Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 119 (2017) 72–85

Energy Procedia

www.elsevier.com/locate/procedia

International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES17, 21-24 April 2017, Beirut Lebanon

Optimizing the Methodology of Characterization of Municipal Solid Waste in EU Under a Circular Economy Perspective

* ElenaCristina Rada[a,b,*], Lucian Cioca[b,c]

[a]Department of Civil, Environmental and Mechanical Engineering, University of Trento, via Mesiano, 77, 38123, Trento, Italy
[b]Department of Industrial Engineering and Management, Faculty of Engineering, Lucian Blaga University of Sibiu, Str. Emil Cioran, 4, 550025, Sibiu, Romania
[c]Academy of Romanian Scientists, Splaiul Independentei, 54, sector 5, 050094 Bucharest, Romania

Abstract

The methodology for the characterization of residual municipal solid waste (RMSW) is available since decades. Some modifications have been introduced in order to modernize it. Now, in order to take into account the targets of the circular economy, an additional effort must be made to be sure of generating the right information suitable for the optimization of municipal solid waste in that frame. In that perspective, the Authors present a few proposals in order to avoid mistakes and to deepen the reliability of the data generated during the analysis performed to classify the residual municipal solid waste in fractions. A new model of characterization is thus proposed, suitable for planning waste management in the frame of the circular economy principles.

Peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD).

Keywords: analysis; circular economy; methodology; model; residual municipal solid waste; respirometry.

1. Introduction

In the last decades, the characterization of Municipal Solid Waste (MSW) in the European Union has shown a remarkable evolution in terms of efforts made from the local management Authorities in zooming on its composition. In the same time, the increase of the rate between collected MSW and generated MSW, today very

* Corresponding author. Tel.: +39 0461282613; fax: +39 0461282672.
E-mail address: elena.rada@unitn.it

1876-6102
Peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD).
10.1016/j.egypro.2017.07.050

close to 100% in the best managed regions, simplified the efforts in assessing the quantities produced: indeed, the collected streams can be easily weighted. The growing reliability of information has positive implications on the design of the MSW treatment plants [1-3]. For that reason, the present paper focuses mainly on the methodology of MSW characterization, specifically on the characterization of the residual MSW (RMSW) that is the waste remaining after source separation. It must be pointed out that source separation (also named selective collection, SC) is compulsory in the European Union (EU) thus the methodology must see beyond the present needs of information in a region, looking at the need of a good planning for the expected scenarios of MSW management, necessarily based on high efficiency of SC. Only through a deep knowledge of the waste streams a sustainable management of waste can be performed. Before analyzing the methodology of RMSW characterization it is important to clarify what is MSW in the EU [4-8]. In practice, we must consider four main subcategories to understand what MSW is:

- Household generated waste (the household waste)
- Waste generated out of domestic building but similar to it (the assimilable waste)
- Bulky waste generated at urban level
- Waste from street sweeping

This paper will consider the methodology related to the characterization of the first two sub-categories, because they are the most important for a correct planning of the management of MSW. These two categories are collected according to the principles of SC; thus, they can be easily characterized when we deal with source separated streams (paper, glass, etc.) but they include also the fraction of RMSW whose characterization is crucial for a correct management of MSW [5,9-11]. Just to understand, an overestimation of few percentage points of the energy content of RMSW in a small region where a waste to energy plant must be constructed (e.g. an incinerator with energy recovery) can give an extra cost in its implementation that can account million Euros. It is clear that a reliable methodology for RMSW characterization is compulsory in the sector of engineering and management. In spite of that, the history of the sector showed an underestimation of the problem, with limited efforts (also from the economic point of view) when a RMSW characterization had to be performed. As an example, the literature has shown a trend in the number of fractions taken into account decade after decade but even recently the number of fractions taken into account is often around ten, with limited information for a good MSW management planning in the key of a circular economy perspective [9].

If we consider the target of the circular economy [12] we shall see that we must accept as adequate a characterization based even over 20 fractions and sub-fractions (a fraction is a class of material like paper, glass, etc.).

2. Critical analysis of the basic characterization

We can consider *basic characterization* the one referring to the following steps that can be reconstructed from the studies reviewed by Goetze [9]:

- Selecting a pathway representative of an area of RMSW generation
- Selecting a day representative of RMSW generation
- Selecting the fractions to be characterized in percentage
- Selecting additional parameters of the fractions to be characterized
- Preparing a site for the fractions characterization
- Preparing the tools for the fractions characterization
- Preparing the team for the fractions characterization
- Collecting an amount of RMSW representative of that area
- Analyzing the results in terms of fraction percentages
- Managing the additional laboratory analyses

The present paper analyzed critically the conventional approach in order to put forward some considerations to enhance it.

2.1. Selecting a pathway

Typically, the choice of this pathway is made thanks to the existing expertise of the local company managing the MSW collection; it is clear that in a context like the one of EU this company is always present. What is not clear is how to avoid mistakes in this choice, as the approach of the local company is more technical than scientific. In order to help the selection of this pathway, a support can come from the analysis of orthophotos (taken from aircrafts and post-processed) as this analysis allows classifying the urbanized territory according to homogeneous criteria.

2.2. Selecting a day

In the EU, the working days are typically from Monday to Friday (apart from specific sectors). Thus, the collection of MSW can be affected from the weekend on Monday. It is a good choice to select a central day (e.g. Wednesday) for the collection of the representative sample, obviously if this day is far from specific holidays. Early hours must be exploited for an easier collection; to this concern, time must be saved as much as possible because the following analysis needs many hours and must be performed within the day of collection.

