td>159,014.16</td>
<td>4.85</td>
</tr>
<tr>
<td>2001</td>
<td>18</td>
<td>687,412</td>
<td>124,643.81</td>
<td>181,202.20</td>
<td>45.38</td>
</tr>
<tr>
<td>2002</td>
<td>19</td>
<td>927,399</td>
<td>161,238.29</td>
<td>201,627.05</td>
<td>25.05</td>
</tr>
<tr>
<td>2003</td>
<td>20</td>
<td>756,177</td>
<td>150,051.36</td>
<td>219,035.93</td>
<td>45.97</td>
</tr>
<tr>
<td>Calendar year (year)</td>
<td>Time (year)</td>
<td>Quantity of waste (tonnes/year)</td>
<td>Leachate production (m³/year)</td>
<td>Relative error (%)</td>
<td>Obs.</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------</td>
<td>---------------------------------</td>
<td>-----------------------------</td>
<td>-------------------</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mathematical model</td>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>21</td>
<td>699,906</td>
<td>151,081.63</td>
<td>232,280.17</td>
<td>53.74</td>
</tr>
<tr>
<td>2005</td>
<td>22</td>
<td>644,257</td>
<td>151,310.18</td>
<td>240,440.09</td>
<td>58.91</td>
</tr>
<tr>
<td>2006</td>
<td>23</td>
<td>587,864</td>
<td>150,601.61</td>
<td>242,930.49</td>
<td>61.31</td>
</tr>
<tr>
<td>2007</td>
<td>24</td>
<td>562,279</td>
<td>152,576.41</td>
<td>239,570.06</td>
<td>57.02</td>
</tr>
<tr>
<td>2008</td>
<td>25</td>
<td>539,922</td>
<td>154,115.05</td>
<td>230,603.16</td>
<td>49.63</td>
</tr>
<tr>
<td>2009</td>
<td>26</td>
<td>606,682</td>
<td>165,035.86</td>
<td>216,670.48</td>
<td>31.29</td>
</tr>
<tr>
<td>2010</td>
<td>27</td>
<td>0</td>
<td>198,423.90</td>
<td>198,733.35</td>
<td>1.92</td>
</tr>
<tr>
<td>2011</td>
<td>28</td>
<td>0</td>
<td>100,255.76</td>
<td>177,964.19</td>
<td>77.51</td>
</tr>
<tr>
<td>2012</td>
<td>29</td>
<td>0</td>
<td>101,388.14</td>
<td>155,620.33</td>
<td>53.49</td>
</tr>
<tr>
<td>2013</td>
<td>30</td>
<td>0</td>
<td>101,846.63</td>
<td>132,920.17</td>
<td>30.51</td>
</tr>
<tr>
<td>2014</td>
<td>31</td>
<td>0</td>
<td>101,656.19</td>
<td>110,937.97</td>
<td>9.13</td>
</tr>
<tr>
<td>2015</td>
<td>32</td>
<td>0</td>
<td>100,841.04</td>
<td>90,529.36</td>
<td>10.23</td>
</tr>
<tr>
<td>2016</td>
<td>33</td>
<td>0</td>
<td>99,424.61</td>
<td>72,292.75</td>
<td>27.29</td>
</tr>
<tr>
<td>2017</td>
<td>34</td>
<td>0</td>
<td>97,429.50</td>
<td>56,565.68</td>
<td>41.94</td>
</tr>
<tr>
<td>2018</td>
<td>35</td>
<td>0</td>
<td>94,877.44</td>
<td>43,450.14</td>
<td>54.20</td>
</tr>
<tr>
<td>2019</td>
<td>36</td>
<td>0</td>
<td>91,789.35</td>
<td>32,857.45</td>
<td>64.20</td>
</tr>
<tr>
<td>2020</td>
<td>37</td>
<td>0</td>
<td>88,185.27</td>
<td>24,562.63</td>
<td>72.15</td>
</tr>
<tr>
<td>2021</td>
<td>38</td>
<td>0</td>
<td>84,084.42</td>
<td>18,259.15</td>
<td>78.28</td>
</tr>
<tr>
<td>2022</td>
<td>39</td>
<td>0</td>
<td>79,505.23</td>
<td>13,607.14</td>
<td>82.89</td>
</tr>
<tr>
<td>2023</td>
<td>40</td>
<td>0</td>
<td>74,465.33</td>
<td>10,271.01</td>
<td>86.21</td>
</tr>
<tr>
<td>2024</td>
<td>41</td>
<td>0</td>
<td>68,981.61</td>
<td>7,945.09</td>
<td>88.48</td>
</tr>
<tr>
<td>2025</td>
<td>42</td>
<td>0</td>
<td>63,070.22</td>
<td>6,367.93</td>
<td>89.90</td>
</tr>
<tr>
<td>2026</td>
<td>43</td>
<td>0</td>
<td>56,746.64</td>
<td>5,327.45</td>
<td>90.61</td>
</tr>
<tr>
<td>2027</td>
<td>44</td>
<td>0</td>
<td>50,025.65</td>
<td>4,659.43</td>
<td>90.69</td>
</tr>
<tr>
<td>2028</td>
<td>45</td>
<td>0</td>
<td>42,921.42</td>
<td>4,241.93</td>
<td>90.12</td>
</tr>
<tr>
<td>2029</td>
<td>46</td>
<td>0</td>
<td>35,447.51</td>
<td>3,987.88</td>
<td>88.75</td>
</tr>
<tr>
<td>2030</td>
<td>47</td>
<td>0</td>
<td>27,616.88</td>
<td>3,837.33</td>
<td>86.11</td>
</tr>
<tr>
<td>2031</td>
<td>48</td>
<td>0</td>
<td>19,441.96</td>
<td>3,750.44</td>
<td>80.71</td>
</tr>
<tr>
<td>2032</td>
<td>49</td>
<td>0</td>
<td>10,934.64</td>
<td>3,701.59</td>
<td>66.15</td>
</tr>
<tr>
<td>2033</td>
<td>50</td>
<td>0</td>
<td>2,106.32</td>
<td>3,674.83</td>
<td>74.47</td>
</tr>
<tr>
<td>2034</td>
<td>51</td>
<td>0</td>
<td>-</td>
<td>3,660.55</td>
<td>-</td>
</tr>
<tr>
<td>2035</td>
<td>52</td>
<td>0</td>
<td>-</td>
<td>3,653.12</td>
<td>-</td>
</tr>
<tr>
<td>2036</td>
<td>53</td>
<td>0</td>
<td>-</td>
<td>3,649.36</td>
<td>-</td>
</tr>
<tr>
<td>2037</td>
<td>54</td>
<td>0</td>
<td>-</td>
<td>3,647.50</td>
<td>-</td>
</tr>
<tr>
<td>2038</td>
<td>55</td>
<td>0</td>
<td>-</td>
<td>3,646.60</td>
<td>-</td>
</tr>
<tr>
<td>2039</td>
<td>56</td>
<td>0</td>
<td>-</td>
<td>3,646.18</td>
<td>-</td>
</tr>
<tr>
<td>2040</td>
<td>57</td>
<td>0</td>
<td>-</td>
<td>3,645.99</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 25 continued.**

Doesn’t exist leachate production according mathematical model.
The variation of leachate production that can be collected from Potenza landfill, Italy.

<table>
<thead>
<tr>
<th>Calendar year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Leachate production (m³/year)</th>
<th>Relative error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mathematical model</td>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>1</td>
<td>16,000</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>2</td>
<td>28,062</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1991</td>
<td>3</td>
<td>28,062</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>4</td>
<td>28,062</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>5</td>
<td>27,895</td>
<td>3,272.50</td>
<td>3,558.99</td>
<td>8.75</td>
</tr>
<tr>
<td>1994</td>
<td>6</td>
<td>27,840</td>
<td>4,363.27</td>
<td>4,003.87</td>
<td>8.24</td>
</tr>
<tr>
<td>1995</td>
<td>7</td>
<td>27,955</td>
<td>5,149.99</td>
<td>4,470.75</td>
<td>13.19</td>
</tr>
<tr>
<td>1996</td>
<td>8</td>
<td>28,279</td>
<td>5,699.15</td>
<td>4,949.73</td>
<td>13.15</td>
</tr>
<tr>
<td>1997</td>
<td>9</td>
<td>28,224</td>
<td>6,086.11</td>
<td>5,429.06</td>
<td>10.80</td>
</tr>
<tr>
<td>1998</td>
<td>10</td>
<td>26,612</td>
<td>6,396.30</td>
<td>5,895.52</td>
<td>7.83</td>
</tr>
<tr>
<td>1999</td>
<td>11</td>
<td>25,700</td>
<td>6,571.28</td>
<td>6,335.01</td>
<td>3.60</td>
</tr>
<tr>
<td>2000</td>
<td>12</td>
<td>26,930</td>
<td>6,577.32</td>
<td>6,733.26</td>
<td>2.37</td>
</tr>
<tr>
<td>2001</td>
<td>13</td>
<td>27,985</td>
<td>6,522.24</td>
<td>7,076.52</td>
<td>8.50</td>
</tr>
<tr>
<td>2002</td>
<td>14</td>
<td>27,985</td>
<td>6,453.91</td>
<td>7,352.39</td>
<td>13.92</td>
</tr>
<tr>
<td>2003</td>
<td>15</td>
<td>28,508</td>
<td>6,321.29</td>
<td>7,550.57</td>
<td>19.45</td>
</tr>
<tr>
<td>2004</td>
<td>16</td>
<td>1,880</td>
<td>7,213.45</td>
<td>7,663.45</td>
<td>6.24</td>
</tr>
<tr>
<td>2005</td>
<td>17</td>
<td>0</td>
<td>7,110.53</td>
<td>7,686.64</td>
<td>8.10</td>
</tr>
<tr>
<td>2006</td>
<td>18</td>
<td>0</td>
<td>6,910.95</td>
<td>7,619.22</td>
<td>10.25</td>
</tr>
<tr>
<td>2007</td>
<td>19</td>
<td>0</td>
<td>6,692.56</td>
<td>7,463.84</td>
<td>11.52</td>
</tr>
<tr>
<td>2008</td>
<td>20</td>
<td>0</td>
<td>6,458.99</td>
<td>7,226.51</td>
<td>11.88</td>
</tr>
<tr>
<td>2009</td>
<td>21</td>
<td>0</td>
<td>6,213.26</td>
<td>6,916.22</td>
<td>11.31</td>
</tr>
<tr>
<td>2010</td>
<td>22</td>
<td>0</td>
<td>5,957.83</td>
<td>6,544.41</td>
<td>9.85</td>
</tr>
<tr>
<td>2011</td>
<td>23</td>
<td>0</td>
<td>5,694.79</td>
<td>6,124.20</td>
<td>7.54</td>
</tr>
<tr>
<td>2012</td>
<td>24</td>
<td>0</td>
<td>5,425.86</td>
<td>5,669.72</td>
<td>4.49</td>
</tr>
<tr>
<td>2013</td>
<td>25</td>
<td>0</td>
<td>5,152.49</td>
<td>5,195.25</td>
<td>0.83</td>
</tr>
<tr>
<td>2014</td>
<td>26</td>
<td>0</td>
<td>4,875.92</td>
<td>4,714.52</td>
<td>3.31</td>
</tr>
<tr>
<td>2015</td>
<td>27</td>
<td>0</td>
<td>4,597.17</td>
<td>4,240.09</td>
<td>7.77</td>
</tr>
<tr>
<td>2016</td>
<td>28</td>
<td>0</td>
<td>4,317.12</td>
<td>3,782.87</td>
<td>12.38</td>
</tr>
<tr>
<td>2017</td>
<td>29</td>
<td>0</td>
<td>4,036.51</td>
<td>3,351.75</td>
<td>16.96</td>
</tr>
<tr>
<td>2018</td>
<td>30</td>
<td>0</td>
<td>3,755.96</td>
<td>2,953.45</td>
<td>21.37</td>
</tr>
<tr>
<td>2019</td>
<td>31</td>
<td>0</td>
<td>3,476.03</td>
<td>2,592.51</td>
<td>25.42</td>
</tr>
<tr>
<td>2020</td>
<td>32</td>
<td>0</td>
<td>3,197.14</td>
<td>2,271.41</td>
<td>28.95</td>
</tr>
<tr>
<td>2021</td>
<td>33</td>
<td>0</td>
<td>2,919.71</td>
<td>1,990.78</td>
<td>31.82</td>
</tr>
<tr>
<td>2022</td>
<td>34</td>
<td>0</td>
<td>2,644.04</td>
<td>1,749.70</td>
<td>33.82</td>
</tr>
<tr>
<td>2023</td>
<td>35</td>
<td>0</td>
<td>2,370.42</td>
<td>1,546.02</td>
<td>34.78</td>
</tr>
<tr>
<td>2024</td>
<td>36</td>
<td>0</td>
<td>2,099.08</td>
<td>1,376.72</td>
<td>34.41</td>
</tr>
<tr>
<td>2025</td>
<td>37</td>
<td>0</td>
<td>1,830.22</td>
<td>1,238.24</td>
<td>32.34</td>
</tr>
<tr>
<td>2026</td>
<td>38</td>
<td>0</td>
<td>1,564.08</td>
<td>1,126.74</td>
<td>27.96</td>
</tr>
<tr>
<td>2027</td>
<td>39</td>
<td>0</td>
<td>1,300.58</td>
<td>1,038.33</td>
<td>20.16</td>
</tr>
<tr>
<td>2028</td>
<td>40</td>
<td>0</td>
<td>1,040.05</td>
<td>969.29</td>
<td>6.80</td>
</tr>
<tr>
<td>2029</td>
<td>41</td>
<td>0</td>
<td>782.51</td>
<td>916.19</td>
<td>17.08</td>
</tr>
<tr>
<td>2030</td>
<td>42</td>
<td>0</td>
<td>528.04</td>
<td>875.94</td>
<td>65.88</td>
</tr>
<tr>
<td>2031</td>
<td>43</td>
<td>0</td>
<td>-</td>
<td>845.90</td>
<td></td>
</tr>
<tr>
<td>2032</td>
<td>44</td>
<td>0</td>
<td>-</td>
<td>823.79</td>
<td></td>
</tr>
<tr>
<td>2033</td>
<td>45</td>
<td>0</td>
<td>-</td>
<td>807.75</td>
<td></td>
</tr>
<tr>
<td>2034</td>
<td>46</td>
<td>0</td>
<td>-</td>
<td>796.29</td>
<td></td>
</tr>
</tbody>
</table>

Table 26. Doesn’t exist leachate production according mathematical model.
Table 27. The variation of leachate production that can be collected from Enna landfill, Italy.

