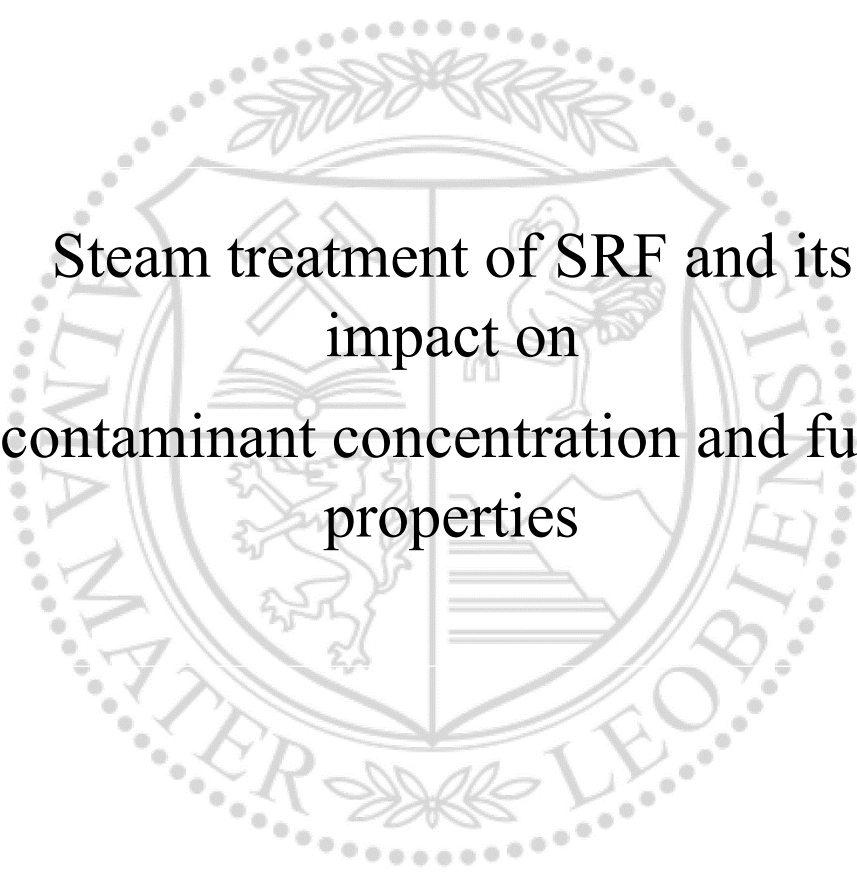




Chair of Waste Processing Technology and Waste Management

Master Thesis



Steam treatment of SRF and its
impact on
contaminant concentration and fuel
properties

Ali Golnahali

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MONTANUNIVERSITÄT LEOBEN

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Abstract

Steam treatment of SRF and its impact on contaminant concentration and fuel properties

Global warming is a major environmental challenge that humankind is facing today. The Kyoto Protocol aims to reduce greenhouse gas emissions, reduce reliance on fossil fuels, and promote the use of renewable energy. It also encourages collaboration between developed and developing countries using clean development mechanisms. Municipal solid waste disposal and management is a major issue faced by urban communities worldwide. To address this, various sophisticated technologies and strategies have been employed. Cities across the globe have taken several steps to reduce the environmental impact of MSW treatment strategies, and thermal treatment. The energy recovery is one of the most effective ways to extract clean, renewable energy from waste. Solid Recovered Fuel (SRF) derived from both household and industrial waste has high potential as an alternative fuel source to aid in the worldwide effort to combat global warming and reduce greenhouse gas emissions. Due to European Union regulations that prohibit the disposal of waste with a calorific value higher than 6 MJ/kg in landfills (Fritz Kleemaann 2010) also support the production of SRF. With increasing energy demands, SRF can serve as an alternative fuel source with high energy producing potentials. If no improvements are made in the sector, waste-related emissions are expected to increase to 2.6 billion tonnes of CO₂ equivalent by the year 2050. Using an alternative fuel like SRF in the manufacturing industry, especially industrial products that contain pollutants. This applies in particular to chlorine and heavy metals. The aim of the current study was to analyze SRF samples through steam treatment, with a particular focus on the presence of chlorine in the samples before and after treatment. Achieving low chlorine concentrations in SRF is a significant goal for the cement industry, as high levels of chlorine can have negative effects on cement quality (Ryunosuke Kikuchi et al. 2008). The presence of chlorine during the clinker burning process can lead to the volatilization of chlorides in hot zones, which can then condense in cooler zones and cause the formation of chlorine deposits and undesirable chlorine-cycles. These issues can impair the clinker burning process and ultimately result in a lower quality of cement. Therefore, it is important for the cement industry to carefully monitor and control the chlorine content in SRF to ensure the production of high-quality cement. Waste materials often contain chlorine, which can noticeably affect the effectiveness and environmental consequences of waste-to-energy procedures. Hence, this study focused on the steam treatment of SRF samples, with a particular focus on the presence of chlorine and heavy metals in the samples before and after treatment to assess the effect of the treatment on chlorine and heavy metal contents. This study investigated the impact of steam treatment on the chlorine removal from SRF sample. Despite the absence of additional chlorine introduction, an increase in chlorine content was observed. The findings suggest a high fluctuation of chlorine content in SRF, which points to the need for more comprehensive experiments to obtain consistent results. Overall, this study highlights the importance of careful sample handling and suggests further investigation to enhance our understanding of chlorine concentration in SRF. Finally, the results of the experiments indicate that the steam treatment process was ineffective in removing chlorine from two categories of experiments: those involving solely washed SRF, and those involving washed SRF with PVC.

Kurzfassung

Einfluss der Dampfbehandlung von EBS auf Schadstoffkonzentrationen und Brennstoffeigenschaften

Die globale Erwärmung ist eine der größten ökologischen Herausforderungen, mit denen die Menschheit heute konfrontiert ist. Das Kyoto-Protokoll zielt darauf ab, die Treibhausgasemissionen zu reduzieren, die Abhängigkeit von fossilen Brennstoffen zu verringern und die Nutzung erneuerbarer Energien zu fördern. Außerdem fördert es die Zusammenarbeit zwischen Industrie- und Entwicklungsländern im Rahmen von Mechanismen für eine saubere Entwicklung. Die Entsorgung und Bewirtschaftung fester Siedlungsabfälle ist ein großes Problem für städtische Gemeinden weltweit. Um dieses Problem zu lösen, wurden verschiedene hoch entwickelte Technologien und Strategien eingesetzt. Städte auf der ganzen Welt haben verschiedene Schritte unternommen, um die Umweltauswirkungen von Strategien zur Behandlung von Siedlungsabfällen und zur thermischen Behandlung zu verringern. Die Energierückgewinnung ist eine der effektivsten Möglichkeiten, saubere, erneuerbare Energie aus Abfall zu gewinnen. Der aus Haushalts- und Industrieabfällen gewonnene feste Ersatzbrennstoff (EBS, englisch: Solid Recovered Fuel, SRF) hat ein großes Potenzial als alternative Brennstoffquelle, um die weltweiten Bemühungen zur Bekämpfung der globalen Erwärmung und zur Verringerung der Treibhausgasemissionen zu unterstützen. Auch die Vorschriften der Europäischen Union, die die Entsorgung von Abfällen mit einem Heizwert von mehr als 6 MJ/kg auf Deponien verbieten, unterstützen die Herstellung von SRF (Fritz Kleemaann 2010). Angesichts des steigenden Energiebedarfs kann EBS als alternative Brennstoffquelle mit hohem Energieerzeugungspotenzial dienen. Wenn in diesem Sektor keine Verbesserungen vorgenommen werden, werden die abfallbedingten Emissionen bis zum Jahr 2050 voraussichtlich auf 2,6 Milliarden Tonnen CO₂-Äquivalente ansteigen. Bei Verwendung eines alternativen Brennstoffs wie EBS in der verarbeitenden Industrie, sind jedoch die enthaltenen Schadstoffe zu berücksichtigen. Dies gilt vor allem für Chlor und Schwermetalle.