2.3. Selecting the fractions

In this paragraph, each fraction of potential interest is discussed in order to understand its relevance in the frame of an adequate characterization of RMSW. The adequacy is related to the generation of information suitable to an optimized management of MSW through the knowledge of the contents of RMSW. The relationship depends on the fact that RSMW composition can point out the amount (in percentage) of recyclable materials that the SC strategy cannot yet separate. Merging this information with the amount of RMSW generated and with the characterization of the streams of SC (in terms of materials and weights), it is possible to assess the percentages of source separation for each material (fraction) of interest. This information allows decision makers to verify if SC is evolving well or not. Recent experiences in EU have shown percentages of SC for specific fractions that can overcome 90%. As an example, in Italy the SC of glass, green waste and wood in the Trentino region (North of Italy) overcome 90% each, since 2013 [13]. In the frame of circular economy, it is important to know in details the streams of materials that can be recovered by MSW. In previous/present scenarios when landfill was/is dominant (and/or incineration was/is dominant) the level of knowledge about the composition of MSW was not so important because, at the end, landfilling could solve the consequences of an approximate planning.

Household and urban non-household *food waste* are present together in the RMSW. That is a limitation of information if a food waste SC of only restaurants, canteen and markets is planned as a first step of source separation of this stream. In this case an additional study is needed to know data suitable to design the collection system. This double step can be useful in regions where there is no tradition in SC and the population must know gradually this option. A part of food waste can be so fragmented to be classified as a generic fine fraction (undersieve). The management of this problem (loss of information) is discussed in another section of this document.

Green waste generation is strongly seasonal thus a characterization once by year can be critical. In case of presence of an anaerobic digester in the area, the collection of significant amounts of woody waste with kitchen waste is not compatible because of the troubles that the digester could have (not compatible with lignin, present in woody material). In this case, domestic composting should be promoted to avoid co-collection of food waste and green waste. These restrictions apply for cases of significant generation of woody green waste like in private gardens. Public gardens can be managed independently from the presence of an anaerobic digester as in these areas only woody waste and grass are collected (no food waste is co-collected). Summing up, green waste must be always present as fraction of a RMSW characterization in EU. The way of performing correctly SC of green waste is sensible to the local context.

Paper and cardboard moisture can be affected by the presence of wet fractions in the RMSW. Thus, it is important to characterize this parameter locally in order to avoid mistakes generated by literature data. The importance to keep separated the cardboard stream is related to the higher commercial value of this cellulosic material compared to paper.

The interest of managing sub-fractions of *glass* related to colors (white, green, brown) is limited because it is easier for a citizen to deliver mixed glass and to take advantage on the automatic sorting that optic pre-treatments at a glassware can guarantee.

The importance to get information on the presence of *aluminium* depends on the high value of this metal. Generally, the limitation to its SC is related to the cost of collection that could not counter balance the value of collected aluminium in case of small amounts available in the MSW.

The importance to get information on the presence of *ferrous materials* depends on the good value of this metal, generally present in significant amounts that can cover the costs of collection giving also a gain, depending on the market.

A sub-fraction of *other metals* must be known to close the mass balance of metals. A recycling way should be found also for mixed metals in the vision of the circular economy approach.

Light packaging is a complex category that can be sub-classified in many ways (according to the polymers, according to the rigidness of the material, etc.). The proposed classification is related mainly to the pathways of material valorization.

- PET: this is the plastic with the highest value in the market of recycling
- HDPE: this is a plastic with a good value in the market of recycling
- PVC: this plastic should not be sent to combustion for keeping low the environmental impact of its valorization (PVC contains Chlorine in its molecule, thus it can be a potential generator of dioxin when combusted)
- *Other light packaging:* this sub-fraction must be known to close the mass balance. A recycling way should be found also for mixed packaging in the vision of the circular economy approach.

The fraction *wood* is not the woody waste present in the green waste. This fraction refers to end of life wood products coming from household buildings or from similar urban activities (e.g. toys, public offices, etc.).

Typically, in the RMSW studies, *textiles* are considered together. In reality, in this case two sub- categories must be taken into account for a correct characterization of the overall waste: *natural* fibers and *artificial* fibers. The importance of knowing their presence separately is related to the biodegradability of their volatile solids (natural fibers are biodegradable, artificial fibers are not biodegradable).

The importance of the knowledge of the presence of *leather* is related to the biodegradability of their volatile solids (even if slowly biodegradables).

The importance of the knowledge of the presence of waste from electric and electronic equipment (*WEEE*) is related to the non-biodegradability of their volatile solids (from plastics), to the dangerousness of their heavy metals and on the fact that all of them should not be present in the RMSW: a dedicated pathway of collection (at the selling points) is activated in well organized systems. An indicator aimed to assess the management of MSW should consider this presence in the RMSW as a demonstration of inefficiency.

Similarly to WEEE, the importance of the knowledge of the presence of *exhausted batteries* is related to the non-biodegradability of their volatile solids (from plastics), to the dangerousness of their heavy metals and on the fact that all of them should not be present in the RMSW as a dedicated pathway of collection is activated in well organized systems.

The importance of the knowledge of the presence of *expired medicaments* and of *contaminated containers* is related to the fact that all of them should not be present in the RMSW as a dedicated pathway is activated in well organized systems.

The fraction *inert* is not the one from significant civil works of construction/rehabilitation. They are the ones generated from domestic (or assimilable) activities. The importance of the knowledge of their presence is related to the fact that they are not combustible and not biodegradable.