<table>
<thead>
<tr>
<th>Calendar year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Leachate production (m³/year)</th>
<th>Relative error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mathematical model</td>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>1</td>
<td>28,884</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>2</td>
<td>70,534</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>3</td>
<td>72,000</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>4</td>
<td>72,000</td>
<td>12,909.74</td>
<td>16,092.25</td>
<td>24.65</td>
</tr>
<tr>
<td>2011</td>
<td>5</td>
<td>72,000</td>
<td>17,154.11</td>
<td>19,854.32</td>
<td>15.74</td>
</tr>
<tr>
<td>2012</td>
<td>6</td>
<td>72,000</td>
<td>19,863.41</td>
<td>20,524.88</td>
<td>3.33</td>
</tr>
<tr>
<td>2013</td>
<td>7</td>
<td>60,000</td>
<td>18,666.33</td>
<td>17,748.40</td>
<td>4.92</td>
</tr>
<tr>
<td>2014</td>
<td>8</td>
<td>0</td>
<td>5,433.49</td>
<td>12,942.23</td>
<td>138.19</td>
</tr>
<tr>
<td>2015</td>
<td>9</td>
<td>0</td>
<td>5,794.62</td>
<td>8,159.79</td>
<td>40.82</td>
</tr>
<tr>
<td>2016</td>
<td>10</td>
<td>0</td>
<td>5,806.25</td>
<td>4,727.31</td>
<td>18.58</td>
</tr>
<tr>
<td>2017</td>
<td>11</td>
<td>0</td>
<td>5,583.99</td>
<td>2,833.50</td>
<td>49.26</td>
</tr>
<tr>
<td>2018</td>
<td>12</td>
<td>0</td>
<td>5,209.98</td>
<td>2,008.27</td>
<td>61.45</td>
</tr>
<tr>
<td>2019</td>
<td>13</td>
<td>0</td>
<td>4,743.20</td>
<td>1,720.25</td>
<td>63.73</td>
</tr>
<tr>
<td>2020</td>
<td>14</td>
<td>0</td>
<td>4,226.37</td>
<td>1,639.07</td>
<td>61.22</td>
</tr>
<tr>
<td>2021</td>
<td>15</td>
<td>0</td>
<td>3,690.60</td>
<td>1,620.50</td>
<td>56.09</td>
</tr>
<tr>
<td>2022</td>
<td>16</td>
<td>0</td>
<td>3,158.68</td>
<td>1,617.04</td>
<td>48.81</td>
</tr>
<tr>
<td>2023</td>
<td>17</td>
<td>0</td>
<td>2,647.28</td>
<td>1,616.51</td>
<td>38.94</td>
</tr>
<tr>
<td>2024</td>
<td>18</td>
<td>0</td>
<td>2,168.57</td>
<td>1,616.45</td>
<td>25.46</td>
</tr>
<tr>
<td>2025</td>
<td>19</td>
<td>0</td>
<td>1,731.40</td>
<td>1,616.44</td>
<td>6.64</td>
</tr>
<tr>
<td>2026</td>
<td>20</td>
<td>0</td>
<td>1,342.07</td>
<td>1,616.44</td>
<td>20.44</td>
</tr>
<tr>
<td>2027</td>
<td>21</td>
<td>0</td>
<td>1,005.02</td>
<td>1,616.44</td>
<td>60.84</td>
</tr>
<tr>
<td>2028</td>
<td>22</td>
<td>0</td>
<td>723.22</td>
<td>1,616.44</td>
<td>123.50</td>
</tr>
<tr>
<td>2029</td>
<td>23</td>
<td>0</td>
<td>498.58</td>
<td>1,616.44</td>
<td>224.21</td>
</tr>
<tr>
<td>2030</td>
<td>24</td>
<td>0</td>
<td>332.14</td>
<td>1,616.44</td>
<td>386.67</td>
</tr>
<tr>
<td>2031</td>
<td>25</td>
<td>0</td>
<td>224.33</td>
<td>1,616.44</td>
<td>620.57</td>
</tr>
<tr>
<td>2032</td>
<td>26</td>
<td>0</td>
<td>175.07</td>
<td>1,616.44</td>
<td>823.32</td>
</tr>
<tr>
<td>2033</td>
<td>27</td>
<td>0</td>
<td>183.92</td>
<td>1,616.44</td>
<td>778.86</td>
</tr>
<tr>
<td>2034</td>
<td>28</td>
<td>0</td>
<td>250.18</td>
<td>1,616.44</td>
<td>546.11</td>
</tr>
<tr>
<td>2035</td>
<td>29</td>
<td>0</td>
<td>372.90</td>
<td>1,616.44</td>
<td>333.47</td>
</tr>
<tr>
<td>2036</td>
<td>30</td>
<td>0</td>
<td>551.02</td>
<td>1,616.44</td>
<td>193.35</td>
</tr>
<tr>
<td>2037</td>
<td>31</td>
<td>0</td>
<td>783.33</td>
<td>1,616.44</td>
<td>106.35</td>
</tr>
<tr>
<td>2038</td>
<td>32</td>
<td>0</td>
<td>1,068.58</td>
<td>1,616.44</td>
<td>51.27</td>
</tr>
<tr>
<td>2039</td>
<td>33</td>
<td>0</td>
<td>1,405.43</td>
<td>1,616.44</td>
<td>15.01</td>
</tr>
<tr>
<td>2040</td>
<td>34</td>
<td>0</td>
<td>1,792.54</td>
<td>1,616.44</td>
<td>9.82</td>
</tr>
<tr>
<td>2041</td>
<td>35</td>
<td>0</td>
<td>2,228.55</td>
<td>1,616.44</td>
<td>27.47</td>
</tr>
<tr>
<td>2042</td>
<td>36</td>
<td>0</td>
<td>2,712.09</td>
<td>1,616.44</td>
<td>40.40</td>
</tr>
<tr>
<td>2043</td>
<td>37</td>
<td>0</td>
<td>3,241.79</td>
<td>1,616.44</td>
<td>50.14</td>
</tr>
<tr>
<td>2044</td>
<td>38</td>
<td>0</td>
<td>3,816.33</td>
<td>1,616.44</td>
<td>57.64</td>
</tr>
<tr>
<td>Calendar year (year)</td>
<td>Time (year)</td>
<td>Quantity of waste (tonnes/year)</td>
<td>Leachate production (m³/year)</td>
<td>Relative error (%)</td>
<td>Obs.</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------</td>
<td>--------------------------------</td>
<td>-----------------------------</td>
<td>--------------------</td>
<td>------</td>
</tr>
<tr>
<td>2005</td>
<td>1</td>
<td>2,2240.2</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>2</td>
<td>126,071.44</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>3</td>
<td>130,551.98</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>4</td>
<td>199,486.44</td>
<td>27,961.41</td>
<td>33,019.31</td>
<td>18.09</td>
</tr>
<tr>
<td>2009</td>
<td>5</td>
<td>141,882.38</td>
<td>29,941.70</td>
<td>36,217.24</td>
<td>20.96</td>
</tr>
<tr>
<td>2010</td>
<td>6</td>
<td>172,660.91</td>
<td>36,216.73</td>
<td>38,185.39</td>
<td>5.44</td>
</tr>
<tr>
<td>2011</td>
<td>7</td>
<td>249,558.48</td>
<td>44,273.01</td>
<td>38,669.60</td>
<td>12.66</td>
</tr>
<tr>
<td>2012</td>
<td>8</td>
<td>135,924.48</td>
<td>35,414.78</td>
<td>37,605.82</td>
<td>6.19</td>
</tr>
<tr>
<td>2013</td>
<td>9</td>
<td>126,871.16</td>
<td>34,228.60</td>
<td>35,133.99</td>
<td>2.65</td>
</tr>
<tr>
<td>2014</td>
<td>10</td>
<td>116,796.03</td>
<td>32,383.05</td>
<td>31,567.85</td>
<td>2.52</td>
</tr>
<tr>
<td>2015</td>
<td>11</td>
<td>0</td>
<td>21,443.94</td>
<td>27,329.53</td>
<td>27.45</td>
</tr>
<tr>
<td>2016</td>
<td>12</td>
<td>0</td>
<td>19,840.67</td>
<td>22,867.83</td>
<td>15.26</td>
</tr>
<tr>
<td>2017</td>
<td>13</td>
<td>0</td>
<td>18,124.32</td>
<td>18,581.86</td>
<td>2.52</td>
</tr>
<tr>
<td>2018</td>
<td>14</td>
<td>0</td>
<td>16,368.93</td>
<td>14,767.48</td>
<td>9.78</td>
</tr>
<tr>
<td>2019</td>
<td>15</td>
<td>0</td>
<td>14,627.42</td>
<td>11,594.71</td>
<td>20.73</td>
</tr>
<tr>
<td>2020</td>
<td>16</td>
<td>0</td>
<td>12,937.64</td>
<td>9,114.41</td>
<td>29.55</td>
</tr>
<tr>
<td>2021</td>
<td>17</td>
<td>0</td>
<td>11,326.56</td>
<td>7,285.32</td>
<td>35.68</td>
</tr>
<tr>
<td>2022</td>
<td>18</td>
<td>0</td>
<td>9,813.24</td>
<td>6,009.55</td>
<td>38.76</td>
</tr>
<tr>
<td>2023</td>
<td>19</td>
<td>0</td>
<td>8,410.90</td>
<td>5,166.32</td>
<td>38.58</td>
</tr>
<tr>
<td>2024</td>
<td>20</td>
<td>0</td>
<td>7,128.44</td>
<td>4,637.40</td>
<td>34.95</td>
</tr>
<tr>
<td>2025</td>
<td>21</td>
<td>0</td>
<td>5,971.56</td>
<td>4,322.21</td>
<td>27.62</td>
</tr>
<tr>
<td>2026</td>
<td>22</td>
<td>0</td>
<td>4,943.54</td>
<td>4,143.60</td>
<td>16.18</td>
</tr>
<tr>
<td>2027</td>
<td>23</td>
<td>0</td>
<td>4,045.86</td>
<td>4,047.29</td>
<td>0.04</td>
</tr>
<tr>
<td>2028</td>
<td>24</td>
<td>0</td>
<td>3,278.67</td>
<td>3,997.85</td>
<td>21.94</td>
</tr>
<tr>
<td>2029</td>
<td>25</td>
<td>0</td>
<td>2,641.11</td>
<td>3,973.67</td>
<td>50.45</td>
</tr>
<tr>
<td>2030</td>
<td>26</td>
<td>0</td>
<td>2,131.57</td>
<td>3,962.40</td>
<td>85.89</td>
</tr>
<tr>
<td>2031</td>
<td>27</td>
<td>0</td>
<td>1,747.91</td>
<td>3,957.39</td>
<td>126.41</td>
</tr>
<tr>
<td>2032</td>
<td>28</td>
<td>0</td>
<td>1,487.58</td>
<td>3,955.27</td>
<td>165.89</td>
</tr>
<tr>
<td>2033</td>
<td>29</td>
<td>0</td>
<td>1,347.76</td>
<td>3,954.42</td>
<td>193.41</td>
</tr>
<tr>
<td>2034</td>
<td>30</td>
<td>0</td>
<td>1,325.44</td>
<td>3,954.09</td>
<td>198.32</td>
</tr>
<tr>
<td>2035</td>
<td>31</td>
<td>0</td>
<td>1,417.50</td>
<td>3,953.96</td>
<td>178.94</td>
</tr>
<tr>
<td>2036</td>
<td>32</td>
<td>0</td>
<td>1,620.73</td>
<td>3,953.92</td>
<td>143.96</td>
</tr>
<tr>
<td>2037</td>
<td>33</td>
<td>0</td>
<td>1,931.93</td>
<td>3,953.91</td>
<td>104.66</td>
</tr>
<tr>
<td>2038</td>
<td>34</td>
<td>0</td>
<td>2,347.87</td>
<td>3,953.90</td>
<td>68.40</td>
</tr>
<tr>
<td>2039</td>
<td>35</td>
<td>0</td>
<td>2,865.37</td>
<td>3,953.90</td>
<td>37.99</td>
</tr>
<tr>
<td>2040</td>
<td>36</td>
<td>0</td>
<td>3,481.30</td>
<td>3,953.90</td>
<td>13.58</td>
</tr>
<tr>
<td>2041</td>
<td>37</td>
<td>0</td>
<td>4,192.58</td>
<td>3,953.90</td>
<td>5.69</td>
</tr>
<tr>
<td>2042</td>
<td>38</td>
<td>0</td>
<td>4,996.21</td>
<td>3,953.90</td>
<td>20.86</td>
</tr>
<tr>
<td>2043</td>
<td>39</td>
<td>0</td>
<td>5,889.25</td>
<td>3,953.90</td>
<td>32.86</td>
</tr>
<tr>
<td>2044</td>
<td>40</td>
<td>0</td>
<td>6,868.86</td>
<td>3,953.90</td>
<td>42.44</td>
</tr>
<tr>
<td>2045</td>
<td>41</td>
<td>0</td>
<td>7,932.27</td>
<td>3,953.90</td>
<td>50.15</td>
</tr>
</tbody>
</table>

Table 28. The variation of leachate production that can be collected from Bihor landfill, România.
The variation of leachate production that can be collected from Piatra Neamț landfill, România.

<table>
<thead>
<tr>
<th>Calendar year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Leachate production (m³/year)</th>
<th>Relative error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>1</td>
<td>55.000</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>2</td>
<td>79.179</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>3</td>
<td>77.331</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>4</td>
<td>62.878</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>5</td>
<td>57.579</td>
<td>10.536</td>
<td>11.542</td>
<td>9.54</td>
</tr>
<tr>
<td>2009</td>
<td>6</td>
<td>54.299</td>
<td>12.196</td>
<td>12.778</td>
<td>4.77</td>
</tr>
<tr>
<td>2010</td>
<td>7</td>
<td>40.935</td>
<td>13.796</td>
<td>13.828</td>
<td>0.23</td>
</tr>
<tr>
<td>2011</td>
<td>8</td>
<td>35.186</td>
<td>14.139</td>
<td>14.620</td>
<td>3.40</td>
</tr>
<tr>
<td>2012</td>
<td>9</td>
<td>30.352</td>
<td>14.007</td>
<td>15.098</td>
<td>7.79</td>
</tr>
<tr>
<td>2013</td>
<td>10</td>
<td>34.175</td>
<td>12.880</td>
<td>15.227</td>
<td>18.23</td>
</tr>
<tr>
<td>2014</td>
<td>11</td>
<td>0</td>
<td>14.834</td>
<td>14.998</td>
<td>1.10</td>
</tr>
<tr>
<td>2015</td>
<td>12</td>
<td>0</td>
<td>13.784</td>
<td>14.426</td>
<td>4.66</td>
</tr>
<tr>
<td>2016</td>
<td>13</td>
<td>0</td>
<td>12.690</td>
<td>13.555</td>
<td>6.82</td>
</tr>
<tr>
<td>2017</td>
<td>14</td>
<td>0</td>
<td>11.586</td>
<td>12.445</td>
<td>7.41</td>
</tr>
<tr>
<td>2018</td>
<td>15</td>
<td>0</td>
<td>10.496</td>
<td>11.170</td>
<td>6.42</td>
</tr>
<tr>
<td>2019</td>
<td>16</td>
<td>0</td>
<td>9.437</td>
<td>9.809</td>
<td>3.93</td>
</tr>
<tr>
<td>2020</td>
<td>17</td>
<td>0</td>
<td>8.422</td>
<td>8.435</td>
<td>0.16</td>
</tr>
<tr>
<td>2021</td>
<td>18</td>
<td>0</td>
<td>7.457</td>
<td>7.115</td>
<td>4.59</td>
</tr>
<tr>
<td>2022</td>
<td>19</td>
<td>0</td>
<td>6.550</td>
<td>5.898</td>
<td>9.95</td>
</tr>
<tr>
<td>2023</td>
<td>20</td>
<td>0</td>
<td>5.704</td>
<td>4.820</td>
<td>15.49</td>
</tr>
<tr>
<td>2024</td>
<td>21</td>
<td>0</td>
<td>4.920</td>
<td>3.898</td>
<td>20.78</td>
</tr>
<tr>
<td>2025</td>
<td>22</td>
<td>0</td>
<td>4.201</td>
<td>3.135</td>
<td>25.37</td>
</tr>
<tr>
<td>2026</td>
<td>23</td>
<td>0</td>
<td>3.547</td>
<td>2.526</td>
<td>28.80</td>
</tr>
<tr>
<td>2027</td>
<td>24</td>
<td>0</td>
<td>2.958</td>
<td>2.053</td>
<td>30.59</td>
</tr>
<tr>
<td>2028</td>
<td>25</td>
<td>0</td>
<td>2.432</td>
<td>1.697</td>
<td>30.20</td>
</tr>
<tr>
<td>2029</td>
<td>26</td>
<td>0</td>
<td>1.969</td>
<td>1.438</td>
<td>26.97</td>
</tr>
<tr>
<td>2030</td>
<td>27</td>
<td>0</td>
<td>1.568</td>
<td>1.254</td>
<td>20.03</td>
</tr>
<tr>
<td>2031</td>
<td>28</td>
<td>0</td>
<td>1.228</td>
<td>1.127</td>
<td>8.18</td>
</tr>
<tr>
<td>2032</td>
<td>29</td>
<td>0</td>
<td>946.60</td>
<td>1.042</td>
<td>10.18</td>
</tr>
<tr>
<td>2033</td>
<td>30</td>
<td>0</td>
<td>722.48</td>
<td>987.75</td>
<td>36.72</td>
</tr>
<tr>
<td>2034</td>
<td>31</td>
<td>0</td>
<td>554.21</td>
<td>952.81</td>
<td>71.92</td>
</tr>
<tr>
<td>2035</td>
<td>32</td>
<td>0</td>
<td>440.18</td>
<td>931.29</td>
<td>111.57</td>
</tr>
<tr>
<td>2036</td>
<td>33</td>
<td>0</td>
<td>378.77</td>
<td>918.39</td>
<td>142.47</td>
</tr>
<tr>
<td>2037</td>
<td>34</td>
<td>0</td>
<td>368.39</td>
<td>910.87</td>
<td>147.26</td>
</tr>
<tr>
<td>2038</td>
<td>35</td>
<td>0</td>
<td>407.47</td>
<td>906.60</td>
<td>122.50</td>
</tr>
<tr>
<td>2039</td>
<td>36</td>
<td>0</td>
<td>494.45</td>
<td>904.24</td>
<td>82.88</td>
</tr>
<tr>
<td>2040</td>
<td>37</td>
<td>0</td>
<td>627.83</td>
<td>902.97</td>
<td>43.82</td>
</tr>
<tr>
<td>2041</td>
<td>38</td>
<td>0</td>
<td>806.12</td>
<td>902.30</td>
<td>11.93</td>
</tr>
<tr>
<td>2042</td>
<td>39</td>
<td>0</td>
<td>1.027.90</td>
<td>901.96</td>
<td>12.25</td>
</tr>
<tr>
<td>2043</td>
<td>40</td>
<td>0</td>
<td>1.291.77</td>
<td>901.79</td>
<td>30.19</td>
</tr>
</tbody>
</table>
### Table 30.

