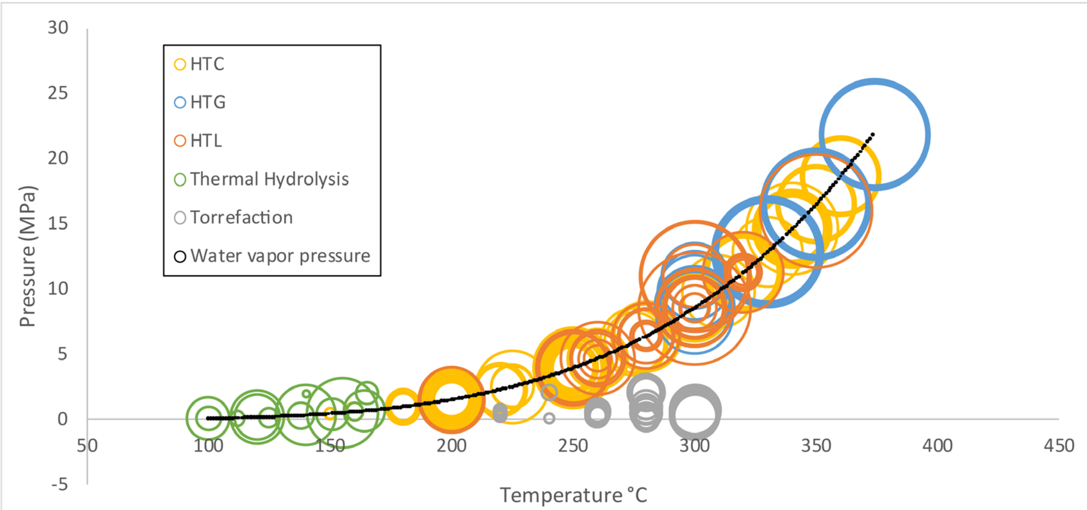
LICENTIATE THESIS

Treatment oriented waste characterization



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Waste Science & Technology

LULEÅ UNIVERSITY OF TECHNOLOGY

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Abstract

New types of materials and products are developed every day, and subsequently, new types of wastes. At the same time, new regulations are put forth to protect human health and the ecosystems from the negative impacts of wastes. Often, the waste management industry is responsible to deal with these problems, and hence, good knowledge about wastes and their treatment is crucial. Waste is normally characterized in order to determine a treatment; however, this usually implies a known treatment method.

This thesis aims to provide a structured approach about how to describe different treatments, and to provide guidance on how to characterize wastes in a solution oriented manner. A distinction is made between two types of treatments: those based on separation processes and those based on transformation processes, as well as combinations of the two. Separation processes are common in mechanical treatment such as sieving or air-classification. Transformation processes are common in such treatments as shredding, electroporation, radiation treatment, and stabilization. Most treatments consist of both a transformation and a separation process, such as incineration, in which the organic carbon is oxidized (transformed) into CO_2, that then is separated from the remaining solids. Other examples of combined processes are composting and anaerobic digestion.

A framework is presented that enables a quantitative description of different waste treatments such as anaerobic digestion and incineration in the same context. All transformation processes take place in an environment that can be described by environmental factors such as temperature, pH, redox, radiation etc. By relating different treatments or observations to each other in an n-dimension matrix, it is possible to not only locate the currently known treatments, but also to locate unexplored areas, i.e. combinations of environmental factors that could be used to treat wastes in new ways.

The addition of the n-dimensional framework to the general characterization model, together with the “top down” strategy for characterization provide valuable insights useful for dealing with new types of wastes in an efficient manner.

List of papers

Paper I: Marklund, E., Andreas, L., Lagerkvist, A., (In manuscript). The impacts of environments on waste: Part 1: The influence of thermal environments on organic wastes – *Literature review*.

Paper II: Marklund, E., Andreas, L., Lagerkvist, A., Float-sink separation of construction and demolition waste fines, *Detritus,* ISSN 2611-4135, Vol. 3, p. 13-18

Paper III: Marklund, E., Andreas, L., Lagerkvist, A., (Submitted to *Waste Management*). Characterization and mechanical separation of organic matter in construction and demolition waste fines

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Contents

1. Introduction

Solid wastes may be considered the detritus of society, and as such, they typically are a heterogeneous mix of the various materials the society once consisted of. Wastes are produced by all activities, and as complexity increases in modern society, so does the complexity of the wastes. New materials, especially compound materials are often difficult to recycle. In some processes different materials are mixed, such as during the demolition of buildings or cars, creating waste materials that are difficult to manage. Wastes have to be managed by some process in order to avoid uncontrollable spreading into our ecosystems. It can be managed through various treatment methods, ranging from simple dumpsites, to advanced material recovery systems.