A *mixed waste* fraction should be avoided at the end of the classification of the sample of RMSW, thanks to a careful classification that should locate each piece into a fraction depending on the most relevant material. The presence of this sub-fraction could be taken as a sort of indicator of presence of materials in the area not designed for recycling (because not classifiable in specific fractions).

The importance of the knowledge of the presence of *rubber* is related to its energy content.

The importance of the fraction *diapers* is growing in EU as in case of high efficiency of SC of conventional fractions, their percentage in the RMSW becomes high. In such a situation, they deserve a specific strategy in order to avoid landfilling.

Undersieve is generated by the use of a sieve with a mesh of 20 mm. The original idea in the sector was related to the presumed impossibility to separate fines. The growing attention to the quality of MSW characterization opened to new approaches. In some cases, the approach evolved towards the introduction of an additional sieve with a finer mesh: 10 mm; that cannot be considered adequate as the additional information cannot be fully exploited (materials are still aggregated). The most interesting solution was checked in Trentino [13] where the RMSW characterization analyses are made with a reclassification of the undersieve into inert and food-waste-like, that can be added to their respective fractions.

In Table 1 an overview of the criticalities is presented.

Table 1. Proposed fractions for the characterization of RMSW and criticalities/remarks or proposals (the proposals at high originality in the sector of MSW characterization are marked in **bold**; the proposals relevant for the development of an efficiency indicator are marked in *italics*)

Fractions and sub-fractions	Criticalities/remarks	Proposals
Organic*	A part of food waste is lost in the fines during the classification of RMSW	Use the term "organic*" (with a star) as sum of food waste and the percentage of undersieve (< 20 mm) that can be classified food-waste-like; keep this last information available for future checks
Green waste	Lignin in woody waste can be critical in case of treatment in anaerobic digesters	**Keep always separated from organic when classifying RMSW**
Paper	Moisture can vary a lot, case by case, because of the interaction with the wet fractions	Generate always local data of moisture for paper in RMSW
Cardboard	Moisture can vary a lot case by case because of the interaction with the wet fractions	Generate always local data of moisture for cardboard in RMSW
Glass	It is usually collected in mixed colors	**Keep the color mixed: the recycling plants can easily separate them by optic systems**
Metals: Aluminium	This fraction has a high value	**Keep this information available**
Metals: Ferrous materials	This fraction has a good value	**Keep this information available**
Metals: other	Other metals can be suitable as input in industrial processes	**Keep this information available**
Light packaging: PET	This fraction has a high value on the market	**Keep this information available**
Light packaging: HDPE	This fraction has a good value on the market	**Keep this information available**
Light packaging: PVC	This fraction can cause a significant environmental impact from combustion	**Keep this information available**
Light packaging: other	They can be suitable as input in industrial processes (possibly not combustion, in the perspective of circular economy)	**Keep this information available**
Wood	The importance of the knowledge of their presence is related to their energy content.	**Keep in the list**
Textiles: natural fibres	The importance of knowing their presence separately is related to the biodegradability of their volatile solids.	Keep separated from synthetic textiles
Textiles: synthetic fibres	The importance of knowing their presence separately is related to the non-biodegradability of their volatile solids.	Keep separated from natural textiles
Leather	It contributes to the biodegradability of the waste	**Keep in the list**
WEEE	It should be found absent in the RMSW as a dedicated pathway of collection is activated in well organized systems	**An indicator aimed to assess the management of MSW must consider its presence in the RMSW as a demonstration of inefficiency of the collection system.**

Hazardous: exhausted batteries	It should be found absent in the RMSW as a dedicated pathway is activated in well organized systems	**An indicator to assess the management of MSW must consider this presence in the RMSW as a demonstration of inefficiency of the collection system.**
Hazardous: expired medicaments	It should be found absent in the RMSW as a dedicated pathway is activated in well organized systems	**An indicator to assess the management of MSW must consider this presence in the RMSW as a demonstration of inefficiency of the collection system.**
Hazardous: contaminated containers	It should be found absent in the RMSW as a dedicated pathway is activated in well organized systems	**An indicator to assess the management of MSW must consider this presence in the RMSW as a demonstration of inefficiency of the collection system.**
Inert*	At present, it is not valorized, but it could become an input of an industrial process in the perspective of the circular economy	Use the term "inert*" (with a star) as sum of inert and the percentage of undersieve (< 20 mm) that can be classified inert; keep this last information available for future checks
Mixed waste	It should be zero thanks to a careful classification that can locate each piece into a fraction depending on the most relevant material.	**This fraction must be taken as indicator of presence of materials in the area not designed for recycling.**
Rubber	The importance of the knowledge of their presence is related to their energy content.	**Keep this fraction in the list**
Diapers	Relevant in percentage in RMSW where selective collection is high for other materials	It can be object of source separation aimed to a specific treatment when citizens are already used to conventional selective collection
Undersieve	**Its presence does not make sense for decision maker requirements**	It must be re-classified in organic (food-waste-like) or inert depending on its content

2.4. Selecting additional parameters

After the analysis of the fractions in a representative sample characterizing an area, the typical sequence of analyses for a detailed characterization of each fraction is as follows:

- Get a representative sample of 3-4 kg by a quadrant analysis (create a pie with the fraction to be reduced in weight, remove two opposite quadrants and go on with the remaining amount of waste, replicate the method until remaining with 3-4 kg)
- Send the 3-4 kg sample to a laboratory
- Get the initial weight W_i of the sample
- Use a lab dryer at 103°C to evaporate the moisture; the run could last 2 hours but the waste has a hygroscopic behavior, thus a more representative value of the final weight of the dried sample, W_d, can be obtained after a few hours.
- Calculate the percentage of moisture M%: M% = (Wi - Wd) / Wi [%]
- Calculate total solids, TS, named also dried matter, as 1 - M%
- Divide the dried sample into two sub-samples and weight them
- Put one of the dried samples into a lab oven, after getting its weight (Wd1) where to perform a combustion at 600°C
- Get the final weight Wb of the sample after burning and define that as ash, named also non-volatile solids, NVS, or ash
- Calculate the percentage of combustible matter, volatile solids, VS, named also organic matter: VS% = (Wd1 - Wb) / Wd1 [%]
- Ask to the laboratory to analyse the second sub-sample of weight Wd2 to characterize the percentage of C_{org}, H, O, N_{org}, S_{org}.
- To obtain the value of Lower Heating Value (LHV), two ways are available:
  - Use the Dulong formula (multiple sources of literature are available)

  - In alternative, use the Mahler Bomb obtaining LHV through HHV
  - There are some criticalities in the presented approach:
- No information on biodegradability is suitable by this approach (a part of VS is not biodegradable)
- The Dulong formula has strong approximations:
  - In spite of being a good way to model the waste, the Dulong formula has a limit in the reliability of the coefficients that should be specific for each fraction; on the contrary in the literature no one detailed them depending on the fraction (possibly for cost reasons as such a research will need a high number of determinations).
  - After a treatment, the coefficients should change as the structure of the material changes, but the literature does not detail it, demonstrating that the approximation of the Dulong formula is out of control.

The Biochemical Methane Potential (BMP) is an additional parameter suitable to characterise biomass, the organic, either alone or mixed in the RMSW, in term of suitability for biogas generation [14]. The interest concerns the case where an anaerobic digestion reactor is a first step before composting from source separated food waste or the case where an anaerobic pre-treatment of RMSW is planned before landfilling (the anaerobic pre-treatment of RMSW before landfilling is not common but still present in the sector: the difficulties of this approach are related to the management of the anaerobic process because of the impurities in the input). BMP can be considered an additional parameter interesting for decision makers. BMP refers to 4 weeks of biogas generation in laboratory, thus it needs time. For that reason, an original method based on the respirometric index (RI) to reduce the laboratory time has been set, together with other Authors, as alternative to conventional BMP [15-17]. BMP can be assessed according to the following principle, applicable to one of more fractions:

BMP = f(RI) $[l_{CH4}\ kg_{VS}^{-1}]$ or $[l_{CH4}\ kg_{RMSW}^{-1}]$

Details on the role of RI for the proposal of an enhanced characterization of MSW are presented in another section of this article.

2.5. Preparing a site for the characterization

In this case the risk of generating unreliable data is related to the difficulties of guaranteeing an analysis performed in a site where the meteorological condition does not affect the results and where a smoothed surface avoids the interaction between the analyzed sample and the ground (with potential contamination of inert). It is clear that in most of the EU Countries, the investment in MSW analyses can be adequate to guarantee the compliance of the above-described requirements, but in extreme cases (e.g. countries just entered into the EU; regions with a lower income; lack of expertise) the risk of affecting the results, because of an inadequate site of analyses, is real.

2.6. Preparing the tools for the characterization

The following tools are needed at the site of analysis:

- Adequate containers (labelled) for placing the pieces of each fraction when a 250 kg sample is remained to be analyzed, as a result of a quadrant analysis (pie based) starting from 4 tons; these containers must be at least of the number of the selected fractions to characterize; this does not seem a criticality.
- Adequate individual protections (not critical in the EU).
- An oversieve with a mesh of 20 mm. This can be critical from many points of view; indeed, the methodology asks to classify only the pieces having a characteristic dimension making impossible to cross the oversieve surface; the fact that the mesh is squared and is often preferred to 20 mm circular holes can introduce potential mistakes in the selection. Apart from that, it has been demonstrated [13] in the practice that the undersieve is rich in biodegradable material (similar to food waste) and the rest is generally inert. Thus, the 20 mm can be confirmed in form of hole, but something must be improved in relation to the high percentage of undersieve that in some cases can be found. A proposal to improve the detail of the overall analysis managing the undersieve has been discussed in this article.

2.7. Preparing the team for the characterization

Often during the procedure of RMSW analysis, there is an underestimation of the role of the operators generally helping a technician expert in the field. It must be underlined that the representative sample to be collected for a specific area (typically 4 tons) must be mixed correctly and the single pieces of the fractions must be managed carefully to be representative of the referring area. Moreover, the conventional methodology asks for a reduction of the initial 4 tons thanks to the formation of pies of waste with progressively reduced height: 0.6, 0.3, 0.25 m and 0.20 m with consequent diameter considering that the initial amount must be reduced down to 2 tons, 1 ton and 0.5 tons by the extraction of two opposite quadrants each time. Additionally, the presence of bulky waste (where this stream is not correctly managed within a specific organization of collection) makes it necessary the side management of this waste that must be taken into account when the final percentages of fractions must be assessed. If the team does not understand the importance of these analyses, the results could have a lower reliability. The personal devices for the protection of the operators and of the technician in charge for the analyses does not appear a criticality in a context in the EU because personal devices of protection are part of the common work in many sectors.

2.8. Collecting a representative amount of RMSW

The collection must be performed by an adequate truck, as the sample is considered representative of an area if the amount collected is around 4 tons. In a few technical reports issued in the sector, this amount is not always reached with risky consequences on the representativeness of the sample.