The variation of biogas production that can be collected from Turin landfill, Italy.

<table>
<thead>
<tr>
<th>Calendar year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Biogas production (m³/year)</th>
<th>Relative error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mathematical model</td>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>1</td>
<td>341,477</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>2</td>
<td>331,321</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>3</td>
<td>356,477</td>
<td>19,097,426.81</td>
<td>25,620,200.00</td>
<td>34.16</td>
</tr>
<tr>
<td>1987</td>
<td>4</td>
<td>376,782</td>
<td>36,009,050.63</td>
<td>34,610,800.00</td>
<td>3.88</td>
</tr>
<tr>
<td>1988</td>
<td>5</td>
<td>542,339</td>
<td>54,350,061.57</td>
<td>42,161,500.00</td>
<td>22.43</td>
</tr>
<tr>
<td>1989</td>
<td>6</td>
<td>636,893</td>
<td>69,433,568.36</td>
<td>55,014,600.00</td>
<td>20.77</td>
</tr>
<tr>
<td>1990</td>
<td>7</td>
<td>655,536</td>
<td>81,235,682.20</td>
<td>68,682,400.00</td>
<td>15.45</td>
</tr>
<tr>
<td>1991</td>
<td>8</td>
<td>701,117</td>
<td>92,109,248.54</td>
<td>79,625,200.00</td>
<td>13.55</td>
</tr>
<tr>
<td>1992</td>
<td>9</td>
<td>650,444</td>
<td>99,416,806.55</td>
<td>89,730,500.00</td>
<td>9.74</td>
</tr>
<tr>
<td>1993</td>
<td>10</td>
<td>686,941</td>
<td>107,286,518.50</td>
<td>94,994,700.00</td>
<td>11.46</td>
</tr>
<tr>
<td>1994</td>
<td>11</td>
<td>795,583</td>
<td>115,465,205.70</td>
<td>100,495,000.00</td>
<td>12.97</td>
</tr>
<tr>
<td>1995</td>
<td>12</td>
<td>1,041,490</td>
<td>125,467,017.00</td>
<td>109,333,000.00</td>
<td>12.86</td>
</tr>
<tr>
<td>1996</td>
<td>13</td>
<td>1,278,410</td>
<td>134,139,545.00</td>
<td>126,664,000.00</td>
<td>5.57</td>
</tr>
<tr>
<td>1997</td>
<td>14</td>
<td>263,360</td>
<td>114,123,638.00</td>
<td>149,891,000.00</td>
<td>31.34</td>
</tr>
<tr>
<td>1998</td>
<td>15</td>
<td>515,659</td>
<td>121,049,845.90</td>
<td>122,590,000.00</td>
<td>1.27</td>
</tr>
<tr>
<td>1999</td>
<td>16</td>
<td>896,268</td>
<td>129,982,518.10</td>
<td>113,340,000.00</td>
<td>12.80</td>
</tr>
<tr>
<td>2000</td>
<td>17</td>
<td>1,013,210</td>
<td>132,207,582.90</td>
<td>123,264,000.00</td>
<td>6.76</td>
</tr>
<tr>
<td>2001</td>
<td>18</td>
<td>687,412</td>
<td>123,884,897.10</td>
<td>135,743,000.00</td>
<td>9.57</td>
</tr>
<tr>
<td>2002</td>
<td>19</td>
<td>927,399</td>
<td>127,339,386.40</td>
<td>130,703,000.00</td>
<td>2.64</td>
</tr>
<tr>
<td>2003</td>
<td>20</td>
<td>756,177</td>
<td>121,073,364.70</td>
<td>137,492,000.00</td>
<td>13.56</td>
</tr>
<tr>
<td>2004</td>
<td>21</td>
<td>699,906</td>
<td>116,762,788.30</td>
<td>135,013,000.00</td>
<td>15.63</td>
</tr>
<tr>
<td>2005</td>
<td>22</td>
<td>644,257</td>
<td>111,946,292.40</td>
<td>130,710,000.00</td>
<td>16.76</td>
</tr>
<tr>
<td>2006</td>
<td>23</td>
<td>587,864</td>
<td>106,654,144.80</td>
<td>125,082,000.00</td>
<td>17.28</td>
</tr>
<tr>
<td>2007</td>
<td>24</td>
<td>562,279</td>
<td>101,641,624.30</td>
<td>118,440,000.00</td>
<td>16.53</td>
</tr>
<tr>
<td>2008</td>
<td>25</td>
<td>539,922</td>
<td>96,357,444.37</td>
<td>112,397,000.00</td>
<td>16.65</td>
</tr>
<tr>
<td>2009</td>
<td>26</td>
<td>606,682</td>
<td>92,753,118.48</td>
<td>106,940,000.00</td>
<td>15.30</td>
</tr>
<tr>
<td>2010</td>
<td>27</td>
<td>0</td>
<td>74,053,110.05</td>
<td>105,825,000.00</td>
<td>42.90</td>
</tr>
<tr>
<td>2011</td>
<td>28</td>
<td>0</td>
<td>68,563,121.85</td>
<td>78,397,300.00</td>
<td>14.34</td>
</tr>
<tr>
<td>2012</td>
<td>29</td>
<td>0</td>
<td>62,944,876.03</td>
<td>58,078,200.00</td>
<td>7.73</td>
</tr>
<tr>
<td>2013</td>
<td>30</td>
<td>0</td>
<td>57,248,281.22</td>
<td>43,025,400.00</td>
<td>24.84</td>
</tr>
<tr>
<td>2014</td>
<td>31</td>
<td>0</td>
<td>51,521,745.06</td>
<td>31,874,000.00</td>
<td>38.13</td>
</tr>
<tr>
<td>2015</td>
<td>32</td>
<td>0</td>
<td>45,812,174.12</td>
<td>23,612,800.00</td>
<td>48.46</td>
</tr>
<tr>
<td>2016</td>
<td>33</td>
<td>0</td>
<td>40,164,973.94</td>
<td>17,492,800.00</td>
<td>56.45</td>
</tr>
<tr>
<td>2017</td>
<td>34</td>
<td>0</td>
<td>34,624,049.03</td>
<td>12,959,000.00</td>
<td>62.57</td>
</tr>
<tr>
<td>2018</td>
<td>35</td>
<td>0</td>
<td>29,231,802.87</td>
<td>9,600,250.00</td>
<td>67.16</td>
</tr>
<tr>
<td>2019</td>
<td>36</td>
<td>0</td>
<td>24,029,137.89</td>
<td>7,112,040.00</td>
<td>70.40</td>
</tr>
<tr>
<td>2020</td>
<td>37</td>
<td>0</td>
<td>19,055,455.48</td>
<td>5,268,730.00</td>
<td>72.35</td>
</tr>
<tr>
<td>2021</td>
<td>38</td>
<td>0</td>
<td>14,348,656.02</td>
<td>3,903,170.00</td>
<td>72.80</td>
</tr>
<tr>
<td>2022</td>
<td>39</td>
<td>0</td>
<td>9,945,138.82</td>
<td>2,891,540.00</td>
<td>70.93</td>
</tr>
<tr>
<td>2023</td>
<td>40</td>
<td>0</td>
<td>5,879,802.18</td>
<td>2,142,110.00</td>
<td>63.57</td>
</tr>
<tr>
<td>2024</td>
<td>41</td>
<td>0</td>
<td>2,186,043.35</td>
<td>1,586,910.00</td>
<td>27.41</td>
</tr>
<tr>
<td>2025</td>
<td>42</td>
<td>0</td>
<td>-</td>
<td>1,175,610.00</td>
<td>-</td>
</tr>
<tr>
<td>2026</td>
<td>43</td>
<td>0</td>
<td>-</td>
<td>870,915.46</td>
<td>-</td>
</tr>
<tr>
<td>2027</td>
<td>44</td>
<td>0</td>
<td>-</td>
<td>645,190.04</td>
<td>-</td>
</tr>
<tr>
<td>2028</td>
<td>45</td>
<td>0</td>
<td>-</td>
<td>477,968.54</td>
<td>-</td>
</tr>
<tr>
<td>2029</td>
<td>46</td>
<td>0</td>
<td>-</td>
<td>354,087.80</td>
<td>-</td>
</tr>
<tr>
<td>2030</td>
<td>47</td>
<td>0</td>
<td>-</td>
<td>262,314.70</td>
<td>-</td>
</tr>
<tr>
<td>2031</td>
<td>48</td>
<td>0</td>
<td>-</td>
<td>194,327.51</td>
<td>-</td>
</tr>
<tr>
<td>2032</td>
<td>49</td>
<td>0</td>
<td>-</td>
<td>143,961.36</td>
<td>-</td>
</tr>
<tr>
<td>2033</td>
<td>50</td>
<td>0</td>
<td>-</td>
<td>106,649.20</td>
<td>-</td>
</tr>
<tr>
<td>2034</td>
<td>51</td>
<td>0</td>
<td>-</td>
<td>79,007.67</td>
<td>-</td>
</tr>
</tbody>
</table>

Doesn’t exist leachate production according mathematical model

NOTE: Data from Table 30.
Table 30 continued.

<table>
<thead>
<tr>
<th>Calendar year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Biogas production (m³/year)</th>
<th>Relative error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2035</td>
<td>52</td>
<td>0</td>
<td>-</td>
<td>58,530.32</td>
<td>-</td>
</tr>
<tr>
<td>2036</td>
<td>53</td>
<td>0</td>
<td>-</td>
<td>43,360.33</td>
<td>-</td>
</tr>
<tr>
<td>2037</td>
<td>54</td>
<td>0</td>
<td>444,623.60</td>
<td>32,122.12</td>
<td>92.78</td>
</tr>
<tr>
<td>2038</td>
<td>55</td>
<td>0</td>
<td>4,619,085.41</td>
<td>23,796.65</td>
<td>99.48</td>
</tr>
<tr>
<td>2039</td>
<td>56</td>
<td>0</td>
<td>9,485,959.48</td>
<td>17,628.99</td>
<td>99.81</td>
</tr>
<tr>
<td>2040</td>
<td>57</td>
<td>0</td>
<td>15,054,626.48</td>
<td>13,059.88</td>
<td>99.91</td>
</tr>
</tbody>
</table>

Leachate recirculation – biogas production (**)

Table 31.

The variation of biogas production that can be collected from Potenza landfill, Italy.