In order to properly manage wastes and to select treatment methods, the properties and characteristics of the waste need to be known. Thus there is a need for waste characterization, which can be undertaken both to find out the content or properties of a waste, e.g. content of carbon, heavy metals, pH, density etc., and the behavior of the waste. The content of a substance in a waste gives little information on its behavior. For example, as shown in *Paper III*, the carbon content has little or no bearing on the actual behavior in an aerobic or anaerobic process. Another example is the leaching of metals, which can be low, even though the total content of metals is rather high, as shown in *Paper II*. Characterization should therefore also provide information on actual behavior, rather than just content. Typical assays for estimating waste behavior in different environments include leaching tests, thermogravimetric analysis (TGA), and biochemical methane potential (BMP) tests. However, there are many different characterization assays available, and choosing characterization assays are not always trivial. Doing analyses is costly and should be done as efficiently as possible.

A waste characterization model is described by (Bergman, 1996; Lagerkvist, 2003) (Figure 1). However, this model and other literature on waste characterization e.g. (Lagerkvist, Ecke and Christensen, 2010) provides mainly information on characterization assays, or on characterization results e.g. (Tchobanoglous and Kreith, 2002). This provides little insight into the selection of characterization assays. Standards exists (e.g. EN 16123, (2013)) that should aid the choice of screening methods in order to characterize wastes. *Paper III* shows a broad characterization effort, eventually concluding that the waste may be treated mechanically. From a treatment selection perspective, additional characterization assays such as TGA provide no information about that specific mechanical treatment. This shows the need for characterization to be treatment oriented to avoid unnecessary analyses.

Typically when choosing a treatment, a clear knowledge of all treatment options is implied. The characterization model (Figure 1) also implies a known treatment goal. However, new types of wastes emerges continuously, and regulations on treatment change. At the same time, there is pressure from legislators to move upwards in the waste hierarchy, towards new treatments, to increase material recycling and move away from landfilling and waste-to-energy. Thus waste treatment is a moving target, and getting an overview of all viable treatment options becomes more difficult.

Proper structuring of treatments can be of help for treatment selection. In *Paper I*, a framework to structure different treatments is presented. By arranging treatments according to the environment in which the treatment takes place, different treatments can be compared, and unexplored areas can be revealed. However, not all treatments are based on a transformative environment. Mechanical treatments such as shredding, milling, sieving/screening, and optical sorting cannot easily be described in the 'environmental framework' presented in *Paper I*.

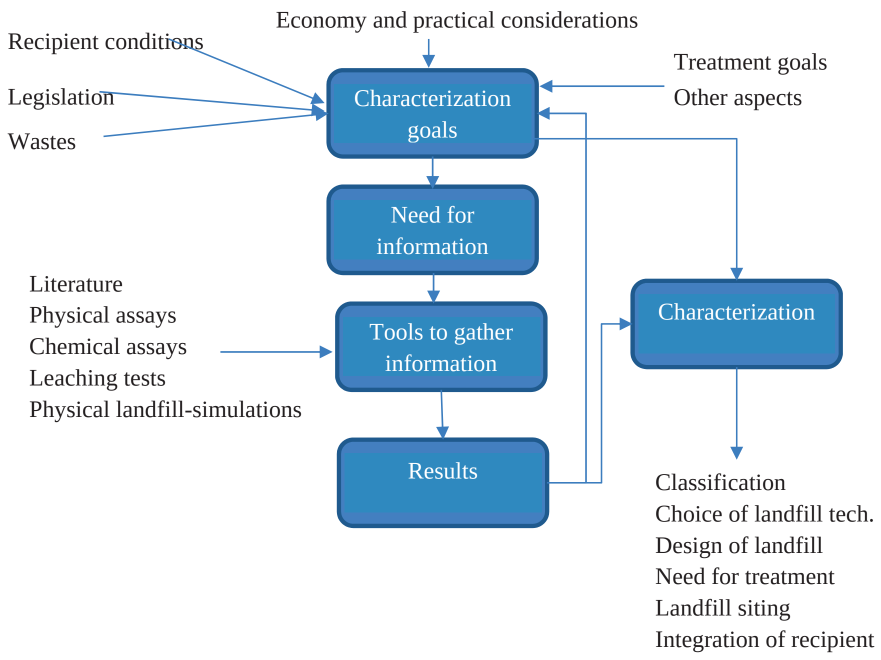

Figure 1 Waste characterization-working model. Adapted from (Lagerkvist, 2003).