2.9. Analyzing the results

In this paragraph the results in terms of percentages of fractions characterizing RMSW are discussed. A typical problem concerns the representativeness of the digits of the percentages calculated. Some sub-fractions as exhausted batteries may result absent if zero decimals are assumed as standard for presenting the results. Thus at least one decimal is needed. Taking into account also the origin of the 4 ton sample, one decimal of representativeness makes sense.

There is not the habit of take photos to illustrate the samples, thus the origin of some anomalies in the data could not be found (e.g. a too low percentage of food waste).

If the results are related to an area where the MSW collection is not optimized, the bulky waste in RMSW can affect the reliability of the results.

The change of the person in charge for the quadrant analysis can be critical: this aspect must be checked always.

2.10. Managing the additional analyses

This approach (MSW modelling) should be overcome in case of waste management planning because of a few criticalities.

- The costs and limits in the representativeness of the samples aimed to know C, H, O, etc.
- The absence of adequate information on the biodegradability of the waste
- The limited reliability of the Dulong formula

Concerning the first item, the elemental analysis can be useful in case of design of specific treatment plants: e.g. S can be useful for assessing the maximum amount of Sulphur oxides to be managed in an off-gas treatment line of an incinerator. Thus, the effort in generating elemental analyses of VS could be optimized after the waste management planning stage.

A proposal for RMSW characterization is put forward in the next chapter.

3. Proposal of RMSW characterization model

An important parameter in efficient design of treatment plants and process control of biodegradable waste treatments is the biological stability of biomass [18]. This points out the degree to which the biodegradable organic matter decomposes. Thus, measurement of biological reactivity has become more and more important in the sector of MSW as it allows classification of treated and untreated MSW and derived products, prior to their disposal in landfill or to their use (e.g. compost) on the basis of their potential impact [19]. One of the most used methods for biological stability measurement is the respirometric index (RI), with a high interest encountered in the specialized literature.

The present article bases a part of the proposed RMSW characterization model on the adoption of RI as parameter suitable for generating a useful information on the biodegradability of the waste, not available in the conventional approach.

The respirometric technique is an indirect method determining the degree to which the biomass organic fraction decomposes, in relation to two important biochemical phenomena: the biological activity and the substrate consumption [20]. The respirometric method is an oxidative exothermic process, operated by aerobic microorganisms which consume oxygen with simultaneous production of water and carbon dioxide [21]. As reported by Raviv [20], the respirometric index is the amount of oxygen consumed by microorganisms per unit of present volatile solids and per time.

The respirometric tests, based on the oxygen consumption measurement, can be categorized as static or dynamic methods [21,24], measurements performed in the absence (static) or presence (dynamic) of continuous aeration of the biomass. The static methods, performed at steady volume or at steady pressure, have the disadvantage of limiting diffusion and dispersion of oxygen in the biomass; therefore, they slow down the decomposition of the organic fraction [22]. They must be avoided as they underestimate the RI. In dynamic systems, the continuous aeration of the substrate guarantees an optimum oxygen concentration for the biological activity at each moment of time [16,17, 22].

Worldwide several methods for respiration index determination are adopted [16,17]. In this frame, as explained, the dynamic method shows several important advantages, such as:

- Presence of continuous airflow during measurement which does not limit the oxygen transfer through the biomass layer;
- Possibility of working on large amounts of samples and on full-scale particle size;
- Opportunity of measuring the airflow rate required to degrade waste under optimal conditions.

For that reason, the here proposed method for RMSW characterization refers always to dynamic RI even if, in short, only RI abbreviation will be used.

According to classifications found in a research study [25]:

- RI above 3,000 $mgO^2\ kg_{VS}^{-1}h^{-1}$ are characteristic of fresh material and belong to class I of stability
- RI over 2,000 $mgO_2\ kg_{VS}^{-1}h^{-1}$ and below or equal 3,000 $mgO_2\ kg_{VS}^{-1}h^{-1}$ belong to class II
- RI over 1,000 $mgO_2\ kg_{VS}^{-1}h^{-1}$ and below or equal 2,000 $mgO_2\ kg_{VS}^{-1}h^{-1}$ are typical of materials considered to be in course of biological decomposition and belong to class III
- For class IV, RI is RI over 500 $mgO_2\ kg_{VS}^{-1}h^{-1}$ and below or equal 1,000 $mgO_2\ kg_{VS}^{-1}h^{-1}$ and the materials are moderately stable
- For values below or equal 500 $mgO_2\ kg_{VS}^{-1}h^{-1}$, which represent the Vth class, the substrate is considered biologically stable

Using the above approach the MSW can be seen no longer as the sum of C, H, O, N, S, moisture and ash, but as a sum of VS of different classes, plus moisture plus ash. It must be pointed out that moisture and ash can be easily obtained from a laboratory; VS determination needs a stove; IR determination to classify VS needs a respirometer; in this last case, for each fraction, a unique device can generate information for classifying a parameter (VS in different classes) in spite of asking additional 5 parameters from a laboratory (C, H, O, N, S). From the economic point of view, the cost for an analysis of RI is lower than the sum of analyses of C, H, O, N, S in VS.