Ziel der vorliegenden Arbeit war es, EBS-Proben mit überhitztem Dampf zu behandeln, wobei der Schwerpunkt auf dem Vorhandensein von Chlor in den Proben vor und nach der Behandlung lag. Niedrige Chlorkonzentrationen in EBS sind ein wichtiges Ziel für die Zementindustrie, da hohe Chlorkonzentrationen negative Auswirkungen auf die Zementqualität haben können (Ryunosuke Kikuchi et al. 2008). Das Vorhandensein von Chlor während des Klinkerbrennprozesses kann zur Verflüchtigung von Chloriden in den heißen Zonen führen, die dann in den kühleren Zonen kondensieren und die Bildung von Chlorablagerungen und unerwünschten Chlorkreisläufen verursachen können. Diese Probleme können den Klinkerbrennprozess beeinträchtigen und letztlich zu einer schlechteren Zementqualität führen. Daher ist es für die Zementindustrie wichtig, den Chlorgehalt in EBS sorgfältig zu überwachen und zu steuern, um die Herstellung von hochwertigem Zement zu gewährleisten.

In dieser Studie wurde die Auswirkung einer Dampfbehandlung auf die Chlorentfernung aus einer EBS-Probe untersucht. Obwohl im Prozess kein zusätzliches Chlor zugeführt wurde, wurde ein Anstieg des Chlorgehalts beobachtet. Die Ergebnisse deuten auf eine starke Fluktuation des Chlorgehalts in EBS hin, was auf die Notwendigkeit umfassenderer Experimente hinweist, um konsistente Ergebnisse für ein so heterogenes Material wie EBS

zu erhalten. Insgesamt unterstreicht diese Studie die Bedeutung einer sorgfältigen Probenbehandlung und regt weitere Untersuchungen an, um unser Verständnis der Chlorkonzentration in EBS zu verbessern. Schließlich deuten die Ergebnisse der Experimente darauf hin, dass das Dampfbehandlungsverfahren bei der Entfernung von Chlor in zwei Kategorien von Experimenten unwirksam war: bei den Experimenten, die nur gewaschene SRF beinhalteten, und bei denen, die gewaschene SRF mit PVC beinhalteten.

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1 Introduction

The amount of municipal solid waste (MSW) is increasing due to multiple reasons such as increasing urbanization. A decade ago, the amount of MSW generated per year was 0.68 billion tonnes. Currently, this number has increased to about 1.3 billion tonnes annually. It is expected that by the year 2025, the amount of produced MSW will likely reach up to 2.2 billion tonnes per year. In the next fifteen years, there will be a significant increase in capita waste generation, from 1.2 kg to 1.42 kg per person per day (Daniel Hoornweg and Perinaz Bhada-Tata 2012). There is a great potential for MSW to be a valuable resource as substantial energy resource. Recently, there has been a significant increase in the global market of recycling different components by various techniques. The process of recycling, particularly in low- and middle-income nations, is often conducted by an active but typically informal sector. The production of new items using secondary materials has the potential to save a substantial amount of energy. The European Union's Waste Framework Directive (1975/442/EEC) adheres to a widely accepted hierarchy. This directive was the first to introduce the principles of the waste hierarchy concept into European waste policy. The waste management hierarchy prioritizes waste prevention as the most favourable option, followed by reuse, recycling, recovery (including energy recovery), and finally, disposal as a last resort (Official Journal of the European Communities 1975). The hierarchy not only considers financial, environmental, social, and management factors, but it also promotes the reduction of greenhouse gas (GHG) emissions.

Many countries are facing various challenges in energy production from landfill due to the growing quantities of MSW, decreasing availability of sanitary landfill sites, raising costs for treatment and disposal, and more strict environmental regulations. Incineration is preferable waste management technology according to the waste hierarchy that offers advantages such as energy recovery and volume reduction (up to 90%) (Wenchao Ma and Susanne Rotter 2008). To optimize waste combustion, non-combustibles are removed, and combustibles are converted into refuse derived fuel (RDF), which has a more uniform particle size distribution and higher heating value than untreated MSW. Globally, over 130 million tonnes of MSW and RDF are incinerated annually in over 600 waste-to-energy (WTE) plants that produce heat and power. However, WTE plants have low energy efficiency (15-25%) due to low steam temperature that prevents severe boiler corrosion, fouling, and slagging. New WTE plants can reach a maximal electrical efficiency of 30% (at 580°C and 289 bar steam pressure).

The high chlorine content in MSW & RDF plays a critical role in corrosion mechanisms. The fractions that exhibit the greatest levels of chlorine are plastics, composites, textiles, and electronic devices, and it can be inferred that PVC is the primary chlorine source in these fractions. The most notable levels of chlorine were found in PVC products, such as electric sheaths and tubes (Thomas Astrup et al. 2011), as well as in non-packaging plastics (Wenchao Ma et al. 2010), which could also contain PVC. While PVC is officially comprised of 56.7% chlorine, the actual quantity of chlorine may differ considerably based on the quantity of additives employed (Sandra Viczek et al. 2020).

Chlorine is mainly present in paper and plastic fractions. The paper fraction contains one-third to half of its chlorine in the water-soluble form, and the plastic fraction contains over 90% of its chlorine in the water-insoluble form (K. Churney et al. 1985; Susan Delia Freese and Dj Nozaic 2004; Ruth Stringer and Paul Johnston 2001). When undergoing combustion, an elevated concentration of chlorine promotes the development of eutectics with a low melting

point in fly ashes. These eutectics subsequently condense on superheaters and leave behind low melting chlorides, causing damage from chlorine-induced corrosion and unplanned operational shutdowns.

To mitigate costly chlorine-associated issues, it is crucial to investigate chlorine concentration, species, and thermal behavior in waste. However, the heterogeneous and complex matrix of MSW and RDF poses a challenge for quality assurance analytical methods in determining chlorine concentration. Standards have been developed to determine total chlorine content (TCC) for coal and later modified by CEN for MSW (CEN/TC 292) (Martijn van Rijn, European Committee for Standardization 2012), biofuel (CEN/TC 335) (European committee for standardization 2009), and SRF (CEN/TC 393). The combustion in a calorimetric bomb is a standardized method for determining TCC in SRF (CEN/TS 15408:2006), while CEN/TC 335 has developed a "quick test" for water-soluble compounds in biofuel (CEN/TS 15105:2005) (Wenchao Ma et al. 2010).

In addition, the issue of waste management encompasses more than just the technical aspects of creating incinerators or landfills, as it also includes concerns regarding the environment and society. The burning of waste in WTE plants can result in the emission of various pollutants, including dioxins, furans, and heavy metals, which pose a risk to human health and the environment. Therefore, WTE plants must be equipped with advanced emission control systems to minimize the release of harmful substances.

Furthermore, the siting of WTE plants and landfills is a contentious issue, as local communities often resist the development of such facilities due to perceived health risks and negative impacts on property values. This has led to the "not in my backyard" (NIMBY) phenomenon, which hinders the expansion of waste management infrastructure in many areas.

To address these challenges, it is important to engage with stakeholders and promote public awareness and education about the benefits and risks of different waste management technologies. Moreover, to encourage the adoption of more environmentally friendly waste management practices like waste reduction, recycling, and composting, there is a need for the implementation of policies and regulations that offer incentives. Effective chlorine removal from SRF is crucial to prevent corrosion and ensure the safe and efficient operation of waste-to-energy plants. By optimizing the steam treatment process, it is possible to produce high-quality SRF with reduced chlorine content and acceptable physical and chemical properties for use as a fuel. This has the potential to diminish the environmental repercussions of waste disposal and encourage the utilization of renewable energy resources.

The objective of this research was to assess the efficacy of utilizing steam treatment to eliminate chlorine from SRF. The study entailed exposing SRF to steam treatment at a consistent temperature and duration (150°C for 60 minutes). Additionally, the analysis explored the impact of varying durations on the steam treatment procedure and revealed the effectiveness of steam treatment in dehydrating the SRF samples.