1.1. Objective

The objective of this thesis is to add to the framework shown in Figure 1, and provide a structured approach on how to describe treatments and do characterization. The aim is to answer the following research questions:

- How can all types of waste treatment methods be systemized to show both known treatments and where there are possibilities for innovation?
- How can wastes be characterized to determine a proper treatment employing as few analyses as possible?

2. Results and discussion

2.1. Waste treatment

There are many definitions of waste treatment. Reforsk (1998) defines treatment as an activity where the properties of the waste are changed. The Swedish Center of Technical Terminology defines treatment as “procedures involving changes in the properties of waste” but also states “Waste treatment can be subdivided into separation and processing [“konvertering” in the Swedish translation in the book, meaning conversion]” (Selander, 1977). European law takes a broader approach to waste treatment and states “‘treatment’ means recovery or disposal operations, including preparation prior to recovery or disposal;” (European Council, 2008). ASTM (ASTM D5681-17, 2017) and the landfill dictionary, published by the IEA (international energy agency) and ISWA (international solid waste association) (Lagerkvist, 1997) provides no definition of treatment or waste treatment. In this thesis the terms transformation and separation are used, and the broad definition of treatment made by The Swedish Center of Technical Terminology.

There may be several goals when treating waste, but inertization may be considered the primary goal (Bilitewski, Härdtle and Marek, 1997), i.e. to end up with a material that is inert and does not react with its environment. Another goal is mass reduction, although a system perspective is necessary to not just move or worsen the problem elsewhere, e.g. incineration of waste leaving oxidized ashes leaching heavy metals.

A waste treatment process may be considered a process with one or more steps in which waste is treated to achieve a goal. More precisely, a waste treatment may be said to consist of at least one of either a separation process and/or a transformation process, according to the definition above.

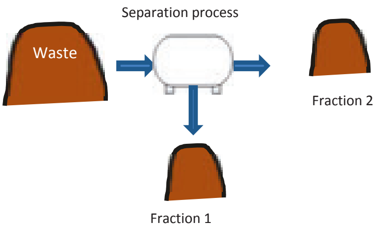

Figure 2 A separation process

Figure 2 shows a model of a separation process. In such a process, wastes are separated into their constituents, depending on differences in particle size, density, color, elemental composition etc. Examples include sieving, magnetic separation, air classification, optical or robotic sorting. The properties of the two fractions will differ, but the property of each particle will not change during the separation process.

Separation could also occur after a transformation process (Figure 4) or in a combined process (as described below (Figure 5)). One example is anaerobic digestion, where reduction of organic compounds (the transformation process) results in the formation of methane (CH_4). The CH_4 moves through the waste body by a series of processes including convection and due to buoyancy forces, thus becomes separated from the solid matrix from which it originated.

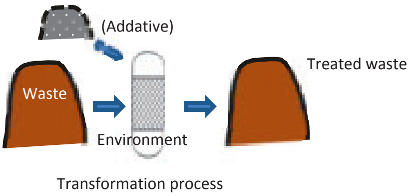

Figure 3 Transformation processes

Transformation processes occur when waste is subjected to an environment, which influences the waste and changes the properties of the particles or waste body. The environment is sustained by energy and/or mass flows into the point of transformation. Examples of transformation based waste treatments include crushing, electroporation, radiation treatment and stabilization.