A proposal for the VS classification of the solids of each fraction can be:

- IRVS = 0 — non-biodegradable VS: nbVS
- 0 $mgO_2\ kg_{VS}^{-1}h^{-1} < IR_{VS} \leq 500\ mgO_2\ kg_{VS}^{-1}h^{-1}$ — slowly biodegradable VS: sbVS

- 500 mgO_2 $kg_{VS}^{-1}h^{-1}$ < $IR_{VS} \leq$ 2,000 mgO_2 $kg_{VS}^{-1}h^{-1}$ averagely biodegradable VS: abVS
- IR_{VS} > 2,000 mgO_2 $kg_{VS}^{-1}h^{-1}$ highly biodegradable VS: hbVS

That must be added to:

- NVS = non-volatile solids = ash
- Moisture = the water content of the fraction

This classification allows an aggregation of the VS, ash and moisture of each fraction in order to calculate the classification of the overall waste, that can come from literature data or experimental data related to a specific case study.

What must be done to complete this proposal is to verify if a fraction could have a percentage of VS classifiable in a way and the rest in another way. Some considerations can be made for each fraction, as reported in Table 2.

Table 2. VS details in the RMSW fractions. Legend: nbVS = non-biodegradable volatile solids; sbVS = slowly biodegradable volatile solids; abVS = averagely biodegradable volatile solids; hbVS = highly biodegradable volatile solids

Fractions	VS comments	VS kind
Organic*	Putrescibility is the main characteristics of this fraction; thus, VS is always readily biodegradable (the * means that organic of undersieve is included because classificable as food-waste-like)	hbVS
Green waste	Depending of the area, VS of woody waste or VS of grass can prevail	abVS (grass) and sbVS (wood)
Paper	The class is homogeneous thus VS are steady	abVS
Cardboard	The class is homogeneous thus VS are steady	abVS
Glass	VS = 0 (impurities can be neglected)	nbVS
Metals	VS = 0 (impurities can be neglected)	nbVS
Light packaging	VS are non-biodegradable (only a negligible part of plastics is presently biodegradable, thus its role can be assumed negligible)	nbVS
Wood	Lignin is characteristic giving VS slowly biodegradable	sbVS
Textiles	Cotton or synthetic fibres give a different VS behavior; a sub-classification is needed	nbVS (synthetic) or sbVS (natural)
Leather	The class is homogeneous thus VS are steady	sbVS
WEEE	A limited presence (% in weight) of plastics makes its VS similar to the one of plastics	nbVS
Hazardous waste	Exhausted batteries: VS=0 Expired medicaments (with no packaging) would need a local characterization but its presence could be negligible Contaminated containers: would need a local characterization but its presence could be negligible	Negligible
Inert*	0 (the * means that inert of undersieve is included)	nbVS
Mixed waste	A careful re-classification of what is not firstly classified makes it negligible the role of this fraction	Negligible
Rubber	The class is homogeneous thus VS are steady	nbVS and/or sbVS depending on the rubber origin
Diapers	In order to know the kind of VS characterising this fraction, an original research should be performed	nbVS, abVS and rbVS

By this way IR runs are potentially limited even to zero when the classification of the RMSW in fractions is very detailed, containing the cost of the characterization (details on local composition of green waste, textiles, rubber and diapers could allow avoiding analyses).

In Figure 1 the scheme of the MSW characterization is reported.

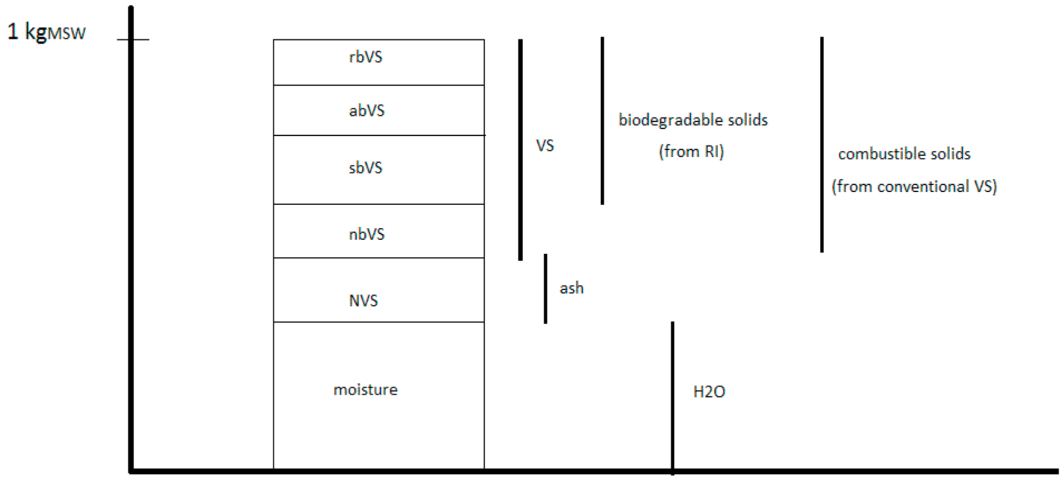

Figure 1 Scheme of the MSW model (valid also for a specific fraction)

We talked about the Dulong limits. Luckily, the use of LHV for each fraction is already present in the literature. However, literature data can be wrong; indeed, what must be taken into account is:

- Organics moisture can vary significantly from region to region, thus a lab run by the Mahler Bomb is useful
- Depending of the area, woody waste or grass can prevail giving a different energy content to the fraction; a lab run by the Mahler Bomb is useful
- Paper and cardboard moisture can vary significantly from region to region, thus lab runs by the Mahler Bomb are useful
- Light packaging is a mix of polymers with different composition; a lab run by the Mahler Bomb could be useful
- Textiles have a different LHV depending on the fiber, natural or synthetic; lab runs by the Mahler Bomb are useful if specific LHV are not available from the literature

Summing up, the use of LHV for characterizing each fraction must be preferred to the Dulong approach and lab analyses through the Mahler Bomb must be preferred as more reliable at local level.