<table>
<thead>
<tr>
<th>Calendar year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Biogas production (m³/year)</th>
<th>Relative error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>1</td>
<td>16,000</td>
<td>-</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>1990</td>
<td>2</td>
<td>28,062</td>
<td>815,512.36</td>
<td>701,570.52</td>
<td>13.97</td>
</tr>
<tr>
<td>1991</td>
<td>3</td>
<td>28,062</td>
<td>1,806,658.53</td>
<td>1,750,200.00</td>
<td>3.13</td>
</tr>
<tr>
<td>1992</td>
<td>4</td>
<td>28,062</td>
<td>2,617,542.78</td>
<td>2,527,050.00</td>
<td>3.46</td>
</tr>
<tr>
<td>1993</td>
<td>5</td>
<td>27,895</td>
<td>3,262,006.65</td>
<td>3,102,550.00</td>
<td>4.89</td>
</tr>
<tr>
<td>1994</td>
<td>6</td>
<td>27,840</td>
<td>3,759,759.31</td>
<td>3,521,570.00</td>
<td>6.34</td>
</tr>
<tr>
<td>1995</td>
<td>7</td>
<td>27,955</td>
<td>4,126,617.74</td>
<td>3,829,580.00</td>
<td>7.20</td>
</tr>
<tr>
<td>1996</td>
<td>8</td>
<td>28,279</td>
<td>4,377,462.54</td>
<td>4,062,800.00</td>
<td>7.19</td>
</tr>
<tr>
<td>1997</td>
<td>9</td>
<td>28,224</td>
<td>4,517,341.35</td>
<td>4,249,770.00</td>
<td>5.92</td>
</tr>
<tr>
<td>1998</td>
<td>10</td>
<td>26,612</td>
<td>4,542,010.33</td>
<td>4,385,880.00</td>
<td>3.44</td>
</tr>
<tr>
<td>1999</td>
<td>11</td>
<td>25,700</td>
<td>4,496,829.43</td>
<td>4,416,030.00</td>
<td>1.80</td>
</tr>
<tr>
<td>2000</td>
<td>12</td>
<td>26,930</td>
<td>4,414,574.84</td>
<td>4,398,370.00</td>
<td>0.37</td>
</tr>
<tr>
<td>2001</td>
<td>13</td>
<td>27,985</td>
<td>4,272,361.16</td>
<td>4,439,220.00</td>
<td>3.91</td>
</tr>
<tr>
<td>2002</td>
<td>14</td>
<td>27,985</td>
<td>4,067,671.36</td>
<td>4,515,750.00</td>
<td>11.02</td>
</tr>
<tr>
<td>2003</td>
<td>15</td>
<td>28,508</td>
<td>3,833,296.38</td>
<td>4,572,440.00</td>
<td>19.28</td>
</tr>
<tr>
<td>2004</td>
<td>16</td>
<td>1,880</td>
<td>3,173,342.27</td>
<td>4,637,370.00</td>
<td>46.14</td>
</tr>
<tr>
<td>2005</td>
<td>17</td>
<td>0</td>
<td>2,855,599.30</td>
<td>3,517,880.00</td>
<td>23.19</td>
</tr>
<tr>
<td>2006</td>
<td>18</td>
<td>0</td>
<td>2,553,179.95</td>
<td>2,606,110.00</td>
<td>2.07</td>
</tr>
<tr>
<td>2007</td>
<td>19</td>
<td>0</td>
<td>2,245,642.72</td>
<td>1,930,660.00</td>
<td>14.03</td>
</tr>
<tr>
<td>2008</td>
<td>20</td>
<td>0</td>
<td>1,939,396.61</td>
<td>1,430,260.00</td>
<td>26.25</td>
</tr>
<tr>
<td>2009</td>
<td>21</td>
<td>0</td>
<td>1,640,192.20</td>
<td>1,059,570.00</td>
<td>35.40</td>
</tr>
<tr>
<td>2010</td>
<td>22</td>
<td>0</td>
<td>1,353,121.64</td>
<td>784,945.75</td>
<td>41.99</td>
</tr>
<tr>
<td>2011</td>
<td>23</td>
<td>0</td>
<td>1,082,618.69</td>
<td>581,502.11</td>
<td>46.29</td>
</tr>
<tr>
<td>2012</td>
<td>24</td>
<td>0</td>
<td>832,458.71</td>
<td>430,787.36</td>
<td>48.25</td>
</tr>
<tr>
<td>2013</td>
<td>25</td>
<td>0</td>
<td>605,758.62</td>
<td>319,135.13</td>
<td>47.32</td>
</tr>
<tr>
<td>2014</td>
<td>26</td>
<td>0</td>
<td>404,976.94</td>
<td>236,421.12</td>
<td>41.62</td>
</tr>
<tr>
<td>2015</td>
<td>27</td>
<td>0</td>
<td>231,913.80</td>
<td>175,145.07</td>
<td>24.48</td>
</tr>
<tr>
<td>2016</td>
<td>28</td>
<td>0</td>
<td>87,710.90</td>
<td>129,750.66</td>
<td>47.93</td>
</tr>
<tr>
<td>2017</td>
<td>29</td>
<td>0</td>
<td>-</td>
<td>96,121.65</td>
<td>-</td>
</tr>
<tr>
<td>2018</td>
<td>30</td>
<td>0</td>
<td>-</td>
<td>71,208.67</td>
<td>-</td>
</tr>
<tr>
<td>2019</td>
<td>31</td>
<td>0</td>
<td>-</td>
<td>52,752.68</td>
<td>-</td>
</tr>
<tr>
<td>2020</td>
<td>32</td>
<td>0</td>
<td>-</td>
<td>39,080.15</td>
<td>-</td>
</tr>
<tr>
<td>2021</td>
<td>33</td>
<td>0</td>
<td>-</td>
<td>28,951.29</td>
<td>-</td>
</tr>
<tr>
<td>2022</td>
<td>34</td>
<td>0</td>
<td>-</td>
<td>21,447.64</td>
<td>-</td>
</tr>
<tr>
<td>2023</td>
<td>35</td>
<td>0</td>
<td>-</td>
<td>15,888.80</td>
<td>-</td>
</tr>
<tr>
<td>2024</td>
<td>36</td>
<td>0</td>
<td>-</td>
<td>11,770.71</td>
<td>-</td>
</tr>
<tr>
<td>2025</td>
<td>37</td>
<td>0</td>
<td>-</td>
<td>8,719.96</td>
<td>-</td>
</tr>
<tr>
<td>2026</td>
<td>38</td>
<td>0</td>
<td>13,406.24</td>
<td>6,459.90</td>
<td>51.81</td>
</tr>
<tr>
<td>2027</td>
<td>39</td>
<td>0</td>
<td>73,713.01</td>
<td>4,785.62</td>
<td>93.51</td>
</tr>
<tr>
<td>2028</td>
<td>40</td>
<td>0</td>
<td>125,224.45</td>
<td>3,545.27</td>
<td>97.17</td>
</tr>
</tbody>
</table>

Doesn’t exist biogas production. According mathematical model (***)
### Table 31 continued.

<table>
<thead>
<tr>
<th>Calendar Year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Biogas production (m³/year)</th>
<th>Relative Error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mathematical model</td>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>2033</td>
<td>45</td>
<td>0</td>
<td>-</td>
<td>791.06</td>
<td>-</td>
</tr>
<tr>
<td>2034</td>
<td>46</td>
<td>0</td>
<td>-</td>
<td>586.03</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Table 32.

The variation of biogas production that can be collected from Enna landfill, Italy.

<table>
<thead>
<tr>
<th>Calendar Year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Biogas production (m³/year)</th>
<th>Relative Error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mathematical model</td>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>1</td>
<td>28,884</td>
<td>-</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>2008</td>
<td>2</td>
<td>70,534</td>
<td>3,055,236.76</td>
<td>1,266,530.00</td>
<td>58.55</td>
</tr>
<tr>
<td>2009</td>
<td>3</td>
<td>72,000</td>
<td>4,993,579.48</td>
<td>4,031,060.00</td>
<td>19.28</td>
</tr>
<tr>
<td>2010</td>
<td>4</td>
<td>72,000</td>
<td>6,398,124.62</td>
<td>6,143,350.00</td>
<td>3.98</td>
</tr>
<tr>
<td>2011</td>
<td>5</td>
<td>72,000</td>
<td>7,372,178.01</td>
<td>7,708,170.00</td>
<td>4.56</td>
</tr>
<tr>
<td>2012</td>
<td>6</td>
<td>72,000</td>
<td>7,974,018.15</td>
<td>8,867,420.00</td>
<td>11.20</td>
</tr>
<tr>
<td>2013</td>
<td>7</td>
<td>60,000</td>
<td>7,917,815.58</td>
<td>9,726,220.00</td>
<td>22.84</td>
</tr>
<tr>
<td>2014</td>
<td>8</td>
<td>0</td>
<td>6,232,938.67</td>
<td>9,836,250.00</td>
<td>57.81</td>
</tr>
<tr>
<td>2015</td>
<td>9</td>
<td>0</td>
<td>6,033,674.10</td>
<td>7,286,870.00</td>
<td>20.77</td>
</tr>
<tr>
<td>2016</td>
<td>10</td>
<td>0</td>
<td>5,661,174.43</td>
<td>5,398,250.00</td>
<td>4.64</td>
</tr>
<tr>
<td>2017</td>
<td>11</td>
<td>0</td>
<td>5,156,60.29</td>
<td>3,999,120.00</td>
<td>22.45</td>
</tr>
<tr>
<td>2018</td>
<td>12</td>
<td>0</td>
<td>4,557,898.74</td>
<td>2,962,620.00</td>
<td>35.00</td>
</tr>
<tr>
<td>2019</td>
<td>13</td>
<td>0</td>
<td>3,899,303.26</td>
<td>2,194,760.00</td>
<td>43.71</td>
</tr>
<tr>
<td>2020</td>
<td>14</td>
<td>0</td>
<td>3,211,833.76</td>
<td>1,625,920.00</td>
<td>49.38</td>
</tr>
<tr>
<td>2021</td>
<td>15</td>
<td>0</td>
<td>2,523,046.61</td>
<td>1,204,510.00</td>
<td>52.26</td>
</tr>
<tr>
<td>2022</td>
<td>16</td>
<td>0</td>
<td>1,857,084.56</td>
<td>892,324.25</td>
<td>51.95</td>
</tr>
<tr>
<td>2023</td>
<td>17</td>
<td>0</td>
<td>1,234,676.85</td>
<td>661,050.06</td>
<td>46.46</td>
</tr>
<tr>
<td>2024</td>
<td>18</td>
<td>0</td>
<td>673,139.12</td>
<td>489,717.93</td>
<td>27.25</td>
</tr>
<tr>
<td>2025</td>
<td>19</td>
<td>0</td>
<td>186,373.43</td>
<td>362,791.97</td>
<td>94.66</td>
</tr>
<tr>
<td>2026</td>
<td>20</td>
<td>0</td>
<td>-</td>
<td>268,762.90</td>
<td>-</td>
</tr>
<tr>
<td>2027</td>
<td>21</td>
<td>0</td>
<td>-</td>
<td>199,104.45</td>
<td>-</td>
</tr>
<tr>
<td>2028</td>
<td>22</td>
<td>0</td>
<td>-</td>
<td>147,500.21</td>
<td>-</td>
</tr>
<tr>
<td>2029</td>
<td>23</td>
<td>0</td>
<td>-</td>
<td>109,270.84</td>
<td>-</td>
</tr>
<tr>
<td>2030</td>
<td>24</td>
<td>0</td>
<td>-</td>
<td>80,949.83</td>
<td>-</td>
</tr>
<tr>
<td>2031</td>
<td>25</td>
<td>0</td>
<td>-</td>
<td>59,969.11</td>
<td>-</td>
</tr>
<tr>
<td>2032</td>
<td>26</td>
<td>0</td>
<td>-</td>
<td>44,426.21</td>
<td>-</td>
</tr>
<tr>
<td>2033</td>
<td>27</td>
<td>0</td>
<td>-</td>
<td>32,911.74</td>
<td>-</td>
</tr>
<tr>
<td>2034</td>
<td>28</td>
<td>0</td>
<td>-</td>
<td>24,381.62</td>
<td>-</td>
</tr>
<tr>
<td>2035</td>
<td>29</td>
<td>0</td>
<td>48,934.43</td>
<td>18,062.35</td>
<td>63.09</td>
</tr>
<tr>
<td>2036</td>
<td>30</td>
<td>0</td>
<td>325,917.69</td>
<td>13,380.92</td>
<td>95.89</td>
</tr>
<tr>
<td>2037</td>
<td>31</td>
<td>0</td>
<td>578,239.57</td>
<td>9,912.83</td>
<td>98.29</td>
</tr>
<tr>
<td>2038</td>
<td>32</td>
<td>0</td>
<td>775,425.75</td>
<td>7,343.60</td>
<td>99.05</td>
</tr>
<tr>
<td>2039</td>
<td>33</td>
<td>0</td>
<td>883,588.35</td>
<td>5,440.27</td>
<td>99.38</td>
</tr>
<tr>
<td>2040</td>
<td>34</td>
<td>0</td>
<td>865,425.92</td>
<td>4,030.25</td>
<td>99.53</td>
</tr>
<tr>
<td>2041</td>
<td>35</td>
<td>0</td>
<td>680,223.44</td>
<td>2,985.69</td>
<td>99.56</td>
</tr>
<tr>
<td>2042</td>
<td>36</td>
<td>0</td>
<td>283,852.32</td>
<td>2,211.85</td>
<td>99.22</td>
</tr>
<tr>
<td>2043</td>
<td>37</td>
<td>0</td>
<td>-</td>
<td>1,638.58</td>
<td>-</td>
</tr>
<tr>
<td>2044</td>
<td>38</td>
<td>0</td>
<td>-</td>
<td>1,213.89</td>
<td>-</td>
</tr>
</tbody>
</table>
The variation of biogas production that can be collected from Bihor landfill, Romania.

<table>
<thead>
<tr>
<th>Calendar year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Biogas production (m³/year)</th>
<th>Relative error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mathematical model</td>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>1</td>
<td>22,240.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2006</td>
<td>2</td>
<td>126,071.44</td>
<td>3,815,904.79</td>
<td>975,191.79</td>
<td>74.44</td>
</tr>
<tr>
<td>2007</td>
<td>3</td>
<td>130,551.98</td>
<td>9,390,387.93</td>
<td>6,250,440.00</td>
<td>33.44</td>
</tr>
<tr>
<td>2008</td>
<td>4</td>
<td>199,486.44</td>
<td>14,531,717.51</td>
<td>10,354,900.00</td>
<td>28.74</td>
</tr>
<tr>
<td>2009</td>
<td>5</td>
<td>141,882.38</td>
<td>16,949,890.79</td>
<td>16,418,200.00</td>
<td>3.14</td>
</tr>
<tr>
<td>2010</td>
<td>6</td>
<td>172,660.91</td>
<td>19,511,527.32</td>
<td>18,384,200.00</td>
<td>5.78</td>
</tr>
<tr>
<td>2011</td>
<td>7</td>
<td>249,558.48</td>
<td>21,804,768.65</td>
<td>21,190,200.00</td>
<td>2.82</td>
</tr>
<tr>
<td>2012</td>
<td>8</td>
<td>135,924.48</td>
<td>20,938,110.31</td>
<td>26,640,800.00</td>
<td>27.24</td>
</tr>
<tr>
<td>2013</td>
<td>9</td>
<td>126,871.16</td>
<td>20,777,566.56</td>
<td>25,696,000.00</td>
<td>23.67</td>
</tr>
<tr>
<td>2014</td>
<td>10</td>
<td>116,796.03</td>
<td>20,084,864.74</td>
<td>24,599,100.00</td>
<td>22.48</td>
</tr>
<tr>
<td>2015</td>
<td>11</td>
<td>0</td>
<td>17,613,604.70</td>
<td>23,344,800.00</td>
<td>32.54</td>
</tr>
<tr>
<td>2016</td>
<td>12</td>
<td>0</td>
<td>16,298,359.21</td>
<td>17,294,200.00</td>
<td>6.11</td>
</tr>
<tr>
<td>2017</td>
<td>13</td>
<td>0</td>
<td>14,737,769.52</td>
<td>12,811,900.00</td>
<td>13.07</td>
</tr>
<tr>
<td>2018</td>
<td>14</td>
<td>0</td>
<td>13,009,310.18</td>
<td>9,491,280.00</td>
<td>27.04</td>
</tr>
<tr>
<td>2019</td>
<td>15</td>
<td>0</td>
<td>11,183,557.11</td>
<td>7,031,310.00</td>
<td>37.13</td>
</tr>
<tr>
<td>2020</td>
<td>16</td>
<td>0</td>
<td>9,324,187.56</td>
<td>5,208,920.00</td>
<td>44.14</td>
</tr>
<tr>
<td>2021</td>
<td>17</td>
<td>0</td>
<td>7,487,980.09</td>
<td>3,858,870.00</td>
<td>48.47</td>
</tr>
<tr>
<td>2022</td>
<td>18</td>
<td>0</td>
<td>5,724,814.64</td>
<td>2,858,720.00</td>
<td>50.06</td>
</tr>
<tr>
<td>2023</td>
<td>19</td>
<td>0</td>
<td>4,077,672.45</td>
<td>2,117,790.00</td>
<td>48.06</td>
</tr>
<tr>
<td>2024</td>
<td>20</td>
<td>0</td>
<td>2,582,636.13</td>
<td>1,568,900.00</td>
<td>39.25</td>
</tr>
<tr>
<td>2025</td>
<td>21</td>
<td>0</td>
<td>1,268,889.60</td>
<td>1,162,270.00</td>
<td>8.40</td>
</tr>
<tr>
<td>2026</td>
<td>22</td>
<td>0</td>
<td>158,718.13</td>
<td>861,029.41</td>
<td>442.49</td>
</tr>
<tr>
<td>2027</td>
<td>23</td>
<td>0</td>
<td>-</td>
<td>637,866.28</td>
<td>-</td>
</tr>
<tr>
<td>2028</td>
<td>24</td>
<td>0</td>
<td>-</td>
<td>472,542.96</td>
<td>-</td>
</tr>
<tr>
<td>2029</td>
<td>25</td>
<td>0</td>
<td>-</td>
<td>350,068.43</td>
<td>-</td>
</tr>
<tr>
<td>2030</td>
<td>26</td>
<td>0</td>
<td>-</td>
<td>259,337.07</td>
<td>-</td>
</tr>
<tr>
<td>2031</td>
<td>27</td>
<td>0</td>
<td>-</td>
<td>192,121.63</td>
<td>-</td>
</tr>
<tr>
<td>2032</td>
<td>28</td>
<td>0</td>
<td>-</td>
<td>142,327.20</td>
<td>-</td>
</tr>
<tr>
<td>2033</td>
<td>29</td>
<td>0</td>
<td>-</td>
<td>105,438.59</td>
<td>-</td>
</tr>
<tr>
<td>2034</td>
<td>30</td>
<td>0</td>
<td>-</td>
<td>78,110.83</td>
<td>-</td>
</tr>
<tr>
<td>2035</td>
<td>31</td>
<td>0</td>
<td>-</td>
<td>57,865.92</td>
<td>-</td>
</tr>
<tr>
<td>2036</td>
<td>32</td>
<td>0</td>
<td>223,847.01</td>
<td>42,868.13</td>
<td>80.85</td>
</tr>
<tr>
<td>2037</td>
<td>33</td>
<td>0</td>
<td>850,811.40</td>
<td>31,757.49</td>
<td>96.27</td>
</tr>
<tr>
<td>2038</td>
<td>34</td>
<td>0</td>
<td>1,410,678.39</td>
<td>23,526.53</td>
<td>98.33</td>
</tr>
<tr>
<td>2039</td>
<td>35</td>
<td>0</td>
<td>1,836,050.63</td>
<td>17,428.88</td>
<td>99.05</td>
</tr>
<tr>
<td>2040</td>
<td>36</td>
<td>0</td>
<td>2,052,632.11</td>
<td>12,911.63</td>
<td>99.37</td>
</tr>
<tr>
<td>2041</td>
<td>37</td>
<td>0</td>
<td>1,979,228.16</td>
<td>9,565.17</td>
<td>99.52</td>
</tr>
<tr>
<td>2042</td>
<td>38</td>
<td>0</td>
<td>1,527,745.44</td>
<td>7,086.05</td>
<td>99.54</td>
</tr>
<tr>
<td>2043</td>
<td>39</td>
<td>0</td>
<td>603,191.96</td>
<td>5,249.48</td>
<td>99.13</td>
</tr>
<tr>
<td>2044</td>
<td>40</td>
<td>0</td>
<td>-</td>
<td>3,888.91</td>
<td>-</td>
</tr>
<tr>
<td>2045</td>
<td>41</td>
<td>0</td>
<td>-</td>
<td>2,880.97</td>
<td>-</td>
</tr>
</tbody>
</table>
The variation of biogas production that can be collected from Piatra Neamț landfill, Romania.