1.1 Waste

Waste, in European Union under the Waste Framework Directive 2008/98/EC, Art. 3(1) means “an object the holder discards, intends to discard or is required to discard” (Official Journal of the European Union 2008). Waste management is a critical issue for countries around the world. The growing amount of waste generated by a rapidly expanding population and economic development creates environmental, health and economic challenges. In addition, waste generation is a source of greenhouse gas emission, contributing to climate change and has a significant impact on air, soil, and water quality. The effective management of waste is essential for promoting sustainable development and protecting the environment. Efficient waste management encompasses appropriate waste collection, transportation, and disposal, in addition to the implementation of waste reduction and recycling programs that aim to minimize the amount of waste produced. Waste reduction and recycling can help to conserve natural resources and reduce the amount of waste that needs to be managed. Landfills, incinerators, and recycling facilities are common methods of waste disposal, but new technologies and innovative approaches to waste management are also emerging, such as composting and energy recovery from waste. Countries in the Middle East and North Africa generate the least amount of waste, accounting for only 15 percent of the world's waste. Nonetheless, the rate of waste production in these nations is increasing more rapidly than in high-income countries, mainly because of rapid economic development and population growth. In contrast, Europe, Central Asia and East Asia generate about 43 percent of the world's waste. The Pacific and East Asia region generated 468 million tonnes of waste in 2016, while the Middle East and North Africa region generated 129 million tonnes. In North America, the United States and Canada are the largest producers of waste, with an average of 2.21 kg of waste generated per person per day (Carl Wilén 2004). This highlights the need of more effective waste management practices in these countries to reduce the environmental impact of waste and promote sustainable development. In conclusion, waste generation is a global challenge that requires a coordinated effort by governments, businesses, and individuals to reduce waste and promote sustainable waste management practices. Proficient waste management has the potential to enhance the health and well-being of communities, preserve the environment and aid in the creation of a more sustainable future. Figure 1 shows the Amount of generated waste by various global regions (Carl Wilén 2004; Daniel Hoornweg and Perinaz Bhada-Tata 2012).

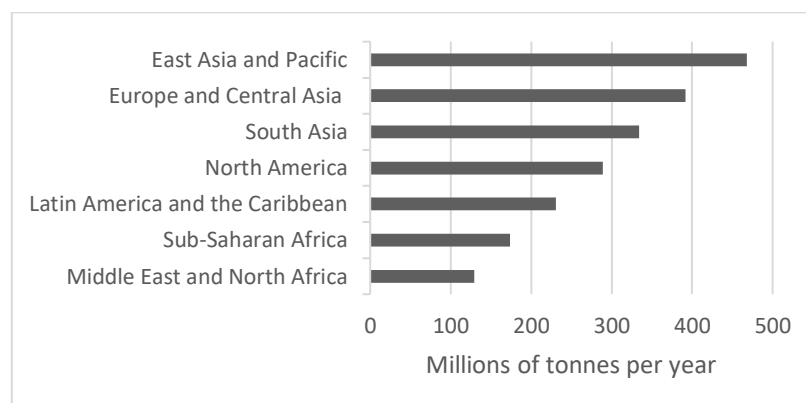


Figure 1: Waste generation by region in millions of tonnes per year. Adapted from Daniel Hoornweg et al., 2016 (Daniel Hoornweg and Perinaz Bhada-Tata 2012).

1.1.1 Waste management

To successfully obtain sustainable waste management, the waste hierarchy should be followed as a top priority in waste management: (Reichel 2013; Official Journal of the European Union 2018; Waste Management & Prevention Division Solid Waste Management Program 2019)

- a) Prevention,
- b) Preparing for re-use,
- c) Recycling,
- d) Other recovery (energy recovery),
- e) Disposal.

The waste hierarchy is a structure that prioritizes waste management alternatives according to their environmental impact and is considered as a crucial principle for achieving sustainable waste management. This framework has been widely adapted by governments, organizations and businesses across the globe. Typically represented as a pyramid, the waste hierarchy places the most favorable waste management option at the top and the least desirable one at the bottom. Figure 2 shows the priority of the above-mentioned waste hierarchy (Reichel 2013).

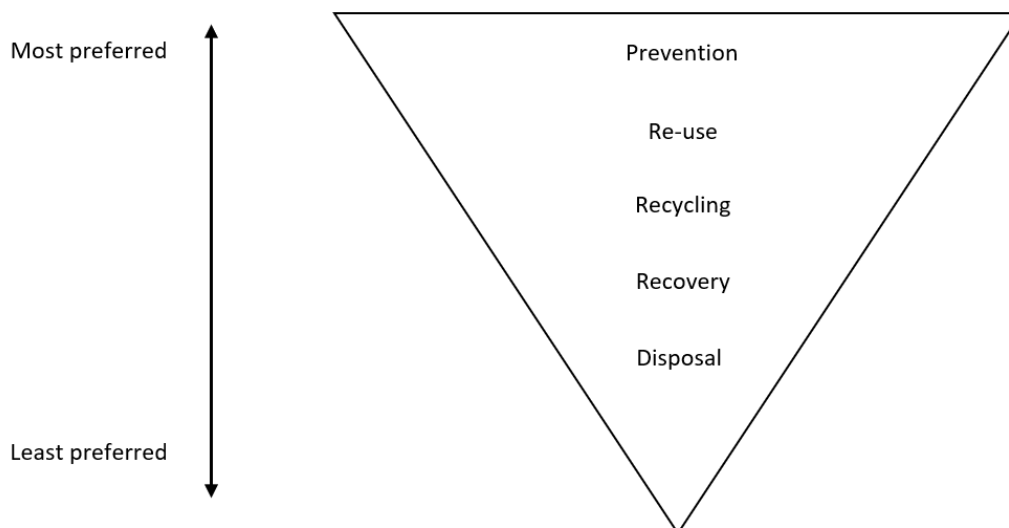


Figure 2: The waste hierarchy (Reichel 2013).

The highest priority in the waste hierarchy is waste prevention, which entails decreasing the quantity of waste generated in the first place. This can be achieved through practices such as product design, procurement, and consumer behavior. For instance, diminishing packaging waste by utilizing reusable or biodegradable packaging materials, or curbing food waste by employing improved planning and storage practices, can be beneficial in reducing the amount of waste produced.

Next on the hierarchy is reuse, which involves using a product more than once before it becomes waste. For example, refillable water bottles, durable shopping bags, and reusable containers can all help to reduce waste. The reuse of products is a significant waste management alternative as it prolongs the lifespan of a product and decreases the requirement for new resources. Recycling is the next step in the waste hierarchy and involves collecting and processing waste materials so that they can be used as raw materials for new products. This can help to conserve natural resources, reduce greenhouse gas emissions, and save energy. Commonly recycled materials include paper, cardboard, glass, plastic, and metal.

Finally, the bottom line of the waste hierarchy is recovery, which involves using waste as a source of energy. For example, incineration and anaerobic digestion are common methods of recovering energy from waste. Although recovery can help to reduce the amount of waste that needs to be disposed of, it is generally considered as the last resort option because it can have negative environmental impacts such as air and water pollution.

By following the waste hierarchy, the goal is to minimize the amount of waste generated and to maximize the reuse, recycling, and recovery of waste materials. This approach can promote sustainable waste management practices, conserve natural resources, reduce greenhouse emissions, and safeguard the environment. By implementing the waste hierarchy, we can move towards a more sustainable future. The waste hierarchy is a system that categorizes waste management options based on their environmental impact and is arranged by the most environmentally friendly to the least. This approach is based on the principle of lifecycle thinking, which considers the impacts of waste generation and management over the entire lifecycle of a product, from its production to its disposal.

In certain situations, it may be necessary to depart from the waste hierarchy to achieve the most favorable overall environmental outcome. For example, in some instances, recovery or energy recovery from waste may be a better option than recycling or disposal in a landfill. Choosing the best waste management option requires careful consideration of its environmental, health, economic, and social impacts. It is important to assess the overall result of each option and select the one that delivers the greatest benefit.

To support this approach, Member States should ensure that their waste legislation and policy development processes are transparent and involve public consultation and stakeholder involvement. The principles of precaution and sustainability, technical feasibility, economic viability, and resource conservation should be carefully considered in addition to the overall impacts on the environment, human health, economics, and society when choosing waste management options. The goal is to minimize the amount of waste sent to landfills and to promote more sustainable waste management practices.

The objective of the European Union is to decrease the quantity of MSW sent to landfills to 10% or below and promote the advancement of recycling and recovery practices (Official Journal of the European Union 2018). This strategy promotes the shift to a circular economy, where waste is considered a valuable resource, and contributes to the preservation of natural resources, the mitigation of greenhouse gas emissions, and the protection of the environment. Encouraging waste management options that yield the best environmental outcomes and adhering to the waste hierarchy are crucial. Member States can support the transition to a more sustainable future by involving the public and stakeholders in the development of waste legislation and policy, and by considering the impacts of waste generation and management

throughout the entire lifecycle of a product (Environmental Protection Agency 2002; Eurostat 2020b).