For the proposed scheme an example of characterization is shown in Table 3 [26].

Table 3. LHV of waste fractions (1 kcal = 4.186 kJ).

Fractions	kcal/kg
Food waste (before addition of the contribution of undersieve)	951
Green waste	1,065
Paper	2,748
Cardboard	2,748
Glass	0
Metals	0
Light packaging	7,527
Wood	3,500
Textiles	3,489
Leather	3,489
WEEE	835
Hazardous waste	4,000

Inert (before addition of the contribution of undersieve)	0
Mixed waste	4,500
Rubber	7,000
Diapers	2,850
Other (undersieve before re-classification into organic and inert)	600

In the literature, a variable attention is put to the composition of NVS. In reality, the growing importance of solid recovered fuel (SRF) in the MSW management in EU, also as expected result of the implementation of circular economy strategies, makes it necessary to characterize at least the content of Cl and Hg [27-32]. In the UNI CEN/TS 15359 the SRF is classified in 5 categories according to 3 specific parameters: Lower Heating Value, Cl and Hg. The first one takes the meaning as economic parameter, the second one as technical parameter related to corrosion problems and the latter as environmental parameter.

Summing up, the energy characterization of RMSW could be based on the scheme of Figure 2.

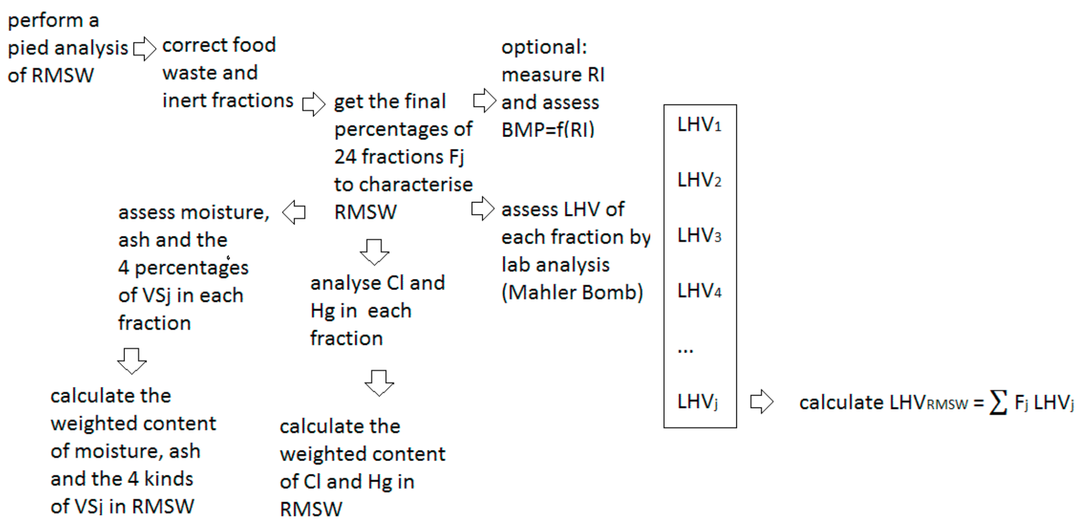

Figure 2 Scheme of the proposed energy characterization of RMSW

4. Expected results

The main practical expected result is the avoiding of underestimation/overestimation of the streams of RMSW; a wrong knowledge of its composition gives a risk of heavy diseconomies because:

- we could have to face with emergency conditions where locally there is not the possibility to treat the waste generated; the adoption of the proposed methodology helps avoiding this criticality;
- we could have to face with loose of money because we could have less waste as input than the expected; the proposed methodology prevents towards this risk;
- we could have a constructed plant with an extra-capacity not exploitable; if a public Administration can demonstrate the availability of correct data for plant design, it can attract easier private investors.

5. Conclusions

This article demonstrates that RMSW characterization in an EU context needs more attention compared to the past. The risk in keeping the conventional approach is to generate information inadequate for a correct design of the management system, both in terms of collection and in term of treatment of RMSW. Indeed, in the past the role of landfill was central in MSW management giving the possibility to have a flexible destination for all the waste not valorized. In that scenario, an underestimation of the capacity of a plant to be implemented was not so critical as today. In fact, the present role of landfill, to be minimized according to the circular economy principles, makes compulsory the construction of treatment plants with precise capacities, suitable for treating exactly what is not source separated; direct landfilling is no longer viable for the authorization point of view (the circular economy principles confirm that). Summing up, it is important that the sector plans the optimization of MSW valorization adopting a model of characterization more detailed than in the past. This effort would cost order of magnitude less than the money that could be wasted in wrong designs of treatment plants. The recent indication of the EU that asks for a threshold limit of landfilling set at 15% of the generated MSW makes it compulsory the generation of data to implement a model of MSW characterization like the one proposed in this article. Additional benefits of the model are related to the deep knowledge of the streams of materials collected from MSW that can have a valorization according to the EU targets of the circular economy.

References

[1] Ranieri E, Montanaro C, Ranieri AC, Campanaro V, Cioca LI, Municipal solid wastes in the South-Eastern Mediterranean region: Quality, quantity and management, Quality - Access to Success 2017, 18:162-169.

[2] Vivekananda B, Nema AK, Forecasting of solid waste quantity and composition: A multilinear regression and system dynamics approach, Int J Environ Waste Manag 2014, 13(2): 179-198.