<table>
<thead>
<tr>
<th>Calendar year (year)</th>
<th>Time (year)</th>
<th>Quantity of waste (tonnes/year)</th>
<th>Biogas production (m³/year)</th>
<th>Relative error (%)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mathematical model</td>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>1</td>
<td>55,000</td>
<td>-</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>2005</td>
<td>2</td>
<td>79,179.5</td>
<td>3,921,168.81</td>
<td>2,411,650.00</td>
<td>38.50</td>
</tr>
<tr>
<td>2006</td>
<td>3</td>
<td>77,331.08</td>
<td>5,886,128.96</td>
<td>5,258,470.00</td>
<td>10.66</td>
</tr>
<tr>
<td>2007</td>
<td>4</td>
<td>62,878.01</td>
<td>6,567,660.42</td>
<td>7,286,390.00</td>
<td>10.94</td>
</tr>
<tr>
<td>2008</td>
<td>5</td>
<td>57,579.89</td>
<td>7,447,987.70</td>
<td>8,154,980.00</td>
<td>9.49</td>
</tr>
<tr>
<td>2009</td>
<td>6</td>
<td>54,299.01</td>
<td>8,106,169.41</td>
<td>8,566,130.00</td>
<td>5.67</td>
</tr>
<tr>
<td>2010</td>
<td>7</td>
<td>40,935.52</td>
<td>7,792,320.51</td>
<td>8,726,860.00</td>
<td>11.99</td>
</tr>
<tr>
<td>2011</td>
<td>8</td>
<td>35,186.85</td>
<td>7,713,748.18</td>
<td>8,259,960.00</td>
<td>7.08</td>
</tr>
<tr>
<td>2012</td>
<td>9</td>
<td>30,352.6</td>
<td>7,470,525.65</td>
<td>7,662,010.00</td>
<td>2.56</td>
</tr>
<tr>
<td>2013</td>
<td>10</td>
<td>34,175.79</td>
<td>7,610,091.12</td>
<td>7,007,060.00</td>
<td>7.92</td>
</tr>
<tr>
<td>2014</td>
<td>11</td>
<td>0</td>
<td>5,099,435.29</td>
<td>6,689,500.00</td>
<td>31.18</td>
</tr>
<tr>
<td>2015</td>
<td>12</td>
<td>0</td>
<td>4,718,524.04</td>
<td>4,955,710.00</td>
<td>5.03</td>
</tr>
<tr>
<td>2016</td>
<td>13</td>
<td>0</td>
<td>4,250,037.39</td>
<td>3,671,280.00</td>
<td>13.62</td>
</tr>
<tr>
<td>2017</td>
<td>14</td>
<td>0</td>
<td>3,721,823.30</td>
<td>2,719,750.00</td>
<td>26.92</td>
</tr>
<tr>
<td>2018</td>
<td>15</td>
<td>0</td>
<td>3,159,147.28</td>
<td>2,014,840.00</td>
<td>36.22</td>
</tr>
<tr>
<td>2019</td>
<td>16</td>
<td>0</td>
<td>2,584,692.38</td>
<td>1,492,630.00</td>
<td>42.25</td>
</tr>
<tr>
<td>2020</td>
<td>17</td>
<td>0</td>
<td>2,018,559.18</td>
<td>1,105,770.00</td>
<td>45.22</td>
</tr>
<tr>
<td>2021</td>
<td>18</td>
<td>0</td>
<td>1,478,265.84</td>
<td>819,172.74</td>
<td>44.59</td>
</tr>
<tr>
<td>2022</td>
<td>19</td>
<td>0</td>
<td>978,748.01</td>
<td>606,858.09</td>
<td>38.00</td>
</tr>
<tr>
<td>2023</td>
<td>20</td>
<td>0</td>
<td>532,358.94</td>
<td>449,571.53</td>
<td>15.55</td>
</tr>
<tr>
<td>2024</td>
<td>21</td>
<td>0</td>
<td>148,869.38</td>
<td>333,050.78</td>
<td>123.72</td>
</tr>
<tr>
<td>2025</td>
<td>22</td>
<td>0</td>
<td>-</td>
<td>246,730.09</td>
<td>-</td>
</tr>
<tr>
<td>2026</td>
<td>23</td>
<td>0</td>
<td>-</td>
<td>182,782.14</td>
<td>-</td>
</tr>
<tr>
<td>2027</td>
<td>24</td>
<td>0</td>
<td>-</td>
<td>135,408.34</td>
<td>-</td>
</tr>
<tr>
<td>2028</td>
<td>25</td>
<td>0</td>
<td>-</td>
<td>100,312.97</td>
<td>-</td>
</tr>
<tr>
<td>2029</td>
<td>26</td>
<td>0</td>
<td>-</td>
<td>74,313.67</td>
<td>-</td>
</tr>
<tr>
<td>2030</td>
<td>27</td>
<td>0</td>
<td>-</td>
<td>55,052.92</td>
<td>-</td>
</tr>
<tr>
<td>2031</td>
<td>28</td>
<td>0</td>
<td>-</td>
<td>40,784.21</td>
<td>-</td>
</tr>
<tr>
<td>2032</td>
<td>29</td>
<td>0</td>
<td>-</td>
<td>30,213.69</td>
<td>-</td>
</tr>
<tr>
<td>2033</td>
<td>30</td>
<td>0</td>
<td>-</td>
<td>22,382.85</td>
<td>-</td>
</tr>
<tr>
<td>2034</td>
<td>31</td>
<td>0</td>
<td>76,558.35</td>
<td>16,581.62</td>
<td>78.34</td>
</tr>
<tr>
<td>2035</td>
<td>32</td>
<td>0</td>
<td>291,251.17</td>
<td>12,283.97</td>
<td>95.78</td>
</tr>
<tr>
<td>2036</td>
<td>33</td>
<td>0</td>
<td>484,661.03</td>
<td>9,100.19</td>
<td>98.12</td>
</tr>
<tr>
<td>2037</td>
<td>34</td>
<td>0</td>
<td>632,986.74</td>
<td>6,741.58</td>
<td>98.93</td>
</tr>
<tr>
<td>2038</td>
<td>35</td>
<td>0</td>
<td>709,844.68</td>
<td>4,994.29</td>
<td>99.30</td>
</tr>
<tr>
<td>2039</td>
<td>36</td>
<td>0</td>
<td>686,268.76</td>
<td>3,699.86</td>
<td>99.46</td>
</tr>
<tr>
<td>2040</td>
<td>37</td>
<td>0</td>
<td>530,710.42</td>
<td>2,740.92</td>
<td>99.48</td>
</tr>
<tr>
<td>2041</td>
<td>38</td>
<td>0</td>
<td>209,038.66</td>
<td>2,030.53</td>
<td>99.03</td>
</tr>
<tr>
<td>2042</td>
<td>39</td>
<td>0</td>
<td>-</td>
<td>1,504.25</td>
<td>-</td>
</tr>
<tr>
<td>2043</td>
<td>40</td>
<td>0</td>
<td>-</td>
<td>1,114.38</td>
<td>-</td>
</tr>
</tbody>
</table>
After analysing mathematical models it can be described the following conclusions:

- for the mathematical model corresponding leachate production that can be collected from landfills, the correlation coefficient is in the range \((57 \div 93)\) %. The lowest correlation coefficient was identified for mathematical model applied for Turin landfill, 57 %. The highest correlation degree was identified for Bihor landfill, România and has the value 93 %. The correlation degree of 57 % identified for Turin landfill can be explained by the fact that for this landfill exist the leachate recirculation process. Through this process, the amount of collected leachate is much higher than the estimated leachate amount produced in landfill.

- considering the mathematical model for biogas production that it can be collected from landfill, the correlation coefficient is between \((87 \div 96)\) %. The highest correlation coefficient was identified for Potenza landfill, Italy (96 %), while the lowest level was identified for Enna landfill, Italy (87 %).

- the difference between the values obtained by the estimation of leachate and biogas quantities that can be collected from analysed Italian and Romanian landfill and the values obtained with mathematical models is:
  
  * for the leachate
    
    o insignificant for:
    
    - Turin landfill, Italy – for the period 2000-2016;
    - Potenza landfill, Italy – for the period 1993-2029;
    - Enna landfill, Italy – for the following periods of time 2010-2027 (excluding year 2014) and 2038-2044;
    - Bihor landfill, Romania – for the following periods of time 2008-2030 and 2038-2045;
    - Piatra Neamţ landfill, Romania – for the following periods of time 2008-2034 and 2039-2043;

    o significant for:
    
    - Turin landfill, Italy – for the period of time 2017-2033 (post-closure);
    - Potenza landfill, Italy – for year 2030 (post-closure period)
    - Enna landfill, Italy – for the period 2028-2037 (post-closure landfill);
    - Bihor landfill, Romania – for the period 2031-2037 (post-closure period);
    - Piatra Neamţ landfill, Romania – for the period 2035-2038 (post-closure period);

* for the biogas
  
  o insignificant for:
- Turin landfill, Italy – for the period 1986-2016 and for year 2024;
- Potenza landfill, Italy – for the period 1990-2016 and for year 2026;
- Enna landfill, Italy – for the period 2009-2024;
- Bihor landfill, Romania – for the period 2007-2025;
- Piatra Neamț landfill, Romania – for the period 2005-2023;

- significant for:
  - Turin landfill, Italy – for the following periods 2017 – 2023 and 2037-2040 (post-closure);
  - Potenza landfill, Italy – for the period 2027-2032 (post-closure);
  - Enna landfill, Italy – for the period 2035-2042 and for the year 2025 (post-closure);
  - Bihor landfill, Romania – for years 2006, 2026 and for the period 2036-2043 (post-closure);
  - Piatra Neamț landfill, Romania – for year 2024 and for the period 2034-2041 (post-closure).

- It can be observed that the relative error recorded the highest values in certain post-closure periods, with high discrepancies between the values calculated with mathematical model and the values obtained from the estimations realised with the calculation of moisture content fractions from waste deposited in landfill. This fact can be explained that for some landfills is happening the leachate recirculation process, influencing both the production capacity of leachate and also the production capacity of biogas.

- Considering analysed landfills from Romania, it can be said that there are no real data for the entire disposal period for quantities of collected leachate. This fact can be explained by the fact that Romania is in the first stages of development concerning waste management domain.

- Some of the available data used in mathematic models are suspect from terms of authorities declarations who administered these landfills.

CHAPTER 8
FACTORS THAT CAN LEAD TO LARGE DISCREPANCIES BETWEEN ACTUAL VALUES AND THE VALUES CALCULATED USING MATHEMATICAL MODELS USED FOR DIFFERENT CASE STUDIES FOR LEACHATE AND BIOGAS

In basis of comparative analysis carried out for the seven landfills from the two countries, it can be identified several factors that explain the large
discrepancies between the real data and the values mathematically obtained. In this sense, it can be enounce the following assumptions:

1. There are large differences even from the landfills structures, the modality of waste disposal and the number of cells, but also exist big differences between the composition of elemental analysis of considered municipal solid waste stored in landfill. It should be mentioned that the presence of industrial waste and also of the waste from constructions represent a defining factor in description of the parameters and also in modelling.

For example, Turin landfill occupies a total volume of $18.628 \times 10^6 \text{ m}^3$ and is extended over an area of $79.9 \times 10^4 \text{ m}^2$, and is divided into nine cells, while Piatra Neamț landfills occupies a volume of $0.864 \times 10^6 \text{ m}^3$ and is extended over an area of $7.6 \times 10^4 \text{ m}^2$, being divided into just 2 cells (Table 9). In this sense, it can be observed some big differences between the compaction degree and waste density from analysed landfills from two countries. The report volume to surface to number of cells is characteristic for each landfill, the structure influencing the productions of leachate and of biogas.

2. Concerning analysed landfills from Romania, it can be said that, till now, not all landfills operators collect data concerning important parameters necessary for mathematical calculations, so is necessary to estimate some parameters or to consider some standard constant values utilised to calibrate the model. Introducing the variable in calculation, increasing or decreasing trends which give leachate or biogas productions are eliminated and the values became constant.

3. Regarding leachate production, it can be noticed the fact that, for analysed landfills from Italy, the real values of the parameters used in mathematical calculations are daily collected for some landfills or monthly for others. For analysed landfills from Romania, isn’t realise the monitoring of leachate quantities which are collected for treatment or for removal. The values utilised in bibliography or in different studies are represented by the maximum capacities measured for a pump utilised for leachate collection or treatment. For example, for Bacău landfill, the production capacity for leachate is calculated by the operation at maximum capacity of the pump for leachate, the leachate production being constant in time. The same situation occurs also for Piatra Neamț and for Timiș landfills.

4. For some analysed landfills from Romania doesn’t exist collection system for biogas and also neither burning in torch system. Therefore, it cannot realise the estimations of biogas quantities, considering that doesn’t
exist an order of comparison with the reality. In Romanian landfills from Bacău, Timiș and Piatra Neamț, the biogas isn’t monitored, a critical situation which may create a risk for the landfill area.

5. Waterproofing systems are better realised for analysed landfills from Italy, which contribute to the correct establishing of leachate or biogas quantities that can be collected.

6. Daily cover and also periodically waste compaction influences the total quantities of leachate and of biogas. These operations aren’t realised for Romanian landfills. Regular compaction assure a good resistance and also a better distribution of waste in landfill. Soil cover eliminates the risk of pollution and also fixes the waste in landfills.