Member states should implement one of the following targets to verify compliance with the municipal waste set in Article 11(2)(a) of directive 2008/98/EC: (Official Journal of the European Union 2008; Eurostat 2016)

a) *“the preparation for reuse and the recycling of paper, metal, plastic and glass household waste”*

Recycling rate of paper, metal, plastic and glass household waste is total recycled amount per total generated amount. (In percentage)

b) *“the preparation for reuse and the recycling of paper, metal, plastic, glass household waste and other single types of household waste or of similar waste from other origins”*

Recycling rate of household and similar waste is recycled amount of paper, metal, plastic, glass and other single waste streams per total amount of mentioned materials and other single waste streams from household or similar waste. (In percentage)

c) *“the preparation for reuse and the recycling of household waste”*

Recycling rate of household waste is total household waste amounts beside certain waste categories.

d) *“the preparation for reuse and the recycling of municipal waste”.*

Recycling of municipal waste is municipal waste recycled per municipal waste generated. (in percentage)

For the calculation of the target in Article 11(2)(b) of directive 2008/98/EC in respect to construction and demolition waste, Member states shall require the calculation method. The waste amount for backfilling operations and waste amount which prepared for reuse must reported separately. The recovery rate of construction and demolition waste (C&DW) is the percentage of the total amount of generated C&DW that is materially recovered (Official Journal of the European Union 2008, 2011).

The classification of waste as hazardous or non-hazardous is a crucial decision in the field of waste management. In the European Union, the directive 2008/98/EC of the European Parliament specifies that, *“a hazardous waste is defined as a waste that displays one or more of fifteen hazardous properties”* (Official Journal of the European Union 2018). These properties include characteristics such as flammability, reactivity, corrosiveness, and toxicity. Hazardous waste is considered to be a subgroup of solid waste and is distinct from non-hazardous waste and municipal waste (Trevor Letcher and Daniel Vallero 2019). The management of hazardous waste is a relatively new field, with the implementation of procedures starting around 30 years ago in developed countries. Developing countries have yet to fully upgrade their hazardous waste management infrastructure. One of the methods that could assist developing countries in enhancing their hazardous waste management is by regulating the import of hazardous waste from developed countries (Trevor Letcher and Daniel Vallero 2019).

Another important aspect of hazardous waste management is to ensure that the standards of international corporations are employed. These corporations have a responsibility to help developing countries manage their hazardous waste in a safe and sustainable manner. This can include providing technical assistance and training programs, as well as investing in the development of local hazardous waste management infrastructure. It is essential that developing countries are equipped with the resources and knowledge needed to manage their own hazardous waste. Enhancing the hazardous waste management system is crucial in developing countries, and one way to achieve this is by creating national hazardous waste management plans, enforcing regulations and guidelines, and offering education and training programs for the waste management industry.

The classification of waste as hazardous or non-hazardous is a critical decision in the field of waste management. The management of hazardous waste is particularly important in developing countries, where there is a need to upgrade existing structures, control exports, employ the standards of international corporations and help these countries to manage their own waste. By taking these steps, it is possible to ensure that hazardous waste is managed in a safe and sustainable manner, and to protect the environment and public health. Table 1 shows an overview of hazardous properties (HP) (Environmental Protection Agency 2002).

Table 1: Characteristics of waste that make it hazardous. (Description taken from WFD) (Official Journal of the European Union 2008).

Hazardous Property	
HP1	Explosive
HP2	Oxidizing
HP3	Flammable
HP4	Irritant – skin irritation and eye damage
HP5	Specific target organ toxicity (STOT)/Aspiration toxicity
HP6	Acute toxicity
HP7	Carcinogenic
HP8	Corrosive
HP9	Infectious
HP10	Toxic for reproduction
HP11	Mutagenic
HP12	Release of an acute toxic gas
HP13	Sensitizing
HP14	Eco toxic
HP15	Waste capable of exhibiting a hazardous property listed above not directly displayed by the original waste

1.2 Municipal waste

Based on OCED, Municipal Waste (MW) is defined as follow *'covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, as well as yard and garden waste, street sweepings, the contents of litter containers, and market cleansing waste if managed as household waste'* (Ryunosuke Kikuchi et al. 2008). MW refers to waste that is collected by or on behalf of local governments. MW consists of household waste, residual waste and waste from municipal service (Daniel Hoornweg and Perinaz Bhada-Tata 2012; jordaka; Eurostat Statistics 2021).

Household waste refers to the waste generated by private households, including food waste, paper, packaging, and other types of waste. It is one of the largest sources of waste and plays a significant role in determining the total amount of waste generated in a region. In many countries, household waste is collected regularly by local authorities and disposed of through various waste management methods (Silpa Kaza et al. 2018).

Residual waste, also known as residual municipal solid waste, is the waste that remains after sorting, composting, and recycling operations have been performed and is composed of a combination of organic and inorganic waste materials that are not suitable for reuse, recycling or recovery. Residual waste is typically sent to landfills or incineration plants for disposal. The composition of residual waste varies depending on the waste management practices of a particular region. However, it usually contains a mix of food waste, garden waste, paper and cardboard, plastic, glass, textiles and other household waste. Properly disposing of residual waste is crucial in order to reduce the environmental impact of waste and minimize the depletion of natural resources (Silpa Kaza et al. 2018).

Waste from municipal services refers to the waste generated from the daily activities of households and other similar facilities, such as schools, hospitals, and offices. A range of materials such as food waste, paper, plastics, metals, glass, textiles, and hazardous waste are all classified as this type of waste. Proper management of MSW is crucial to minimize its environmental impact and promote a sustainable future, as the composition of this waste can vary significantly between communities and regions. In many countries, the collection and disposal of MSW is managed by local governments, who ensure that it is collected, transported, and disposed of in a safe and responsible manner (Silpa Kaza et al. 2018).

1.2.1 Municipal waste treatment

Municipal waste treatment refers to the process of collecting, treating, and disposing of waste generated by households and other similar facilities. Local authorities or private organizations carry out waste management, which is a critical aspect of the process. The main goal of municipal waste treatment is to reduce the amount of waste sent to landfills, minimize its environmental impact and promote recycling and composting.

The methods used for municipal waste treatment include waste collection and transportation, waste sorting and waste treatment and disposal, such as landfill, incineration, composting, recycling and waste-to-energy conversion. The techniques employed for treating municipal waste vary based on factors such as the type and amount of waste produced, as well as regional policies and regulations. The efficiency and sustainability of municipal waste treatment is an important factor in achieving a circular economy and protecting the environment (Jordana; Eurostat 2020b).

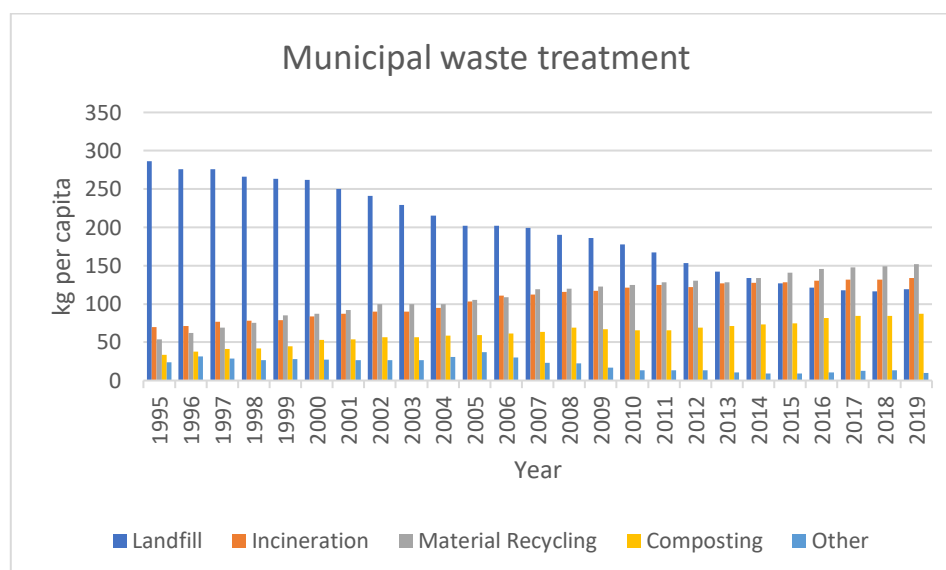


Figure 3: Municipal waste treatment in kg per capita in specific year in European Union. Data cover from 1995 to 2019 for EU27, since data from United Kingdom is considered till 2018 (Eurostat 2020c).