[3] Ragazzi M, Rada EC, Effects of recent strategies of selective collection on the design of municipal solid waste treatment plants in Italy, WIT Transact Ecol Environ 2008, 109:613-620.

[4] Edjabou ME, Jensen MB, Götze R, Pinvenko K, Petersen C, Scheutz C, Astrup TF, Municipal solid waste composition: Sampling methodology, statistical analyses, and case study evaluation, Waste Manag 2015, 36:12-23

[5] Ciuta S, Apostol T, Rusu V, Urban and rural MSW stream characterization for separate collection improvement, Sustainability 2015, 7(1):916-931.

[6] Bing X, Bloemhof JM, Ramos TRP, Barbosa-Povoa AP, Wong CY, van der Vorst JGAJ., Research challenges in municipal solid waste logistics management, Waste Manag 2016,48: 584-592.

[7] Mazzanti M, Nicolli F, Waste dynamics, decoupling and ex post policy effectiveness: Evidence from the EU15, Int Global Environ Issues 2011, 11(1): 61-78

[8] Vehlow J, Bergfeldt B, Visser R, Wilén C, European Union waste management strategy and the importance of biogenic waste, J Mate Cycles Waste Manag 2007, 9(2): 130-139.

[9] Götze R, Pivnenko K, Boldrin A, Scheutz C, Astrup TF, Physico-chemical characterisation of material fractions in residual and source-segregated household waste in Denmark, Waste Manag 2016, 54:13-26.

[10] Consonni S, Giugliano M, Massarutto A, Ragazzi M, Saccani C, Material and energy recovery in integrated waste management systems: Project overview and main results, Waste Manag 2011, 31(9-10): 2057-2065.

[11] Bianchini A, Pellegrini M, Saccani C, Material and energy recovery in integrated waste management system - An Italian case study on the quality of MSW data, Waste Manag 2011, 31(9-10): 2066-2073.

[12] EU, 2015: http://ec.europa.eu/environment/circular-economy/

[13] PAT (2016), Internal database, Waste Office.

[14] Owens JM, Chynoweth DP, Biochemical methane potential of municipal solid waste (MSW) components, Water Sci Technol 1993, 27(2): 1-14.

[15] Morosini C, Conti F, Torretta V, Rada EC, Passamani G, Schiavon M, Cioca LI, Ragazzi M, Biochemical Methane Potential assays to test the biogas production from the anaerobic digestion of sewage sludge and other organic matrices, WIT Transact Ecol Environ 2016, 205:235-243.

[16] Ciuta S, Antognoni S, Rada EC, Ragazzi M, Badea A, Cioca LI, Respirometric index and biogas potential of different food and agricultural discarded biomass. Sustainability 2016, 8(12): 1311.

[17] Antognoni S, Ragazzi M, Ionescu G, Passamani G, Zanoni S, Rada EC, Torretta V, Respirometric index as a tool for biogas generation production from poultry manure. Manag Environ Quality 2016, 27(3): 269-280.

[18] Ionescu G, Marculescu C, Badea A, Alternative solutions for MSW to energy conversion. U.P.B. Sci Bull 2011, 73(3): 243–254.

[19] Rada EC, 2014. Energy from municipal solid waste. WIT Transact Ecol Environ, 190: 945–958.

[20] Raviv M, Can the use of composts and other organic amendments in horticulture help to mitigate climate change? Acta Horticulturae 2015, 1076: 19-28.

[21] Pognani M, Barrena R, Font X, Adani F, Scaglia B, Sánchez A, Evolution of organic matter in a full-scale composting plant for the treatment of sewage sludge and biowaste by respiration techniques and pyrolysis-GC/MS. Bioresour Technol 2011, 102: 4536–43.

[22] Scaglia B, Adani F, An index for quantifying the aerobic reactivity of municipal solid wastes and derived waste products. Sci Total Environ 2008, 394: 183–91.

[23] Chantou T, Feuillade G, Mausset D, Matejka G, Application of stability indicators for the assessment of the degradation of residual household waste before landfilling, Waste Manag Res 2016, 34(12): 1283-1291.

[24] Adhikari BK, Trémier A, Barrington S, Martinez J, Biodegradability of municipal organic waste: A respirometric test, Waste Biomass Valoriz 2013, 4(2): 331-340.
[25] Spanjers H, Vanrolleghem P, Olsson G, Dold P, Respirometry in control of the activated sludge process. Water Sci Technol 1996, 34:117–126.
[26] Rada EC, Zatelli C, Energy content of SRF from RMSW in the Trentino Province as results of biowaste collection strategies. International Symposium on Waste and Biomass Valorization, Venice, 2014.
[27] Passamani G, Ragazzi M, Torretta V, Potential SRF generation from a closed landfill in northern Italy, Waste Manag 2016,47:157-163
[28] Rada EC, Present and future of SRF, Waste Manag 2016, 47: 155-156
[29] Nasrullah M, Vainikka P, Hannula J, Hurme M, Kärki J, Mass, energy and material balances of SRF production process. Part 3: Solid recovered fuel produced from municipal solid waste, Waste Manag Res 2015, 33(2): 146-156.
[30] Flamme S, Ceiping J, Quality assurance of solid recovered fuels (SRF), ZKG Int 2014, 67(5): 54-57.
[31] Flamme S, Geiping J, Quality standards and requirements for solid recovered fuels: A review, Waste Manag Res 2012, 30(4):335-353.
[32] Lorber KE, Sarc R, Aldrian A, Design and quality assurance for solid recovered.