7. The characterization and the identification of leachate and biogas quantities that can be generated from landfills are necessary to identify taking into account the impact that it may have on the environment. It is important to identify in real time daily quantities for leachate and also for biogas to:
   - prevent disasters (explosions that may occur due to biogas accumulations)
   - reducing operating costs;
   - leachate reusing through recirculation to increase the percentage of biogas production;
   - reducing accidental pollution at any level.

8. Following the validation of estimative mathematical models utilised to determinate the production capacities for leachate and for biogas from analysed landfills from Romania and also from Italy, it was observed that exist differences between collected quantities and estimated quantities or obtained by mathematical calculations.
   For Turin landfill, Italy it can be said that appear some differences between collected quantities and calculated quantities for leachate because of leachate recirculation operations in landfill body. This influences the biogas production, which is increasing, that can be observed in the obtained results.
   For Potenza landfill, Italy, referring only to the year 2003, the year for which were published data, exist differences because of filling landfill cells in different periods of time. Cell cultivation was randomly realised and wasn’t constant over time, till to the maximum capacity filling.
   Considering Enna landfill, Italy, it can be observed that the waste was stored for a shorter period of time, production capacity being at a high level for the first year of disposal, till when the post-closure begin. Considering biogas production, it is known that a part of biogas is energetic recovered. It is
recommended the leachate recirculation for additional energy recovery by increasing biogas production.

For Bacău landfill, Romania it was impossible to calculate leachate and biogas productions due to the lack of data concerning the amount of waste deposited. It is recommended to monitor the landfill and carrying an estimation of stored amount of waste, related to the population and to waste generation rate to identify the production capacity for leachate. If, after the verification of real production capacities and also of calculated production capacities, it can be identified big differences, it is recommended to collect a supplementary leachate quantity from landfill. Biogas production can be valorised by operation the biogas collection system. Otherwise, it is recommended that the biogas to be burned in torch to avoid the natural elimination in atmosphere.

For Bihor landfill, Romania, exist some differences between the collected biogas quantity and the calculated values. It is recommended to increase the biogas production and to use the biogas for energy recovery. Concerning leachate quantity, which is treated in storage tank, it is recommended to recirculate this quantity to increase biogas production. This landfill is the only one from analysed Romanian landfills which use biogas for energy recovery.

For Piatra Neamț landfill, Romania, were noticed the biggest differences between leachate collected and leachate calculated. The quantity of leachate collected from landfills is only 990 m³/year, a very low values comparing with waste quantity deposited in landfill. It is important to mention the fact that, although is realised a pre-sorting before landfilling and percentage of organic fraction is higher, the biogas isn’t collected, being naturally eliminated in atmosphere.

For Timiș landfill, România, wasn’t realised any mathematical calculation of production capacity for leachate and for biogas, considering the fact that weren’t reported the quantity of waste stored in landfill.

For analysed Romanian landfills it can be said that exist big differences between calculated and real values and because of the following factors:
- in Romania doesn’t exist any recorded data, and is not monitored throughout the landfill life, being at the beginning of waste storage and also at the beginning of waste management domain;
- some of reported data by authorities or institutions which are managing landfill are suspicious in terms of their declarations.

CHAPTER 9
ENVIRONMENTAL IMPACT ASSESSMENT GENERATED BY LANDFILLS FROM ITALY AND FROM ROMANIA
Environmental impact assessment of these activities represents a process that aims to identify, to describe and to establish, depending of each case, and according with legislation the direct and indirect effects, synergistic, cumulative, main and secondary effects of human activities on the environment and human health, and the establishment of measures on their reduction [36, 87, 114].

In this sense, the directions of action that can be implemented to reduce environmental impact (Figure 178), at landfills activity, Romanian landfills case, refer to the following aspects:

1. The impact on the water environmental factor:
   - wastewater monitoring:
     • consist of waster from waste and precipitation waste (leachate);
     • consist of water from toilets of administrative buildings and from vehicles washing.
   - treated water resulted from leachate treatment in its own wastewater treatment stations for Romanian landfills.

2. The impact on the air environmental factor:
   - Stationary sources:
     • wind entrainment of dust or pathogenic germs from landfills (no daily cover for some Romanian landfills);
     • biogas elimination in the atmosphere due to the lack of collection system or burning in torch systems for Romanian landfills.
   - Mobile sources: road traffic.

3. The impact on the soil environmental factor:
   - improper waste storage on the soil surface which may have negative effects;
   - accidental soil pollution during waste transport from houses to landfills.

**Fig. 178. Measures to reduce environmental impact [36, 87, 114].**

Referring to the analysed case studies it can be achieved different environmental impact assessment:
1. Turin landfill is in post-closure phase since 2010. In this sense, the environmental impact refers to the leachate collection system in post-closure phase and to the elimination of biogas using burning in torch system. Waterproofing and closing system was realised according legislation. In this sense, it can make some assumptions concerning generation of significant impact. It is important the monitoring of all parameters to avoid any accidental pollution due to leachate or biogas collection system failures.

2. Potenza landfill, Italy. Storage in different cells in different periods of activity can generate a significant impact on the environment. Landfill monitoring is required to avoid accidental pollution.

3. Enna landfill, Italy. The landfill is in post-closure phase and is necessary to monitor la landfill to assess the impact on the environment:
   - water. It will be monitored the groundwater in order to avoid possible infiltration of leachate into groundwater. It is necessary to monitor the leachate remained in landfill and which it can be generated in post-closure phase;
   - soil. Leachate collection and transport will be carried out safely to avoid accidental pollution;
   - air. Monitoring and the evaluation of generated biogas in post-closure phase is essential to avoid accidental pollution. In this sense, the biogas can have a significant impact on the environment.

4. Bacău landfill, Romania. The landfill is located near Bistriţa river and exist the contamination risk. This is favoured by the defective waterproofing of the landfill, but also by the management operation of the leachate. The leachate is collected from landfill and stored in a „lagoon” near landfill, while previously was treated. It is important to mention the fact that all treated leachate from lagoon is uncovered. Thus, it may issue two assumptions that can have significant environmental impact. First, in period of heavy rainfall, the leachate level may increase and move to the river, existing risk of soil pollution and also contamination of the river. Considering the fact that the lagoon is uncovered, there is potential impact on the environment through emissions that can be emitted, but also through odours in the area (air pollution). Concerning biogas, considering that aren’t functionally collection system, exist potential impact air pollution and also the presence of high emission of gases from biogas in the atmosphere. However, there is a high risk concerning leachate and biogas productions If there are no monitoring aspects, exist a high risk of explosions of fractures of the deposit.
5. Bihor landfill, Romania. For Bihor landfill was realised the waterproofing of the bottom of landfill, but it is important to monitor parameters to avoid soil and groundwater pollution. Currently, from landfill is collected only a part of leachate quantity, and the part which is not collected can have a negative significant impact on landfill, but also on the environmental factors. Collected biogas in the last activity year was considerably less than in previous years, therefore is necessary a reassessment of generation capacity for biogas.

6. Piatra Neamț landfill, Romania. This landfill collects a small amount of leachate related to the waste deposited in landfill.

Activities with significant environmental impact refer to the following aspects:
- pre-sorting accomplished before disposal must be carried out safely. Also pre-sorted waste disposal can have a significant impact on the environment;
- collection, storage and transport of leachate are activities which must be monitored, referring to the impact that in could generate the leachate on the environment;
- the absence of a functional biogas collection system can have a significant impact on the environment;
- the absence of waste daily cover operations can generate a significant impact on the environment on the air, on fauna and flora in the landfill area.

7. Timiș landfill, Romania. The activities with significant impact on the environment within the landfill refer to the following:
- groundwater monitoring to eliminate the environmental impact on the possible infiltration of leachate;
- leachate collection, treatment and transport in safety conditions;
- the absence of biogas collection system can generate a significant impact on the environment;
- monitoring of all activities to avoid the pollution of groundwater, of soil and of air

CHAPTER 10
TECHNICAL, ECONOMICAL AND ECOLOGICAL ASPECTS OF LANDFILLS FOR MUNICIPAL SOLID WASTE

The main goal of describing the technical-economic and ecological aspects of analysed landfills from two countries refer to highlight the results obtained in Italy and, try, in addition to other technique already used, to elaborate new ways of management, according to legislation, to reduce the
environmental impact and to deliver bigger and also profitable results for Romanian landfill or for any country that opts for waste disposal in landfills.

For each landfill, it is necessary to have a balance between income and expenses. Referring to the incomes, the situation is different for each country.

Even if the collected amounts by the landfill operators for each category of income are different, earnings structure being the same (Figure 180).

Thus, for analysed landfills from countries, Italy and Romania it can achieved an estimated analysis for incomes, as follows:

- landfill construction, analysed landfills from Romania were built through various European programs, ensuring necessary resources for design and construction of the landfill. In Italy, the landfills were designed and built in the ‘80s, at which there weren’t no funding sources;

- waste collection operations, provide financial requirements for landfill closure and for post-closure monitoring. Waste costs differ depending on the area (rural, urban) and by country. If in the rural areas of Romania, each inhabitant pays, in average 50 lei for one year for municipal solid waste collection, in the urban area, for Bacău landfill, the waste collection might be paid with 100 lei/year/capita. In Italy, waste collection is paid up to 120 €/year/capita in Piedmont Region;

- the valorisation of collected biogas is an important source of income for managers of analysed landfills from Italy. Considering that for many cases in Romania landfills aren’t collected biogas quantities, the incomes from this procedure is almost zero.

![Fig. 180. Activities within which it can realise income for landfills.](image)

132
It can be considered that for analysed landfills from Italy, the incomes resulted from valorisation of collected biogas represents the largest percentage from the total amount of incomes. Concerning analysed landfills from Romania, the most significant incomes are from waste collection operations.

Figure 181 presents a structure of all activities which generates costs for a landfill. This structure is applicable to all analysed landfills from Italy and from Romania, with the mention that the costs are varying for each category and are specific for each landfill.

For each carried operation, the costs are considered to different and related to each landfill, as follows:

- Landfill construction. In for Romanian landfills, the design and construction of landfills are income sources, due to European programs, for analysed landfills from Italy, this factor may represent costs concerning bottom waterproofing, the construction itself, but also for initial design of the landfill.

- The waste transport from special areas for residential waste disposal near residential areas to the landfill body represent a significant percentage in the final calculation of costs. Within these costs is entering also the costs with persons involved in waste transport and the costs of equipment.

- Waste management operations are important stages through which the waste quantities are receipt in the landfill area, until the final storage in landfill. The cost of this phase refer to the waste sorting, to the distribution of waste in cells, to the compaction, to the daily cover and to the personnel and equipment serving each individual operation.

- Monitoring of landfill is one of the most important factors for ensuring the safety and the health of landfill area. The costs of this stage refer to monitor each parameter that can have significant impact on the environmental factors: water, air, soil, subsoil and weather and climatological parameters.

- Costs for leachate collection are found also in the first phase of construction of leachate collection system, adding additional costs for the collection, storage and transport of leachate.

- Costs for leachate treatment, either in their own plants for wastewater treatment, either at municipal treatment plants contribute to the general expenses for a landfill. Leachate recirculation can reduce the costs realised for transport or storage, and also can be an important addition by increasing of production capacity of the biogas.

- Costs for landfill closure. It is the stage when are intervening the isolation of landfill costs, the proper waterproofing costs and biogas collection system cost.
Cost of post-closure phase are founding in parameters monitoring for risk elimination concerning ecological aspects of landfills and also for the maintenance of leachate and biogas collection systems.

Considering the estimated values for leachate and biogas quantities, it can be realised a cost assessment and obtain a considerable budget to achieve a good management in the post-closure phase and also to obtain a possible profit from biogas production.

According Italian legislation (legislative decree 36/2003), to obtain the functioning authorization, the manager of a landfill must present a financial plan where are provided all costs for all four periods of the life cycle of a landfill, for collection and treatment of leachate, for biogas collection, for monitoring of the area and for all the necessary parameters for final cover and also for post-closure period (a period of about 30 years). By covering these expenses, it can be establish the amount of waste fee. Considering this point of view and concerning all approvals obtained from financed project through European programs, were established clear budgets for analysed landfills from Romania [82, 91].

![Fig. 181. Activities that generate costs in a landfill.](image)

To realise an analysis of the period in which there is a balance between incomes and expenses, it is necessary to describe the following aspects [32, 82, 91]:

1. **Post-closure costs:** can be classified in secure, unsecure, stationary and variable costs.
Secure costs are the exactly costs which are exactly known and are part of landfill study and from professional experience of management. In this sense, it can be distinguished:

- fixed costs, which doesn’t depend of time evolution of the landfill. These costs can be constant and results from the following processes:
  • the achievement of control of construction and erosion of cover;
  • the monitoring;
  • the landfill maintenance;
  • the maintenance of soil cover (vegetation cover);
  • the administrative costs and reporting costs;
  • the ensure of financial security for fixed costs.

- variable costs, which depend on the time evolution of the landfill and cannot be constant. These costs come from:
  • leachate management;
  • biogas management;
  • the ensure of financial security for variable costs.

The unsecure costs are the costs derived from the accidents of derived from activities cannot be provided. It can have the following causes:

- perforation of the waterproofing system;
- infiltration along the topcoat layer;
- imminent pollution.

In this sense, it is difficult to estimate the final and correct cost, because each parameter is influenced by time.

Background costs – represents the cumulative budget from active phase management from that are supported all the expenses for closure and for post-closure phase of the landfill and from, which were removed initial construction costs.

2. The financial guarantee – represents an insurance to carry out the entire business management.

3. Costs for treatment plants – is the cost of maintaining and operating the leachate treatment plant for each landfill.

Referring to Romanian landfills, part of the required expenses can be covered from the sorting preliminary landfilling.

In this sense can be valorised the following types of municipal solid waste:
- Reusable materials from waste paper. These materials can be reused as raw material for paper mills and must not show deterioration due to rot. After the modality of the materials of paper and cardboard can be reused to produce pulp for use as raw material required to manufacture paper, paperboard, cardboard supporting bitumen etc.

- Reusable plastic materials. It can be sorted and valorised plastic material from low and high density polyethylene (LDPE and HDPE).

- Reusable glass materials. Sorted glass is valorised at glass factories, as raw material, being added material in manufacturing process or entirely reused.

- Reusable textile materials. It is a more difficult process because of the fact that sizing is separated by type of material and by colour group (light, medium, black).

CHAPTER 11
GENERAL CONCLUSIONS

The theoretical and experimental research regarding the evaluation of technological aspects for the post-closure activity of landfills for municipal solid waste presented in this study constitutes an attempt to describe, by means of a detailed analysis, the relations of interdependence that exist between the management operations and the aspects with significant impact for environment for landfills for municipal solid waste from Italy and from Romania.

The results obtained by means of theoretical and experimental investigation lead us to the following conclusions:

A. Concerning the timeliness of the topic/theme

In base of studying specialised literature on waste, it can be stated that:

- The waste quantity generated has an upward trend. The necessary options to reduce the amount of generated waste refer to [57, 80]:
  - reduction at source;
  - reducing the amount of waste streams;
  - waste valorisation: reuse, recycling and energy recovery;
  - waste disposal.

- Municipal Solid Waste consist of household and similar waste collected by or on behalf of municipal authorities. The structure of municipal solid waste is composed of the following fractions [60, 62]:
  - paper, cardboard and paper products;
  - plastic materials;
  - glass;
• metals;
• food waste;
• garden waste and textiles.

- The modalities of waste collection are [98, 99, 111]:
  • traditional door to door collection;
  • differentiated collection on fractions for recovery operations.

- Landfills presents a number of factors to be studied carefully to monitor the manufactured products, which can have significant impact on the environment and can cause harmful effects on the environment or on the population.