Figure 3 shows the Municipal Waste treatment in the EU between 1995 and 2019. For example, in 2019 23% was disposed of through landfill dumping, 30% sent to recycling, 17% to composting operations and 26% was disposed through incineration. Over the years the amount of MSW incinerated in EU has experienced a significant growth, 90% increase from 1995 till 2019. In the same period, landfill dumping decreased by 58% and metal recycling increase by 181% (EU region) landfill dumping decreased by 58% and metal recycling increase by 181% (EU region). Category 'other' is a difference between the amount of treated and waste generated. This amount happens in countries that must estimate waste generation in parts that not covered by Municipal Waste collection. Furthermore, based on EU stat the 'other' category indicates the effect of import and export, temporary stage, weight losses and use of pretreatment like Mechanical biological treatment (MBT) (Eurostat 2020b).

These changes of numbers and the rules which are approved by EU during past years about waste and renewable energy, caused a huge growth in energy utilization and generation from

MSW. Based on Eurostat, in 2018 the whole energy production from waste such IW (industrial waste), non-renewable MSW and non-renewable waste was near 40.4 MTOE (million tons of equivalent).

Energy recovery from MSW (renewable) is mainly used for electricity generation which was 22.7 MWh in 2018 based on IEA (International Energy Agency) that used in CHP (combined heat and power) plants or electricity only plants. Germany has the highest amount of generation from waste which is followed by France, Netherland and Sweden.

In Austria the significant share of waste treatment belongs to recycling and deponing which waste incineration is also another option (Fritz Kleemaann 2010). Table 2 shows the overview of disposal and treatment of municipal waste in Austria 2017. It should be noticed that there are 999 landfills in Austria and It is forbidden to landfill untreated household waste. The only waste materials that are landfilled are inert material from excavation, construction waste, and residuals from incineration (Eurostat 2020b).

Table 2: Municipal Waste treatment in Austria 2019 (Eurostat 2020b).

Austria 2019	Percentage
The process of incinerating waste in waste-to-energy plants	41.4
Organized recycling (paper and cardboard, glass, scrap metal, plastic, organic waste)	27.1
composting	22.1
The biological treatment of mixed municipal solid waste (MSW) and large or bulky waste.	7.2
Management of challenging waste and e-waste treatment	2.1
landfilled	0.1

European countries based on their municipal waste management divided in three country groups. Recovery countries, transition countries and landfilling countries. Table 3 presents a comprehensive ranking of European countries based on their municipal waste treatment practices and how they treat municipal waste.

Table 3: European countries ranking based on municipal waste treatment (Roland Pomberger et al. 2017).

Group	Countries	Recycling & composting and incineration rate	Landfilling rate
Recovery countries	Germany, Belgium, Netherlands, Sweden, Denmark, Austria, Estonia, Finland and Luxembourg	More than 80%	Less than 20%
Transition countries	France, United Kingdom, Italy, Slovenia, Ireland, Portugal, Poland, Spain, Czech Republic and Hungary	40-80 %	20-60%
Landfilling countries	Lithuania, Bulgaria, Cyprus, Slovakia, Greece, Romania, Croatia, Malta and Latvia	Less than 40%	60-100%

'Circular economy' is a new approach being developed in EU countries for municipal waste management. The circular economy model encompasses production and consumption practices that prioritize sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products to maximize their lifespan. By adopting this approach, the lifecycle of products is prolonged, minimizing waste and promoting sustainable practices. The goal is achieving recycling amount 60% for 2025 and 65% for 2030. It is worth mentioning circular economy comes up with some issues like economical, technical and ecological.

The Ternary Diagram was initially introduced in physical chemistry in the late 19th century and has since been known as the "Gibbs Triangle" for the graphical representation of ternary mixtures. Today, this diagram remains a widely used method in various fields, such as chemistry, geology, mineralogy, and process engineering (Richard J. Howarth 1996). Ternary Diagram method in waste management includes three sides which are belong to three treatments in municipal waste management, A (landfilled), B (Incinerated), C (Recycled and composted). The diagram employs a scaling system where each main grid represents a 10% increase in performance. To evaluate each treatment option, a total of 9 main grids are used, representing performance levels from 10% to 90%. Furthermore, the triangle lines depicted in

the diagram represent the lowest (0%) and highest (100%) levels of performance (Roland Pomberger et al. 2017). The implementation of the circular economy, together with the development of new technologies, will play a key role in ensuring the long-term sustainability of waste management in Europe. Figures 4 and 5 show evaluation of municipal waste management in 1995 and 2014.

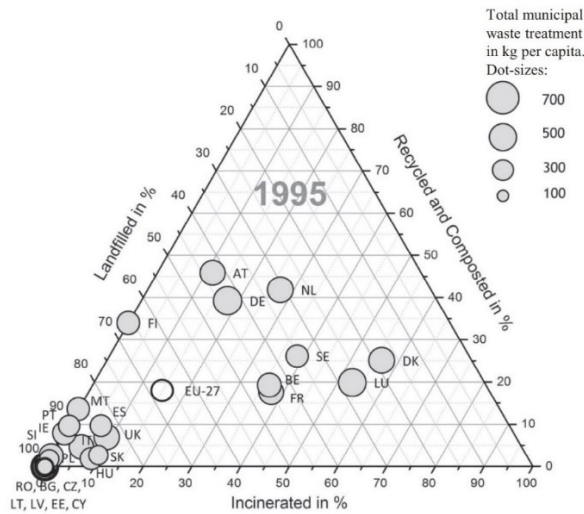


Figure 4: Performance of municipal waste management in individual member states and the EU-27, based on per capita waste generation across three categories (Roland Pomberger et al. 2017).

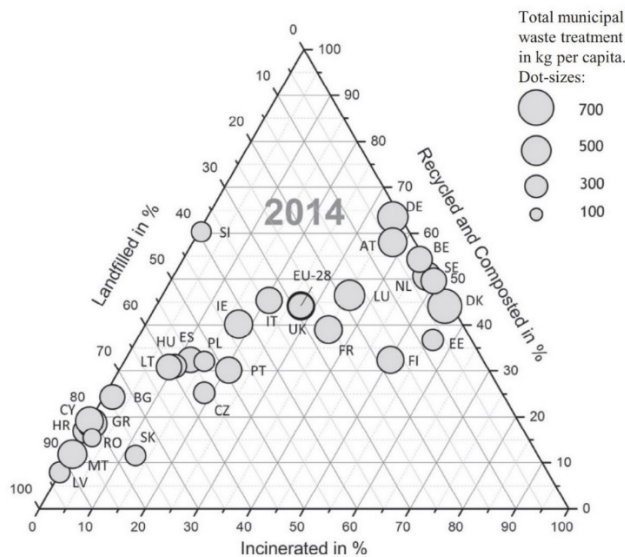


Figure 5: Performance of municipal waste management in individual member states and the EU-28, based on per capita waste generation across three categories (Roland Pomberger et al. 2017).

1.2.2 Treatment of municipal solid waste

Aiming to handle and reduce MSW, new methods must be developed. The choice of the most suitable method depends on factors such as the type of waste, local conditions and regulatory requirements. Effective MSW treatment requires the integration of different components, including source separation, collection, transport, and treatment and disposal. Optimizing the use of resources and minimizing the negative environmental impact of waste are crucial factors in MSW treatment that have significant economic, social and environmental implications. Two main methods are thermal treatment and Mechanical-biological waste treatment (Maxime Hervy et al. 2019; Lars Sørum 2001).