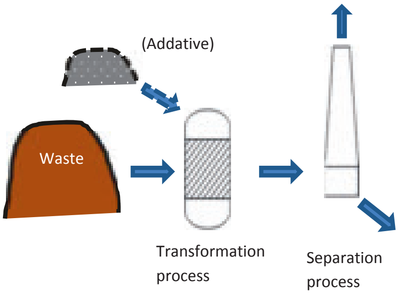

Figure 4 Combination of transformation and separation

Figure 4 shows a generic process consisting of both a transformation and separation process. Most waste treatments includes both of these processes, e.g. composting, anaerobic digestion (AD), pyrolysis, incineration etc. An example of this occurs in a waste incineration process, where the properties of carbon change during oxidation, from being bound in a solid or liquid matrix to eventually being transformed into CO_2 which is separated trough different transport processes such as advection from the remaining solids (the ash).

2.1.1. Separation processes

Separation processes divide the material into two or more fractions. As no transformation takes place, no difference in the total reactivity of the waste can be expected. This means that the purpose of a separation process is not an intertization of the material, but rather to achieve a volume reduction, i.e. to reduce the amount needing further treatment, or to produce a fraction needing no, less or different treatment.

Separation by differences in particle size and density are two common methods to separate wastes. Large particle size typically means low specific surface area, and a smaller surface area leads to fewer possibilities for chemical and physical interaction. This means that in many cases large particles are not expected to take part in reactions with the contaminating substance to any significant extent, and therefore can be separated from the waste and be recycled or require less further treatment. The low specific surface area also makes a physical separation process more efficient compared to transformation based treatments, as it takes relatively more effort to make large particles react, than to just remove them.

Separation by density alone is typically not possible, as most density-based treatments depend not only on density, but also of the size, shape and weight of the particle (USEPA, 1995). As particle size is important for both these groups of separation methods, size can be considered “master variable” when describing these separation processes. Dermont et al, (2008) gives an overview of different separation methods used in soil treatment, sorted by particle size.

Excavators are typically used to sort bulky and large items. Robotic or manual sorting can also be used. As machines or laborers can perform a limited number of picks per time unit, the material value and running cost will determine the minimum particle size. A typical minimum size for a robotic sorting facility is 100 mm (Borkowski, 2016). Float-sink separation has been shown to be useable for <40 mm material (*Paper II*), however, it has virtually no upper limit. Air-classifiers are capable of dealing with particles >500 mm (Norditek, 2018).

Wastes containing too small particles to be separated by a grab sorting can be sorted by a difference in other properties. Virtually any property where there is a large difference within the material can be used for separation. Using density separation, a difference in density of 1 kg dm^{-3} is recommended (Gosselin, Blackburn andBergeron, 1999). Other examples of separation methods are magnetic separators and optical separators. Separation by size or density is most common and there is a variety of equipment, including screens, ballistic separators, air classifiers, and wet separators including float-sink separators and hydrocyclones (Bilitewski, 2010). Trommels are common types of screens suitable for 10-160mm particles (Barton, et al., 1985), down to 6 mm (Dermont, et al., 2008). The finer the screen the more fragile it is, and the throughput is limited for small size fractions.

In the range of 6.3 µm and up to several millimeters, wet separation methods are suitable, such as hydrocyclones or wet screening. Clay and fine silt rich materials are difficult to treat in a separation process (Dermont, et al., 2008). However, smaller particle sizes typically mean larger specific surface areas, and a larger surface area means higher reactivity. This makes a treatment process that changes the properties of the material more suitable. The opposite is valid for larger particles; they are less affected by transformation processes, as previously discussed.

Table 1 Particle size ranges suitable for different types of mechanical separation

<6.3 µm	6.3 µm-10 mm	10-100 mm	>100 mm
Not suitable for mechanical separation	Wet separation (hydrocyclones, sedimentation)	Dry automated separation (screens, air classifiers, etc.)	Grab-sorting, float-sink, air classifier

Any possibility of physical separation should be tested first, since the separation processes usually are simpler than transformation processes. Any further need for treatment typically requires a change of properties of the waste, achieved by subjecting it to an environment in a transformation process.

2.1.2. Transformation processes

If separation of the waste into manageable fractions is not possible, transformation is needed to change its properties or behavior. Transformation processes occur in an environment, which can be more or less controlled. The energy and mass flows to and throughout the treatment volume can be forced or natural, and consequently, the environment can change naturally during the treatment process, as elements are consumed in the transformation reactions. To create a uniform environment across the entire waste matrix and to increase mass transport of both reagents and resulting products as well as to prevent the formation of “hot-spots” inside the treatment volume, steps should be taken to mix the waste during the transformation process. Examples range from turning of composting windrows to fluidized bed combustion.