  - The sources of pollution on the environment can be localized:
    • soil pollution (by disposing waste on the soil);
    • water pollution (by waterproofing systems and by leachate collection);
    • air pollution (by biogas collection system).

- By implementing management systems and monitoring, can be offered new jobs for carrying out different operations in landfills.

- It can recycle large amounts of material, especially in the field of non-hazardous materials.

B. Aspects regarding the theoretical foundation of technological aspects for the post-closure activity of landfills for municipal solid waste

1. From a legislative point of view, it can be said that exists standardized European normative which must to undergo the operators or managers of the landfills. Both, Italy and Romania have their own legislative documents, mandatory to implement for landfill functionality.

2. Each landfill is specific for the category of waste that can be accepted for storage. The waste to be deposited in landfills can be classified into three categories [99]:
   - residential waste;
   - commercial waste;
   - industrial waste.

3. The properties of waste analysed in the research can be classified as follows [24, 99]:
   • physical properties of waste:
     • waste moisture;
• waste granulometry;
• waste density;
• waste permeability;
• waste temperature;
  - chemical properties of waste;
  - biological properties of waste.

4. Considering the type of waste deposited in landfill, the landfills can be classified into three categories [55-57, 99]:
   - landfills for inert waste;
   - landfills for non-hazardous waste:
     • landfills for inorganic waste;
     • landfills for organic waste:
       o landfills - bio-reactor;
       o landfills for pre-treated waste.
     • landfills for waste mixture;
   - landfills for hazardous waste.

5. The life cycle of the landfill is divided into four clearly defined stages (design and construction, active management, closure and passive management), but theoretical analysis and experimental considered important phases the active period (the period during which it stores waste quantities in landfills) and post-closure phase (minimum of 30 years after the final vegetation cover of the deposit).

6. The leachate is the result of decomposition of the organic substance and bacterial expression by extraction of organic contaminants present in the waste by means of the solvent effect of water. This product is very aggressive and can have significant environmental impact in case of mismanagement.

7. The biogas is a gas that is formed by decomposing of organic waste during the methanogenic phase. This decomposition produces a „micelle” composed of methane and carbon dioxide, but also with low levels of nitrogen, oxygen, sulphur, hydrogen and carbon monoxide.

8. Post-closure period of landfills is considered one of the most important period from their life cycle. During this period it is necessary a permanent monitoring of parameters that can have significant impact. It is also important to collect the produced products for the maintenance of landfills out of any danger.
9. The method used in this thesis to identify the quantities of leachate and of biogas, and of parameters of products from landfills is represented by the estimative mathematical modelling.

10. For the impact assessment of the technological aspects for post-closure activity of landfills for municipal solid waste were made different estimations and comparative analyses that can reflect the leachate and biogas quantities that can be collected in different periods of landfill life-cycle. It was identified the influence of meteorological and climatological parameters to the quantities of landfill products. It were established different mathematical relations and the factors that may have influence on technological processes.

11. For the comparative analyses were considered case studies from Italy and Romania, for which were defined and custom the following:
   - description, construction and management of landfills from Italy and from Romania;
   - the structure of landfills considered in case studies;
   - categories of waste stored in each landfill;
   - leachate collection in active phase and the estimation of its quantity in the post-closure phase;
   - biogas collection in active phase and the estimation of its quantity in the post-closure phase.

12. Theoretical and experimental analysis performed enables the estimations and identification of correlation between the amounts of waste, time and production capacity of the leachate and of the biogas for each analysed landfill.

C. Aspects concerning the experimental testing of the theory

1. To study the impact of technological aspects for the post-closure period landfills for municipal solid waste were identified the following:
   - the characteristics and the parameters of landfills from Italy and Romania, namely:
     • Turin landfill, Italy;
     • Potenza landfill, Italy;
     • Enna landfill, Italy;
     • Bacău landfill, Romania;
     • Bihor landfill, Romania;
     • Piatra Neamț landfill, Romania;
     • Timiș landfill, Romania;
- the estimations of quantities of leachate and of biogas from landfills considered from Italy and Romania.

2. In Romania, waste disposal in landfill which are ecological and constructed in accordance with existing legislation began relatively late, after 2000s, when Municipalities or County councils have built and developed area and utilised them to create modern landfills funded from projects financed by the European Union.

3. Regarding the design, landfills made from Italy presents a greater number of cells, each of them equipped with independent systems to collect leachate and biogas, with acceptance of only municipal solid waste.

4. A special feature concerning to the composition of the waste deposited refer to the analysed landfills from Romania, which are performing pre-sorting operations before disposal, but in landfill are also stored industrial and construction waste.

5. It were described estimative mathematical models for leachate and for biogas with which can be identified various parameters. Some models may not apply for some landfills due to limited data for each landfill in hand.

6. For calibrating and verifying the accuracy of the models it were implemented two mathematical models for each product. Thus, for the production of leachate was used, where there were sufficient data:

   - Hydrological Mass Balance Model for:
     - Turin landfill, Italy;
     - Potenza landfill, Italy;
     - Piatra Neamț landfill, Romania;
     - Bihor landfill, Romania;

   - Serial Water Balance Model for Turin landfill, Italy.

For the calculation of biogas production, were used:
- Stoichiometric model for:
  - Turin landfill, Italy;
  - Bihor landfill, Romania;

- LandGEM model for:
  - Turin landfill, Italy;
  - Bihor landfill, Romania.
For the other landfills considered in case studies, it was impossible to realise calibrations of available mathematical models due to a lack of data on the actual waste quantities or for the production of leachate or of biogas which was collected for each landfill.

7. For each landfill was carried out a description of the main features, from structure still observing the difference between the considered case studies.

a. Turin landfill, Italy shows the following characteristics:
   - surface: 79.9·10^4 m^2;
   - volume occupied: 18.628·10^6 m^3;
   - number of cells: 9;
   - active phase between: 1984–2009;

b. Potenza landfill, Italy shows the following characteristics:
   - surface:10·10^4 m^2;
   - volume occupied: 0.579·10^6 m^3;
   - number of cells: 7;
   - active phase between: 1989-2004;

c. Enna landfill, Italy shows the following characteristics:
   - surface:4.5·10^4 m^2;
   - volume occupied: 0.560·10^6 m^3;
   - number of cells: 6;
   - active phase between: 2007-2013;

d. Bacău landfill, Romania shows the following characteristics:
   - surface:22.1·10^4 m^2;
   - volume occupied: 4.123·10^6 m^3;
   - number of cells: 4;
   - active phase between: 2011 - present;

e. Bihor landfill, Romania shows the following characteristics:
   - surface: 7.6·10^4 m^2;
   - volume occupied: 0.864·10^6 m^3;
   - number of cells: 2;
   - active phase between: 2005 - 2014;

f. Piatra Neamţ landfill, Romania shows the following characteristics:
   - surface: 4·10^4 m^2;
   - volume occupied: 1.229·10^6 m^3;
   - number of cells: 2;
   - active phase between: 2004 - 2013;
g. Timiș landfill, Romania shows the following characteristics:
- surface: $35.14 \cdot 10^4 \text{m}^2$;
- volume occupied: $5.131 \cdot 10^6 \text{m}^3$;
- number of cells: 5;
- active phase between: 2011 – 2014;

7. The graphical representations and the mathematical relations of response functions from the case studies have highlighted the technological aspects for post-closure period of landfills for municipal solid waste, respectively for production capacity of the leachate and for production capacity of the biogas:
- it was carried out the estimation of the total quantity of liquid that it can be formed from moisture content of each fraction of different types of waste (municipal solid waste, analogous municipal solid waste, sewage sludge) and from the liquid quantity that can be produced from meteorological and climatological parameters, specific for each landfill;
- from the total liquid quantity, it was realised an estimation of the leachate production for each landfill, for a period of active phase and for a period of at least 30 years of post-closure phase.

8. For Turin landfill, Italy, the data was presented as follows:
- the total amount of waste deposited in the period of activity consist of three types of waste:
  - municipal solid waste - 73%;
  - analogous municipal solid waste -14%;
  - sewage sludge – 13%;

- it was presented the composition of municipal solid waste for the period 2000-2009;
- from the composition for that period, it was established the average percentage composition of fractions of municipal solid waste stored in the landfill, which was used in the calculations for the waste deposited. Fractions contained in waste composition are:
  - paper and cardboard waste;
  - leather and textile waste;
  - wood waste;
  - glass and inert waste;
  - metal waste;
  - plastic waste;
  - organic waste;
  - fine particles of waste;
• other types of waste;

- it was represented the variations of monthly averages of precipitations, of temperature and of solar radiation and were calculated the variations of monthly averages of runoff and of evapotranspiration;
  - it was estimated the moisture content related to each fraction from municipal solid waste and from analogous municipal solid waste;
  - it was estimated the moisture content related to sewage sludge deposited in landfill;
  - it was realised a comparative analysis between the leachate quantity mathematically determined and the leachate quantity estimated with estimative mathematical model for capacity production for leachate. The estimation of leachate quantity was determined for the post-closure phase for a period of 33 years. The correlation coefficient for equation was 0.91155;
  - it was realised an estimation of biogas quantity using an estimative mathematical model used to determinate the capacity production for biogas which was compared with the real quantity of biogas collected from landfill. The estimation of biogas quantity for post-closure phase it was realised for a period of 31 years.

9. For Potenza landfill, Italy, the data was presented as follows:
- the total quantity of waste deposited in landfill in active phase is composed from two types of waste:
  • municipal solid waste - 90%;
  • sewage sludge – 10%;

- it was represented the average percentage of municipal solid waste composition, which it was utilised in mathematical calculations for deposited waste. The fractions from municipal solid waste are:
  • paper and cardboard waste;
  • leather and textile waste;
  • wood waste;
  • glass and inert waste;
  • organic waste;
  • fine particles of waste;
  • other types of waste;

- it were represented the variations of monthly averages for precipitations, for temperature and were calculated the variations of monthly averages for runoff and for evapotranspiration;
- it was estimated the moisture content for each fraction from municipal solid and from sewage sludge;
- it was realised a comparative analysis between the leachate quantity calculated and the leachate quantity estimated with an estimative mathematical model used to determine the production capacity of the leachate. The total quantity of liquid which it can be formed in the landfill has the value 168,162.3 m³. The estimation of leachate quantity for the post-closure phase was realised for a period of 30 years. The correlation coefficient for the equation for estimation was 0.92003;

- it was realised an estimation of biogas quantity using an estimative mathematical model to determinate the production capacity for biogas, which was compared with the real quantity collected from landfill. The estimation of biogas quantity for post-closure phase was carried out for a period of 32 years.

10. For Enna landfill, Italy, the data was presented as follows:

- the total quantity of waste deposited in active phase is composed only from municipal solid waste.
- for this landfill, doesn’t exist a public waste structure. From this point of view it was established the representation of average percentage of composition of municipal solid waste deposited in Turin landfill, which was utilised in calculations for deposited waste. The fractions used in calculations are the following:
  - paper and cardboard waste;
  - leather and textile waste;
  - wood waste;
  - glass and inert waste;
  - metal waste;
  - plastic waste;
  - organic waste;
  - fine particles of waste;
  - other types of waste;

- it were represented the variations of monthly averages for precipitations and for temperature and the variations of monthly averages calculated for runoff and evapotranspiration.
- it was estimated the moisture content related to each fraction from municipal solid waste.
- it was elaborated a comparative analysis between the amount of leachate determined by calculations and the leachate quantity estimated with an estimative mathematical model used to determine the production capacity for leachate. The total quantity of leachate that can be formed in Enna landfill, Italy was 145,833.59 m³. The estimation of leachate quantity for post closure
phase was realised for a period of 30 years. The correlation coefficient for the equation was 0.96841;
- it was realised an estimation of biogas quantity using an estimative mathematical model to determine the production capacity for biogas, which was compared with the real quantity collected from landfill. The estimation of biogas quantity for the post-closure phase was realised for a period of 31 years.

11. For Bacău landfill, Romania, the data was presented as follows:
- There was no data concerning the quantity of deposited waste.
- It were presented the variation of monthly average of the precipitations, and of the temperatures and were calculated the variations of monthly average for runoff and for evapotranspiration.
- If there are no information referring to waste quantity deposited in landfill, it doesn’t realise the estimation of productions of leachate and of biogas.

12. For Bihor landfill, Romania, the data was presented as follows:
- the total quantity of waste deposited in active phase is composed only from municipal solid waste. From waste composition are making part and fractions of industrial or construction waste, but where neglected in mathematical calculations.
- it was represented the average percentage of municipal solid waste composition, which it was utilised in mathematical calculations for deposited waste. The fractions from municipal solid waste are:
  - paper and cardboard waste;
  - leather and textile waste;
  - wood waste;
  - glass and inert waste;
  - metal waste;
  - plastic waste;
  - organic waste;
  - fine particles of waste;
  - other types of waste;
- it were represented the variations of monthly averages of precipitations and of temperature and were calculated the variations of monthly averages of runoff and of evapotranspiration;
- it was estimated the moisture content related to each fraction from municipal solid waste;
- it was elaborated a comparative analysis between the amount of leachate determined by calculations and the leachate quantity estimated with
an estimative mathematical model used to determine the production capacity for leachate. The total quantity of leachate that can be formed in Bihor landfill, Romania was 458,485.6 m$^3$. The estimation of leachate quantity for post closure phase was realised for a period of 30 years. The correlation coefficient for the equation was 0.95516;

- it was realised an estimation of biogas quantity using an estimative mathematical model to determine the production capacity for biogas, which was compared with the real quantity collected from Bihor landfill. The estimation of biogas quantity for the post-closure phase was realised for a period of 32 years.

13. For Piatra Neamţ landfill, Romania, the data was presented as follows:

- the total quantity of waste deposited in active phase is composed only from municipal solid waste. From waste composition from Piatra Neamţ landfill are making part and fractions of industrial or construction waste, but where neglected in mathematical calculations;

- it was represented the average percentage of municipal solid waste composition, which it was utilised in mathematical calculations for deposited waste. The fractions from municipal solid waste are:
  - paper and cardboard waste;
  - leather and textile waste;
  - wood waste;
  - organic waste;
  - fine particles of waste;

- it were represented the variations of monthly averages of precipitations and of temperature and were calculated the variations of monthly averages of runoff and of evapotranspiration;

- it was estimated the moisture content related to each fraction of municipal solid waste deposited in Piatra Neamţ landfill;

- it was developed a comparative analysis between the amount of leachate determined by calculations and the leachate quantity estimated with an estimative mathematical model used to determine the production capacity for leachate. The total quantity of leachate that can be formed in Piatra Neamţ landfill, Romania was 214,702.12 m$^3$. The estimation of leachate quantity for post closure phase was realised for a period of 30 years. The correlation coefficient for the equation was 0.96029;

- it was elaborated an estimation of biogas quantity using an estimative mathematical model to determine the production capacity for biogas, which was compared with the real quantity collected from Piatra Neamţ landfill. The estimation of biogas quantity for the post-closure phase was realised for a period of 30 years.
14. For Timiș landfill, Romania, the data was presented as follows:
- There was no data concerning the quantity of deposited waste.
- It were presented the variation of monthly average of the precipitations, and of the temperatures and were calculated the variations of monthly average for runoff and for evapotranspiration.
- If there are no information referring to waste quantity deposited in landfill, it doesn’t realise the estimation of productions of leachate and of biogas.

15. Referring to operations management, it is necessary to emphasize the following:
- The leachate is collected and monitored for landfills from Italy (Torino and Potenza) and Romania (Bihor and Piatra Neamț) and is treated using different technical solutions in each case. In Romania, besides that aren’t use intermediary liners for periodically covers of landfill, it doesn’t exist a monitoring system for collected leachate, and more than that aren’t realised the leachate recirculation operations;
- The biogas. Only a part of operators, responsible for landfills from Romania use biogas collection and also energy recovery from it (Bihor landfill). Biogas collection involves many positive aspects for operators and also an important aspect of disaster prevention.