1.2.2.1 Thermal treatment

Municipal Solid waste can be handled in alternative ways. There are a wide range of options to reduce and limit the amount for disposal to landfill. ATT (Advanced Thermal Treatment) refers to a broad range of technologies in thermal treatment. Thermal treatment is a method which use heat to treat waste material and convert waste into solid, gas and liquid by release of thermal energy (Kittikorn Sasujit, Natthawud Dussadee, Nakorn Tippayawong 2019).

The main technique that is commonly used in thermal waste is incineration. Most of the time Incineration requires the combustion of residual and raw MSW. Combustion should happen in the presence of the air, in order to gain sufficient quantity of oxygen which causes fully oxidize the waste. Reducing waste volume and transportation cost and greenhouse gas emission are advantages of incineration (Giovanna Pinuccia Martignon). Through the combustion in incineration plant the temperature exceed 850°C and combustible waste converted to water and carbon dioxide. Non-combustible materials like glass and metal stand as solid (Department for Environment, Food & Rural Affairs 2013). While gasification and pyrolysis are potential waste treatment options, they are not commonly used. On the other hand, incineration plants, the production of fuels for use in power plants (fluidized bed), and the use of waste as fuel in the cement industry (rotary kiln) are more commonly employed methods.

Pyrolysis process happens in the presence of the oxygen. The solid residue generated from the pyrolysis process of MSW is similar to charcoal and is called biochar. Raw municipal waste is not appropriate for the pyrolysis of MSW and the temperature during process should be between 300-850 °C (Michał Kuna). The leftover residue from pyrolysis process can be utilized as a soil enhancer or for other purposes, such as generating energy. Conversely, the gas mixture (synthesis gas) produced through pyrolysis can be utilized as a fuel or can be subject to additional processing to manufacture chemicals or fuels for transportation.

One of the benefits of pyrolysis as a waste treatment method is that it reduces the volume of waste and also the emissions produced during the process, making it a more environmentally friendly alternative to incineration. Additionally, the process allows for the recovery of valuable materials from the waste stream, including energy, gases, and solids, which can be used for a variety of applications. Despite advancements in pyrolysis technology, it is still in the developmental stage, requiring further research and development to enhance its efficiency and decrease its process cost. This would make the technology more accessible to waste management agencies and organizations (Department for Environment, Food & Rural Affairs 2013, 2007).

Gasification is a process between combustion and pyrolysis. That means process occur in the presence of oxygen and it includes partial oxidation of substance. This process is exothermic but for initialization the gasification processes some heat required. Temperatures are usually above 650°C and synthesis gas is a main product and the maximum temperature is 1000°C (Giovanna Pinuccia Martignon). Gasification has the flexibility to transform various feedstocks such as coal, biomass, waste materials, and petroleum coke into valuable chemicals and fuels.

The resulting synthesis gas, or syngas, can be used as a fuel for electricity generation, or as a feedstock to produce chemicals, such as methanol and ammonia and transportation fuels, such as ethanol and diesel. Gasification offers a primary benefit over traditional combustion by providing enhanced regulation over the combustion process, which leads to decreased

emissions of harmful pollutants such as nitrogen oxides (NO_x) and sulfur dioxide (SO₂) and particulate matter. In addition, gasification can also lead to the recovery of valuable by-products, such as tar, char and ash, which can be sold or used as fuel.

There are several different types of gasification technologies, including entrained-flow, fluidized-bed and fixed-bed gasifiers. Each of these types has its own unique advantages and disadvantages and the choice of technology depends on the specific application and the type of feedstock being used. Table 4 shows the overview of gasification reactions: (Giovanna Pinuccia Martignon)

Table 4: Overview of gasification reactions (Giovanna Pinuccia Martignon).

Category	Reaction	ΔH (kJ/mol)
Carbon oxidation	$C + O_2 \rightarrow CO_2 + \text{Heat}$	-393.66
Carbon partial oxidation	$C + \frac{1}{2} O_2 \rightarrow CO + \text{Heat}$	-110.56
Water gas reaction	$C + H_2O + \text{Heat} \rightarrow CO + H_2$	+131.2
Boudouard reaction	$C + CO_2 + \text{Heat} \rightarrow 2CO$	+172.52
Hydrogasification	$C + 2H_2 \rightarrow CH_4 + \text{Heat}$	-74.87
Methanation	$CO + 3H_2 + \text{Heat} \rightarrow CH_4 + H_2O$	-206.23
Water gas shift reaction	$CO + H_2O + \text{Heat} \rightarrow H_2 + CO_2$	-41.18

1.2.2.2 Mechanical-biological waste treatment

MBT is defined as combining several waste management processes, such as Materials recovery facilities (MRFs), sorting, composting or anaerobic digestion. It is relatively common in some regions of Europe, including Germany, Italy and Austria (Stuart Wagland et al. 2011). Mechanical treatments have two main roles which are volume reduction by shredding, crushing and separating recyclable materials like plastic, metal and glass from waste.

Biological process includes waste decomposition and relies on bacteria, nematodes, or other small organisms to break down organic wastes. MBT facilities are waste treatment plants that handle mixed waste, primarily aiming to stabilize biodegradable substances. Their design aims to minimize material moisture content and prevent the generation of methane. Additionally, MBT plants can be built for a variety of purposes. Various combinations of processes can be incorporated into them. MBT involves the use of mechanical and biological processes for the treatment of residual waste. Decreasing the environmental effect of landfilling was the target of the first MBT plants. MBT plants have the advantage of being modular, meaning they can be configured to meet a variety of goals. In accordance with EU Landfill Directives and national recycling targets, these include: (Department for Environment, Food & Rural Affairs 2007; Anurag Garg 2014)

- Pre-treatment of waste going to landfill,
- The diversion of non-biodegradable and biodegradable municipal solid waste (MSW) from landfills can be achieved by mechanically sorting MSW into recyclable materials and/or converting it into RDF for energy recovery,
- Diversion of biodegradable MSW going to landfill,
- Transforming into combustible biogas for the purpose of energy retrieval.

The configuration of MBT plants can vary to enable recycling, recovery, and diversion of biodegradable municipal waste (BMW). As shown in figure 6, MBT configurations are illustrated along with the components within each. Advanced biological treatment (ABT), are designed to increase biological processes and can act only on biodegradable organic materials (Department for Environment, Food & Rural Affairs 2007, 2013).

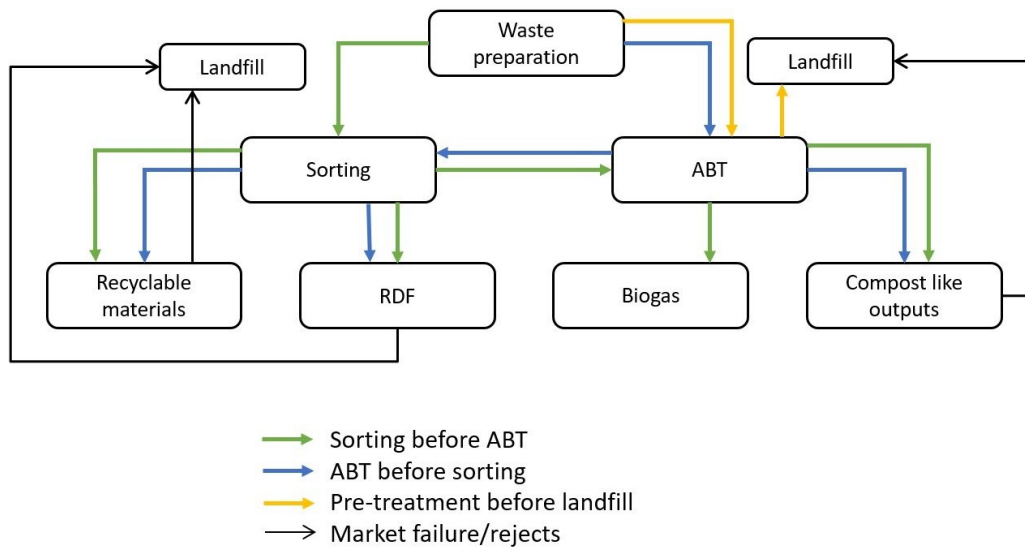


Figure 6: Potential mechanical biological treatment options (Department for Environment, Food & Rural Affairs 2007).