The effects of an environment on a certain waste type can be studied in a structured way, as done in *Paper I*. There, an attempt is made to map the degradation of organic wastes when it is exposed to different environments. To structure and relate different treatment environments to each other, they can be arranged in an n-dimensional framework. *Paper I* shows the example of thermal treatments, but virtually all types of transformation processes can be structured in this way. Figure 5 shows an example of how a few observations of biological treatments can be arranged. Actual processes normally occur across an interval, as suggested by the aerobic respiration/composting, and methane formation observations.

Structuring information this way makes it easy to locate knowledge gaps, and thus to locate room for innovation, as discussed in *Paper I*.

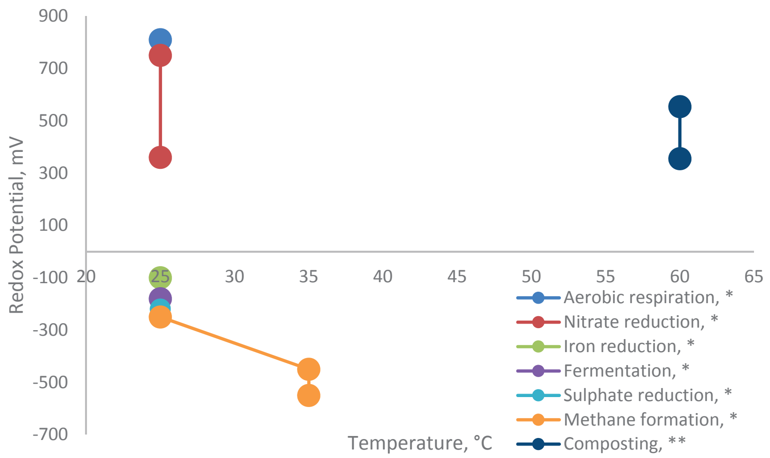

*Figure 5 Observations of biological treatments in the Redox Potential/Temperature plane. *(Lagerkvist, 2003), **(Katayama, et al., 1987)*

Mechanical transformation processes

Mechanical transformation processes such as crushing, milling etc. are processes that changes the properties of the waste, such as the particle size. However, it is difficult to describe these transformation processes in terms of the surrounding environment. One way to fit these treatments into the n-dimensional framework is by regarding the transformation process as a microenvironment. An example is ball milling of soil contaminated with PFOA (Perfluorooctanoic acid). Ball milling is a mechanochemical process that degrades the contaminant. The PFOA is transformed and broken down into fluoride, sulfate and other components (Zhang, et al., 2013), meaning it can be defined as a transformation process. Many different processes occur during ball milling, including tribochemical phenomena such as triboplasma generation (Ross, et al., 2018). These tribomechanical processes create small local spaces – microenvironments – of elevated temperature, photon emissions etc. (Nakayama, 2013). Temperature and photon radiation can be considered environmental factors that span an environmental space (an n-dimensional framework), in which ball milling then can be compared to other treatments. Other mechanical treatments such as shredding can be thought of in the same manner using microenvironments, in which particles locally are subjected to, in that case, shear forces.

2.2. Waste characterization – what is it?

Waste characterization is the process of determining the characteristics of a waste, typically done by employing one or more tests of relevance to the problem at hand. The complexity of a characterization assay can range from simple human sensory observations, to analyses using advanced equipment requiring highly specialized knowledge. Many characterization assays are standardized by national or international standardization institutes such as the International organization for standardization, ISO (https://www.iso.org/), European committee on standardization, CEN, (https://standards.cen.eu/), the American Society for Testing and Materials, ASTM, (https://www.astm.org/) or the Swedish Standards Institute, SIS, (https://www.sis.se/). A search in the CEN and SIS databases gives hundreds of hits explicitly regarding characterization of wastes.

When working with new wastes for which there is no obvious treatment and a myriad of analyses and tests to choose from, a characterization strategy is needed. One strategy is to take a “bottom up” perspective, acquiring an intimate knowledge of the waste by employing a broad spectrum of characterization assays in order to suggest a treatment. Taking a “top down” perspective instead would be to let the inner workings of a treatment processes govern the need for characterization – a *treatment oriented waste characterization* strategy. In such an approach, a few basic characterization assays are suggested, after which the characterization is focused towards a specific treatment – and starting by investigating separation based treatments.