16. The activities from the post-closure phase (approximately 30 years after the final closure of the landfill, according to the specialised literature) is a key pillar in the life cycle of a landfill.

D. Concerning the originality of the thesis

1. Considering bibliographical study and specialised literature based on the evaluation of technological aspects concerning the post-closure phase of landfills for municipal solid waste from Italy and from Romania, were highlighted:
- description, design, construction and management of landfills from Italy and from Romania;
- the structure of landfills considered in case studies;
- categories of waste stored in each landfill;
- leachate collection in active phase and the estimation of its quantity in the post-closure phase;
- biogas collection in active phase and the estimation of its quantity in the post-closure phase.
2. For the comparative analyses achievement due to the complexity of technological processes that occur in landfill for leachate and biogas formation, were used three landfills from Italy and four landfills from Romania in various stages of activity.

3. Following the estimations and comparative analyses, correlations have been established between the quantities of leachate or biogas that can be collected. Mathematical modeling was performed using one mathematical equation to estimate the quantity of leachate and one equation to identify the production of biogas.

4. For the leachate mathematical calculation, the equation estimative for production of leachate showed a degree of truth ($r^2$) in the range of $0.91 \div 0.97$. The maximum degree of truth was carried out for the landfill in Bihor, Romania, while the minimum degree was carried out landfill in Turin, Italy.

5. For the mathematical calculations of biogas was used an estimative mathematical model which is influenced by the amount of waste deposited during the activity and the full life of the landfill (active period and post-closure).

6. Based on the obtained estimations for production capacities of leachate and of biogas for considered landfills from Italy and from Romania were achieved, by using TableCurve3D software, the following mathematical models:
   - For production capacity of leachate from considered landfills from Italy and Romania, the obtained model has the degree of correlation ($r^2$) in the range of $57 \div 93\%$;
   - For production capacity of biogas from considered landfills from Italy and Romania, the obtained model has the degree of correlation ($r^2$) in the range of $87 \div 96\%$.

E. Concerning future developments of the research

1. Landfills represents the method most commonly used for storing waste in Romania. Two of analysed landfills from Italy are in post-closure period, from 2004 and from 2010 and one is in operation phase, while all landfills studied from Romania are in active phase. For mathematical calculations, it was considered the closure of landfills the last year for which data are available concerning amount of waste.

2. For Romania cases, waste storage in landfill which are ecological and constructed in accordance with existing legislation began relatively late, after
2000s, when Municipalities or County Councils have built and developed area and utilised them to create modern landfills funded from projects financed by the European Union.

3. Theoretical studies and comparative analyses from this paper can be a useful material and also indispensable in addressing some of similar issues in this area to identify the various aspects concerning the processes that occur in landfills in different periods of the life cycle.

4. To clarify the correlations between the waste quantity deposited and the production capacity of leachate and of biogas, it is necessary that the future studies and researches to be considered other parameters that may influence the production of leachate and biogas.

5. To eliminate the discrepancies between actual land values and the values calculated using mathematical models is necessary to use mathematical models that involve a number of specific parameters for each landfill. Where differences occur in the composition of waste or structural waterproofing was carried out differently, major differences may occur in the calculations. Other important factors that have an important influence in the production of leachate and biogas refer:
   - The degree of compaction of waste;
   - Regular coverage of waste;
   - Collection system for leachate and for biogas;
   - Leachate recirculation.

6. In the present study were not studied the qualitative parameters of waste or chemical-biological parameters of waste. This can lead, in the future, a variety of research topics.

F. The exploitation of research

The documentation for the work was performed by attending various courses in the Doctoral School from the „Vasile Alecsandri” University of Bacău, Romania and the Polytechnic University of Turin, Italy, as follows:

1. Courses at „Vasile Alecsandri” University of Bacău, Romania:
   - Ethics in Research – Prof. dr. Eng. Dr. h. c. Valentin NEDEFF;
   - Mathematical modeling – Prof. dr. Eng. Maricel AGOP;
   - Project management – Prof. dr. Eng. Carol SCHNAKOVSZKY;
   - physical modeling – Prof. dr. Eng.. Gabriel LAZĂR.
2. Courses at Polytechnic University of Turin, Italy:
- Compatibilità ambientale dei servizi pubblici locali, (Environmental compatibility of local public services) - Prof. dr. Giuseppe GENON;
- Ingegneria dei processi biologici (Biological processes engineering) - Prof. dr. Giuseppe GENON;
- Ingegneria degli acquiferi (Aquifer engineering) - Prof. dr. Rajandrea SETHI;
- Rifiuti solidi (Solid waste) - Prof. dr. Silvia FIORE;
- Descrizione modellistica dei meccanismi ambientali nell'ambito dell'LCIA (Life Cycle Impact Assessment) (Modeling description of environmental mechanisms as part of the LCIA – Life Cycle Impact Assessment) - Prof. dr. Barbara RUFFINO.

3. Participation and papers presented at conferences:
- THE CURRENT STATE OF EX SITU TECHNOLOGIES FOR SOIL DEPOLUTION BY MEANS OF PHYSICAL AND THERMAL PROCEDURES - INTERNATIONAL CONFERENCE ON ENERGY EFFICIENCY AND AGRICULTURAL ENGINEERING, held on May 17-18, 2013, Angel Kanchev" University of RUSE, BULGARIA”;
- THE XTH INTERNATIONAL CONFERENCE CONSTRUCTIVE AND TECHNOLOGICAL DESIGN OPTIMIZATION IN THE MACHINES BUILDING FIELD - OPROTEH – 2015, June 4 – 6, 2015 BACĂU, ROMANIA
- TINOS 2015 3RD INTERNATIONAL CONFERENCE ON SUSTAINABLE SOLID WASTE MANAGEMENT, 1 – 4 July, 2015, Tinos, GRECIA
- Summer School on Sustainable Waste Management “Sustainable Landfilling and Final Sink”, Venice International University, Venice, Italy, 11-20 July
2014. Research report: AFTERCARE PERIOD OF LANDFILLS. LEACHATE AND BIOGAS;

4. Articles published:


5. Articles in press:

- Mihai-Cosmin Belciu, Silvia Fiore, Giuseppe Genon, Valentin Nedeff (in press) -Analysis of MSW landfills management operations in Italy and in Romania;

- Mihai-Cosmin Belciu, Silvia Fiore, Giuseppe Genon, Valentin Nedeff, Alexandra-Dana Chițimuș and Emilian Florin Moșneguțu (in press) -
Evaluation of actual and future residual fluxes deriving from two Italian MSW landfills;

- Mihai-Cosmin Belciu, Silvia Fiore, Giuseppe Genon, Valentin Nedeff (in press) - Review of mathematical models predicting leachate and biogas generated from municipal solid waste landfills;

- Cristian Radu, Alexandra-Dana Chițimuș, Gheorghe Sin, Mihaela Dascălu, Doina Capsa, Mihai Belciu, Dorel Ureche - Studies and research on Typha latifolia (bulrush) absorption capacity of heavy metals from the soil – Environmental Engineering and Management Journal;

- Daniel-Cătălin Felegeanu, Gigel Paraschiv, Mirela Panainte-Lehăduș, Mircea Horubet, Mihai Belciu, Mihai Radu, Ovidiu Leonard Turcu - An analysis of the risk assessment methods in establishments where dangerous substances are used - Environmental Engineering and Management Journal;

- Greta Ardeleanu, Mihai Belciu, Madalin Rotaru, Mariana Turcu, Mihai Deju, Camelia Ureche, Eugenia Harja - Influence of pollution factors on river Bistrita between the sections Bacău – Neamt - Environmental Engineering and Management Journal.

6. Reports and public presentations:

Polytechnic University of Turin, Italy

- Belciu Mihai-Cosmin - PhD student activity analyse and monitoring during documentation and research period in Turin - April 2014, Torino, Italia;
- Belciu Mihai-Cosmin - PhD student activity analyse and monitoring during documentation and research period in Turin - May 2015, Torino, Italia;

„Vasile Alecsandri” University of Bacau, Romania

- Belciu Mihai-Cosmin – Current state of research concerning PhD thesis titled „, Studies and research regarding the evaluation of technological aspects for the post-closure activity of landfills for municipal solid waste” – June 2014, Bacău;
- Belciu Mihai-Cosmin – Establishing research base for the evaluation of technological aspects for the post-closure activity of landfills for municipal solid waste – June 2015, Bacău;
Belciu Mihai-Cosmin – Partial results for the evaluation of technological aspects for the post-closure activity of landfills for municipal solid waste – October 2015, Bacău;

7. Research contracts


CHAPTER 12
RECOMMENDATIONS BASED ON RESEARCH AND COMPARATIVE ANALYSIS CONCERNING LANDFILLS FOR MUNICIPAL SOLID WASTE FROM ITALY AND ROMANIA

Based on research conducted, but also referring to the modality of managing analysed landfills from Italy and Romania, can be make some assumptions that serve as recommendations for landfills from Romania considered.

1. Siting, design and construction of landfill
Regarding the location of the landfill to eliminate potential environmental impact, it is recommended to carefully research the area, taking into account, in addition to existing legislation, the following aspects:
- Distance from the landfill till to the nearest surface water (river, lake, pond, etc.), given that the landfill of Bacau is located close to the Bistrita river;
- Minimum allowed distance to the upper level of groundwater;
- Minimum allowed distance to populated areas across landfill;
- Previous use of the soil over that will perform the waste storage.

Considering the design aspects, it is important to the future shape of a landfill or a cell to facilitate access for collection, transport and treatment of leachate and biogas collection.
The final shape of the deposit will consider and topography of the area where the landfill is located. The construction itself of a landfill must comply with current legislation, taking into account the proper waterproofing measures.

2. The structure of the landfill
   It is important that the landfill to be divided into cells to facilitate the leachate collection and to extract an appropriate amount of liquid from the corresponding moisture content of waste. It is recommended an analysis concerning the maximum capacity to generate products from landfill related to the surface or to the volume occupied.

3. The structure of stored waste in landfill
   Each area that feeds a landfill is specific about the types of deposited waste. In order to conduct studies on the quantities generated by products, it is necessary to know the quantity of landfilled waste types. Identification and sorting of waste composition in advance can be a starting point for the research on the characteristics of the areas in the categories of waste deposited.

4. Waste pre-sorting before disposal
   Differentiated waste collection is mandatory under the law. It is indicated and also preferably to store in landfill only those types of waste and also specific amounts that cannot be reused or recycled. This fact has the effect of reducing the storage surfaces and also obtaining profit from waste quantities that are recycled or reused.

5. The manner of waste disposal in cell and the coverage
   The waste compaction, respectively the modality of compaction of waste is an important factor on the generation of leachate and of biogas. An important element that can be periodically analysed refer to the different periodically coating layers to observe if they have a significant impact in products from landfill.

6. Leachate collection system
   For each landfill is required the leachate quantity analysis and also is important to know the leachate quantities that can be collected. In this regard, it may be advisable to monitor the drainage system for leachate from the landfill construction. Also, using recirculation operations it may identify different biogas quantities that may supplementary generate and also, the use of leachate to avoid an improper disposal of leachate that may have an significant environmental impact. By applying estimative mathematical models, it is much more easier to identify the possible quantities that may be eliminated, eliminating the risk of landfill fractures.
7. Biogas collection system
Some landfills from analysed landfills from Romania haven’t an active collection system for biogas. The accumulations of methane inside the landfill could cause explosions and thereof fractures. The estimation of biogas quantities that can be eliminated from the landfill and the monitoring of real quantities that can be collected represent two essential assumptions in the lifecycle assessment for a landfill.

8. The transport, treatment and recirculation of leachate
Leachate collection system and its transportation constitutes one of the most important steps in managing a landfill. Improper storage of leachate, and poor transport can cause accidents or environmental pollution. It can make recommendations on different ways of treatment of the leachate to reduce the amount thereof. The recirculation of leachate in the landfill solve some shortcomings of storage systems from Romania. When using recirculation removes those storage lagoons for the leachate that may have a significant impact.

9. The use of biogas
The biogas collected during active phase of a landfill can be valorised in co-generation plants for the electrical or thermal energy. It can be performed various studies on the composition of biogas and the percentage of methane from biogas on different stages of the lifecycle of a landfill.

10. The closure of the landfill
The closure of the landfill is not representing the end of life of a landfill. A proper closure of the landfill will eliminate any exchange between the body of the landfill and the environment. In this respect, it can realise different studies concerning the closure modality of a landfill and the structures of leachate and biogas collection systems.

11. Post-closure phase of a landfill.
Post-closure phase represents the time period that starts when the final isolation of a landfill begins and has a duration about 30 years. During this period, it is important to manage the leachate quantities and also the biogas quantities that can be generated, but also to manage the area and to monitor the environmental factors. It is recommended that the studies on generation capacity of biogas, respectively of leachate from landfill for this phase.
BIBLIOGRAPHY


21. Belciu M.C., Fiore S., Genon G. and Nedeff V., (2015), *Analysis of MSW landfills management operations in Italy and in Romania*.


47. Demetracopoulos A.C., Karatzas G.P. and Nawy E.G., (1987), *Production of selected contaminants from municipal solid waste landfills*. Ed. Rutgers University, New Jersey, USA.


160


68. Google Maps, (2015), *Bacău Landfill*. Available at: https://www.google.ro/maps/place/Bac%C4%83u/@46.5097335,26.9431929,1485m/data=!3m1!1e3!4m2!1s0x40b570183882e30b:0x2659d504ae13301!6m1!1e1 accessed: 24.09.2015.

69. Google Maps, (2015), *Bihor Landfill*. Available at: https://www.google.ro/maps/place/Eco+Bihor+-+Depozit+de+de%C8%99uri+Oradea/@47.1103371,21.8691025,1036m/data=!3m1!1e3!4m2!1s0x47464f2e0e764813:0xf423b15f1fde8e7!6m1!1e1 accessed: 24.09.2015.


71. Google Maps, (2015), *Italy Map*. Available at: https://www.google.ro/maps/place/Italia/@41.2135887,8.0850842,7z/data=!3m1!4b1!4m2!1s0x47355449968fa865:0x52d3dedb49e2d0b8!6m1!1e1 accessed: 24.09.2015.

72. Google Maps, (2015), *Piatra Neamț Landfill*. Available at: https://www.google.ro/maps/place/Piatra+Neam%E2%82%AC%89/@46.903437,26.4019446,20y,270h/data=!3m1!4b1!4m2!1s0x47355449968fa865:0x52d3dedb49e2d0b8!6m1!1e1 accessed: 24.09.2015.

73. Google Maps, (2015), *Romania Map*. Available at: https://www.google.ro/maps/place/Rom%C3%A2nia/@45.9419466,25.0094303,7z/data=!3m1!4b1!4m2!1s0x47355449968fa865:0x52d3dedb49e2d0b8!6m1!1e1 accessed: 24.09.2015.

74. Google Maps, (2015), *Timiș Landfill*. Available at: https://www.google.ro/maps/place/Ghizela+307205/@45.793671,21.7538446,1430m/data=!3m1!4b1!4m2!1s0x474f9a8a7a34797d:0xa9f01e06c566dc0!6m1!1e1 accessed: 24.09.2015.

81. Legislative Decree 27.09.2010 - Italy, (2010), in Italian.
84. Mancini G., (2009), Quantificazione degli impatti di una discarica: Il caso di „Cozzo Vulturo”. Dipartimento di Ingegneria Civile e Ambientale, Universita degli Studi di Catania, Enna, Italy, in Italian.