1.2.2.3 Treatment methods in Austria

In Austria, there were a total of 3200 waste treatment plants in operation in 2019 (Doris Weismayr 2021). These facilities are responsible for managing and processing the waste generated by households and industries in the country. The aim of waste treatment plants is to reduce the amount of waste being sent to landfills, increase the recycling of materials. The kinds of waste that are processed differ from one plant to another and may include MSW, hazardous waste, construction and demolition waste, medical waste, and other varieties.

In recent years, there has been a growing trend in Austria towards more sustainable waste management practices, with a focus on reducing waste generation, increasing recycling rates, and improving the management of hazardous waste. The government and local authorities have been investing in novel technologies and systems with the goal of enhancing the efficiency and effectiveness of waste management operations, in order to accomplish this objective. This is reflected in the increasing number of waste treatment plants in the country and the development of new waste treatment technologies. Table 5 shows the number and types of plant in Austria.

Table 5: Waste treatment plants in Austria 2019 (Doris Weismayr 2021).

Types of plants	number
Thermal treatment plants for municipal waste	11
Thermal treatment plants (excluding municipal waste treatment plants)	47
Mechanical-biological treatment plants (MBT)	15
Anaerobic biological treatment plants (biogas plants)	147
Aerobic biological treatment plants (composting plants)	405
Chemical-physical treatment plants	56
Treatment plants for mineral construction and demolition waste	928
Treatment plants for soil contaminated with pollutants	15
Plants for the treatment of metal waste, waste electrical equipment and old vehicles	109
Plastic waste treatment plants (sorting and recycling)	58
Installations for sorting and processing of waste	241
Plants for material recycling of separately collected old materials	89
Treatment plants for special waste	7
landfills	1068

In 2019 there are 11 plants for thermal treatment of MSW that operate with capacity of 2.6 million tonnes. Seven plants are mixed MSW or bulky waste residue from mechanical waste processing are thermally treated. Residues and sewage sludge are mainly used in four plants with fluidized bed firing (Doris Weismayr 2021).

In addition to the plants for the treatment of MSW, 47 thermal plants were in operation under the waste incineration ordinance. In this part co-incineration plants e.g., companies in the cement that use waste as additional fuel are included and plants for the thermal treatment of vegetable waste or fibrous vegetable waste were taken from production of natural pulp and paper not taken into the account. Around 1.6 million t of waste was incinerated in this type of thermal plants in 2019 (Doris Weismayr 2021).

Modern waste management systems rely heavily on mechanical-biological waste treatment (MBT), which plays a crucial role in reducing the amount of waste that is ultimately deposited in landfills and in promoting material recovery through recycling. MBT plants use a combination of mechanical and biological processes to sort, shred and compost waste, producing a stabilized organic fraction that can be further processed or used as a soil amendment.

The principal benefit of MBT is its capacity to minimize the quantity of waste that is directed to landfills. This helps to conserve valuable land resources and reduce greenhouse gas emissions from decomposing waste. In addition, MBT aids in the recuperation of valuable materials, including metals and plastics, which would otherwise be unrecoverable. At the end of 2019, 15 plants for mechanical-biological waste treatment of municipal waste and other waste were in operation with the capacity around 672,800 tonnes (Doris Weismayr 2021). Figure 7 illustrates how the products resulting from mechanical-biological treatment plants are either recycled or disposed of.

However, MBT is not without its challenges. One of the major challenges is the necessity for specialized infrastructure and technology, which can be costly to construct and maintain. There is also the challenge of ensuring that the biological processes used in MBT are safe and effective, and that the resulting products are of high quality. MBT is widely recognized as an important tool for achieving a more sustainable waste management system. Through waste reduction, enhanced recycling and better material recovery. MBT can significantly mitigate the environmental impact of waste and facilitate the transition to a circular economy.

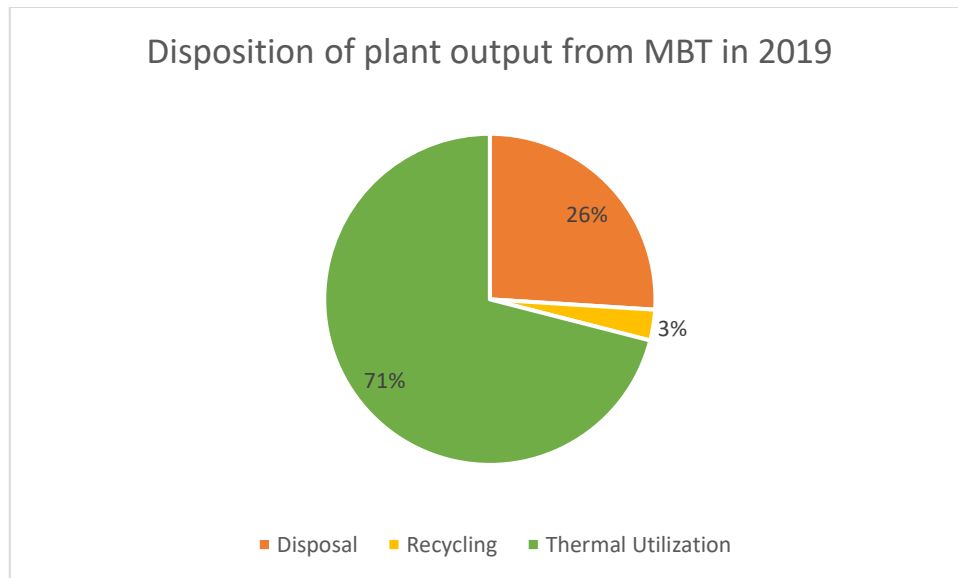


Figure 7: Disposition of plant output from MBT in Austria (2019) (Doris Weismayr 2021).

1.3 MSW

Between different types of Solid waste (SW), MSW is the most challenging around the world. In the EU's Landfill directive 1999/31, municipal solid waste (MSW) is defined as “*waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households*”. MSW was categorized as combustible waste like paper, wood, plastic, textile and non-combustible waste like glass and metal (Trang T.T. Dong and Byeong Kyu Lee 2009). Also reducing MSW effect on health and environment is a never-ending issue. Cities and countries usually manage various waste streams such as municipal solid waste. Other common types of waste include industrial waste, agricultural waste, construction and demolition waste, hazardous waste, electronic waste(e-waste) and medical waste.

Based on the data, the global amount of industrial waste generated is nearly 18 times higher than that of municipal solid waste (Silpa Kaza et al. 2018). In most countries, agricultural waste is separated from other waste streams to avoid generating additional landfill capacity. It could be useful for future agricultural activities. Municipal solid waste is collected through these ways: (Daniel Hoornweg and Perinaz Bhada-Tata 2012)

- House-to-House,
- Community bins,
- Curbside pick-up,
- Self-delivered,
- Contracted or delegated service.

1.3.1 MSW generation

In 2016, the world generated about 2.01 billion tonnes of solid waste, which equals 0.74 kg per person per day. As time passes and the population continues to grow, the annual amount of waste generated is projected to increase by 70%, reaching 3.4 billion tonnes in 2050 (Laura Levaggi et al. 2020). Despite the progress passed through in waste management, this method should be improved. According to Eurostat data Table 6 shows the per capita MSW collected in 2000 and 2010 and 2019 in the EU. In 2019, Denmark has had the highest amount of MSW generation among European countries and Romania has had the lowest. As it shown from table 6 Croatia with around 70% increase has a big change in producing MSW between 2000 and 2019 (Eurostat 2020b).

Table 6: Municipal waste generated among European countries in kg per capita, 2000-2010-2019. (-): data not available (Eurostat 2020b).

	2000	2010	2019	% Changes (2000/2019)
EU28	521	504	- (2018: 491)	- 6
Austria	580	562	588	+ 1
Belgium	471	456	416	- 12
Croatia	262	379	445	+ 70
Czech	335	318	500	+ 49
Denmark	664	- (2009: 762)	844	+ 27
Finland	502	470	566	+ 13
France	514	534	546	+ 6
Germany	642	602	609	- 5
Greece	412	532	524	+ 27
Hungary	446	403	387	- 13
Ireland	599	624	- (2017: 656)	+ 10
Italy	509	547	504	- 1
Netherlands	598	571	508	- 15
Norway	613	469	776	+ 27
Poland	320	316	336	+ 5
Portugal	457	516	513	+ 12
Romania	355	313	280	- 21
Spain	653	510	476	- 27
Sweden	425	441	449	+ 6
Slovakia	254	319	421	+ 66
Turkey	465	407	424	- 9

1.3.2 MSW in Austria

According to figure 8, the average per capita generation of municipal solid waste (MSW) in Austria was approximately 600 kg in 2019. This amount was higher than the EU28 average, which was approximately 483 kg during the same year. The MSW generation per capita in Austria increased by approximately 2.66% from 2000 to 2019, while in EU28, the increase was only about 0.76% in the same period. Despite the increase in MSW generation, Austria has been able to implement several policies and initiatives aimed at reducing waste and promoting sustainable waste management practices. For example, the Austrian government has implemented a comprehensive waste management plan, which focuses on reducing waste, improving waste separation and recycling rates, and increasing the use of renewable energy from waste (Eurostat 2020b, 2020a).