2.2.1. Basic characterization

In order to get a basic knowledge of the waste properties, some basic, inexpensive waste characterization assays should always be done for all wastes under study. Four basic characterization tests have been suggested (Johansson and Fällman, 1995): Optical assessment, particle size distribution, density measurement and water content measurement. Other human sensory organs could also be used as an inexpensive and quick method. Characterization by smell is mandated in some landfill acceptance regulation e.g. (NFS, 2004), in order to indicate petroleum or biologically active contents. Touch is used to assess soil particle sizes (Butler, 1955; Gerrard, 2000) and get a feeling of the general texture of the waste. Taste was used in early chemistry to characterize materials, e.g. (Berzelius, 1808); however, this is not recommended as a waste characterization method today due to the health hazards.

An analysis of particle size distribution is typically done by sieving. Sieving will provide more opportunities to assess the contents of the waste, as more of it is visible for the person doing the sieving. Sieving will not only provide information for selection of treatment; in a laboratory setting it will also provide information on the need of waste comminution for further analysis. However, due to health hazards not all wastes are suitable for sieving, such as wastes containing mercury or other hazardous volatile components.

Knowing the bulk density is useful when transporting, storing or processing the waste. It can be measured by filling a container with a known volume with waste and measuring the weight, as shown in (ASTM E1109-18, 2018) for example.

Water content is given by analysis of Total Solids (TS), which can be analyzed by measuring the mass before and after heating a sample to 105°C, as described in for example (SIS, 1981). Loss on ignition (LOI) is discussed below (section *Thermal treatment characterization assays*).

Wastes typically contain potentially hazardous substances. Unless this information is provided by the waste producer, in addition to the four basic characterization tests, a fifth basic characterization assay is suggested to be one to assess the contents of this potentially hazardous substance, e.g. total content of heavy metals, PFOS, PAH etc.

A summary of characterization assays in the preferred order is shown below.

- Optical/sensory characterization
- TS/LOI
- Density, Sieving (in any order)
- Waste specific contaminants (if applicable)

2.2.2. Characterization and separation

In order to investigate the suitability of sieving or screening, standardized procedures on how to determine particle size distribution (PSD) exists, e.g. (CEN, 2012). Mesh sizes corresponding to the different soil texture classifications (i.e. sand, gravel, silt/clay etc.), typically 0.063, 0.2, 0.63, 2.0, 6.3 and 20 mm can be used. In a practical setting, more sieves can be added to suit the recycling/treatment equipment used.

Characterization of the density gradients of heterogeneous material with large particle sizes can be done by bench scale float-sink separation, see *Paper II*. Montero, et al., (2010) used various liquids with densities between 1.0 g cm^{-3} and 2.28 g cm^{-3} to investigate the density of mixed CDW. Elutriation columns, jugs and shaking tables are other lab test equipment that is suitable, see (USEPA, 1995).

The Swedish Geotechnical Institute (SGI, 2008) provides a comprehensive overview of many different physical measurements and assays, including tests for density and PSD.

2.2.3. Characterization and transformation

Waste characterization can provide information not only about the inherent properties of a waste such as elemental composition, particle size distribution, surface area etc., but also about the behavior of a waste when acted upon by surrounding forces in an environment. This can be done by subjecting the waste to a certain environment, in a smaller or larger size test. Some tests has been scaled down and refined and many of them are more or less standardized, such as TGA, BMP, RA4 (Respiration Activity over four days) etc. Examples of characterization assays for different treatment environments will be given below.

Thermal treatment characterization assays

Observations on 63 of the research articles studied in *Paper I* provide information on characterization assays typically used when studying thermal treatments of organic wastes. Selected characterization assays related to organic separation or transformation in solids are discussed below. Other analytical techniques commonly used are gas chromatography and Fourier transform infrared spectroscopy (FTIR).

Proximate and ultimate analyses are two types of assays, and the most common characterization assays done, with ultimate analysis being done in 59% of the studied articles. Ultimate analysis is defined in ASTM D3176, ISO 17247 and others, and covers the analysis of the content of carbon, nitrogen, hydrogen, sulfur, ash, and by difference oxygen. Proximate analysis typically includes analysis of moisture, volatile matter, fixed carbon and ash by heating a sample to different temperatures in oxidizing or inert atmospheres. Although proximate analysis is standardized (ASTM D3172) and often used in the field of energy and fuels, the term has been used also for other approximate composition analysis, such as methanol, glycerol and fatty acid methyl esters when characterizing crude glycerol for bio-diesel production (Onwudili and Williams, 2010). Proximate analysis is used differently in different fields. Woodman (1900) reviewed the proximate analysis used in analytical chemistry on various topics such as "On the Determination of Volatile Combustible Matter in Coke and Anthracite Coal.", "On the Rancidity of Fats" and "Chemical Methods for Ascertaining the Lime Requirement of Soils". However, when investigating phenomena related to the thermal environment, the ASTM definition (or equivalent) should be used to avoid confusion.

Thermogravimetric analysis (TGA) is a characterization assay used in 29% of the investigated literature, and involves heating a sample at a specified rate from room temperature to about 1000°C, while simultaneously analyzing the mass of the sample. TGA is a versatile characterization assay that can provide a lot of information in a single analysis, especially when combined with DTA/DSC (differential thermal analysis/differential scanning calorimetry) and/or mass spectroscopy. A thermogravimetric analyzer can be used to for proximate analysis, as observed in (Medic, et al., 2012; Brachi, et al., 2017), for which there is a standardized procedure (ASTM D7582). TGA can be done in pressurized (Brachi, et al., 2017) and vacuum (Ashby, et al., 1975) environments. This makes it possible to emulate different environments along the temperature, pressure and redox dimensions discussed in *Paper I*.

The content of total organic carbon (TOC) is characterized by oxidation of a sample at high temperatures using oxygen gas, after the removal of the inorganic carbon (carbonates) by acid addition. This can be done for solids or for liquids, then sometimes called DOC, dissolved organic carbon. Organic carbon can also be analyzed by oxidizing the carbon using potassium dichromate according to the Walkley-Black method (Walkley and Black, 1934), as done by (Mendez, et al., 2009). In the 63 studied articles, these organic carbon analyses are the second least used characterization assays of those discussed here. This could be because ultimate analysis (as described above) gives almost the same information on the carbon content, especially for low carbonate wastes such as biomass.

Loss on ignition (LOI) measures the mass loss when a dry waste is heated to hundreds of degrees for a few hours. Mendez, et al., (2009) did LOI at 540°C for 4 hours, (Neyens, Baeyens and Creemers, 2003; Neyens, et al., 2003) analyzed organic dry solids (ODS) at 605°C, and (Strong, McDonald and Gapes, 2011) measured volatile suspended solids (VSS) according to the American standard (APHA, WEF and AWWA, 1998) at 550°C. In *Paper II & III*, the Swedish standard (SIS, 1981) is used, burning the samples at 550°C for 2 hours. Compared to ultimate and proximate analysis, this assay is found to be the least coherent assay, with different temperatures, durations and even names used. The LOI assays are typically referred to in articles related to sludge and anaerobic digestion. The proximate analysis also measures volatiles, but at 950°C. Depending on the waste, different temperatures are more suitable for different wastes, as some wastes may show a mass gain at high temperatures, such as waste containing metals that are oxidized at high temperatures, increasing in mass, thereby giving false information on the contents of organics.

Bomb-calorimetry is used to determine the heating value of different wastes by combustion in oxygen. Heating values can also be calculated, using the Dulong formula as done by (Akalin, Tekin and Karagöz, 2012; Chen, et al., 2014) or as done by (Liu, et al., 2013) or (Kurkela and Ståhlberg, 1992).

The assay providing the most information on the behavior of a material in a thermal environment is TGA, as it can be used to show the degradation across a large temperature range, under different atmospheres, and under different pressure regimes.

Biological treatment characterization assays

In *Paper III* a broad characterization effort was presented, including biological characterization assays such as the BMP (bio methane potential)-test and RA4, also called AT4.

BMP assesses the potential of the material to produce biogas or methane, by adding waste, water and inoculum to a flask and measuring the gas produced. However, this assay can also be seen as a measure of how the environment influences the material, by subjecting it to a low-redox, wet environment at a certain temperature. Doing so enables easy integration into an n-dimensional framework.

RA_4 assays are used to analyze the oxygen consumed by microbial and other reactions in the waste over four days. Oxitop and Sapromat are two methods commonly used. In principal, both methods involves a glass flask containing the waste to be analyzed, with a holder for NaOH or soda lime to remove CO_2. As oxygen is consumed, CO_2 is formed, which is removed, creating a negative pressure. The oxitop reports the negative pressure, while the Sapromat reports the energy needed to electrolytically produce enough oxygen from $CuSO_4$ to equalize the pressure. See (Binner, Böhm and Lechner, 2012) for a comparison between the two methods.

These two types of methods will cover both the aerobic (RA_4) and the anaerobic (BMP) spectrum of the environmental space depicted in Figure 5.

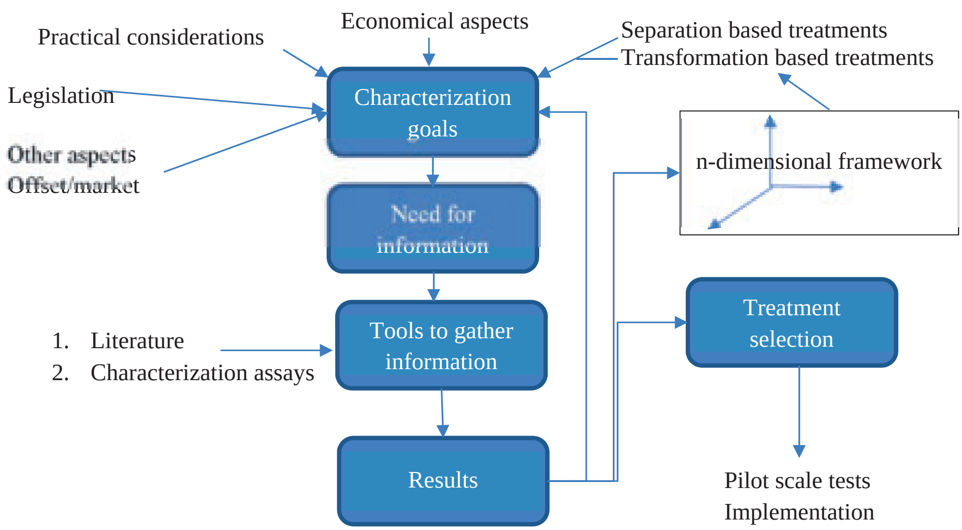

Figure 6 A general treatment oriented waste characterization framework updated for treatment selection, including the n-dimensional framework.

2.2.4. Treatment and characterization

The first steps in characterizing a waste would be a basic characterization, followed by an investigation of separation-based treatments, as discussed above. The selection of the treatment environment for further investigation will depend on a myriad of factors, including properties of the waste, practical and economic issues, legislation, time, knowledge etc. In Figure 6 an adopted version of the characterization model (Figure 1) is shown, which shows the role of the n-dimensional framework in the characterization process. The n-dimensional framework is a tool to help locating new treatment alternatives, and can be updated during the iterative process.

3. Summary and conclusions

Treatments may be divided into two types: based on separation or based on transformation. Combinations of the two are possible as well. The properties of the waste determine the possibility for separation-based treatments. Arranging separation treatments along an axis that quantitatively describes suitable property ranges is one way of systematizing separation-based treatments. The n-dimensional framework provides a platform for a systematic overview of different transformation based waste treatments. As separation based treatments are often simpler and less costly than transformation based treatments, separation based treatments should be tested first.

A characterization strategy consisting of three steps, basic characterization, separation oriented characterization, and transformation oriented characterization is presented. Basic characterization assays are a few inexpensive tests that provide basic information useful in further investigation. Separation and transformation oriented characterization are tests targeted towards a specific treatment process, currently available or not. By putting more effort on the separation and transformation tests and characterization in a “top down” approach, a solution can be found employing less characterization assays. This is summarized in Figure 7.

A clear structuring of different treatments makes the selection of treatment for a certain waste easier, and helps discover new treatments that may be suitable for current and future waste types.

By employing a “top-down”, treatment oriented, waste characterization strategy, the number of assays used can be kept to a minimum, and a treatment can found with less effort. If less effort is put into managing wastes, more effort can be put towards productive activities.

Figure 7 The three steps of the treatment oriented waste characterization strategy, where the height indicates the potential effort that goes into each step.

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