Additionally, the EU has also implemented several policies aimed at reducing waste and promoting sustainable waste management, including the EU Waste framework directive and the EU Landfill directive. These policies aim to reduce waste generation and increase recycling rates, and to prevent hazardous waste from being landfilled. The rise in per capita MSW production in both Austria and the EU28 region underlines the importance of ongoing initiatives to lower waste levels and encourage eco-friendly waste management measures (Eurostat 2020b, 2020a).

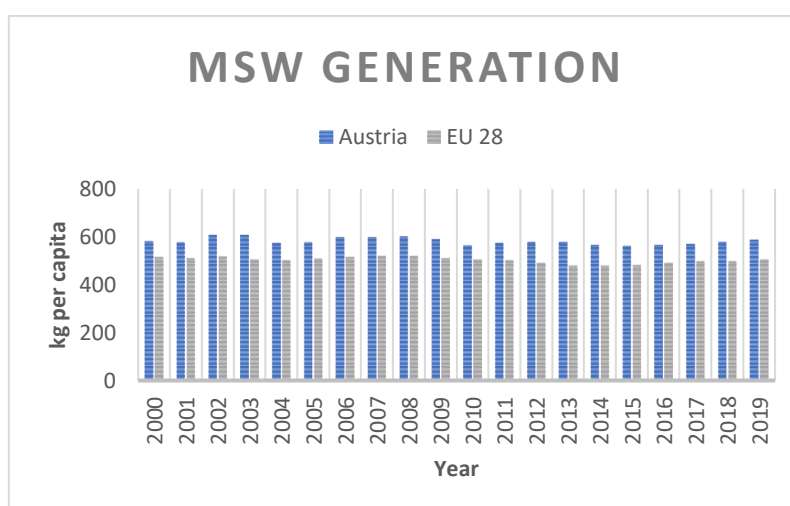


Figure 8: MSW generation in Austria and European countries in kg per capita (Eurostat 2020b, 2020a).

Figure 9 illustrates the total waste generation in Austria in 2019 based on waste group. The share of excavation material in 2019 increased by 28% compared to 2015. In this period household waste increased by 8% and construction and demolition waste increased by 15%. It is important to note that the increase in excavation material, household waste, and construction and demolition waste has a significant impact on the environment and the proper disposal of these waste streams is crucial. Hazardous waste, including problematic substances, pose a threat to human health and the environment if not properly managed. As it can be seen from figure 9, old varnish, waste paints and solvents, waste oil and oil mixtures,

old batteries and accumulators, chemical residues and aerosol dispensers are among the most significant problematic substances in terms of quantity (Doris Weismayr 2021).

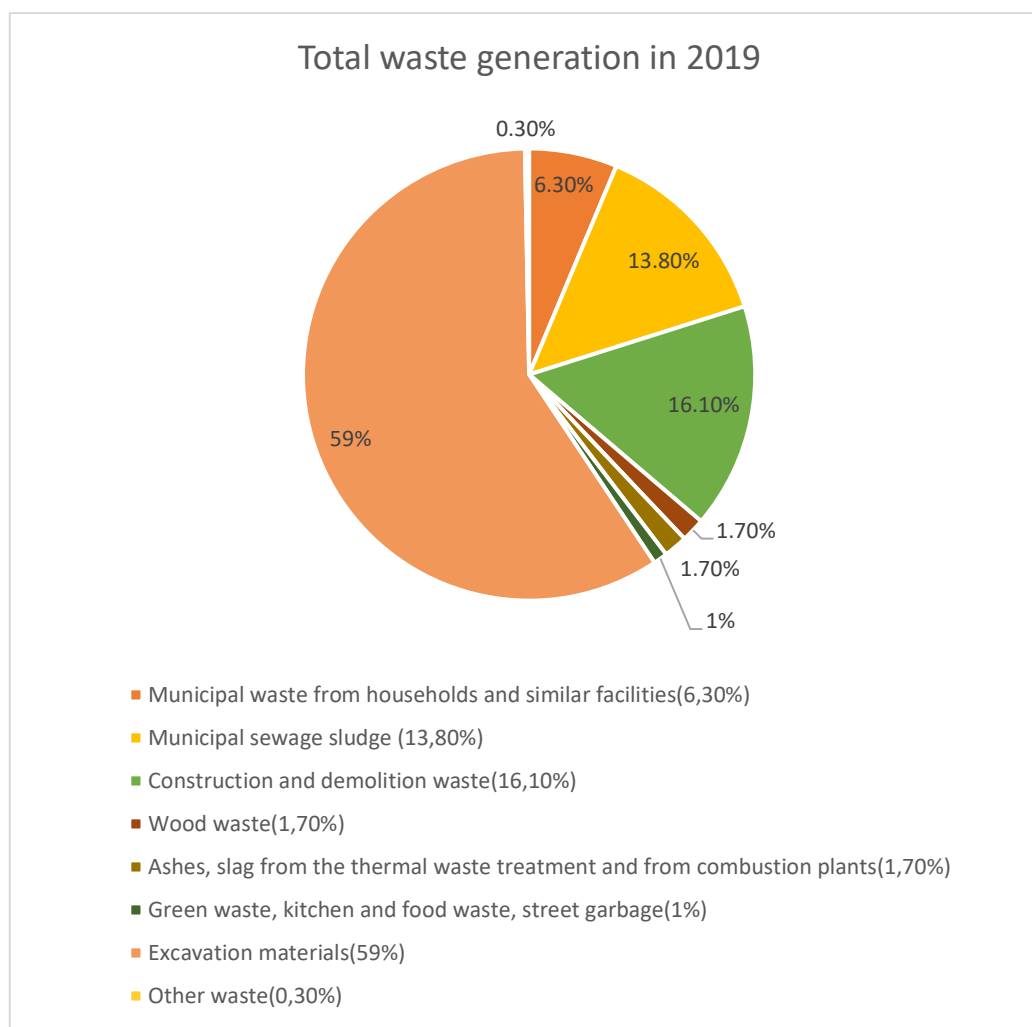


Figure 9: Total amount of waste generated in 2019 in Austria according to waste group (Doris Weismayr 2021).

Municipal waste from households and similar facilities (around 4.50 million t in 2019) shows moderate growth of around 8% compared to Bundes-Abfallwirtschaftsplan 2017 (BAWP) (reference year 2015). However, there are different trends in the individual waste fractions. The quantity of mixed municipal waste is small, while there has been a significant increase in the amount of waste electrical and electronic equipment and textiles. Wastepaper packaging/printed materials are declining slightly (Doris Weismayr 2021; OECD 2022). The volume of municipal sewage sludge is 234,900 t in 2015 and 233,600 t remained almost the same in 2019 (Doris Weismayr 2021). The amount of construction and demolition waste has increased by approximately 15% since the BAWP 2017 (with a base year of 2015), reaching around 11.51 million tonnes in 2019. This increase is due to increased construction activity and improved statistical recording (Doris Weismayr 2021). Some construction waste (CW) and demolition waste (DW) are followed separately from MSW. Sometimes in transfer facilities they merge together and are reported as MSW. It is challenging to separate them in this situation. Compared to the BAWP 2017, the excavated materials have increased by 28%. The

volume of excavated materials in 2019 was around 42 million tons. The quantity of excavated materials in Austria is mainly dependent on significant construction projects, such as the Semmering and Brenner base tunnels or the construction of the Koralmbahn by ÖBB (The Austrian Federal Railways). Another reason for the increased volume is the improvement in statistical recording (Fritz Kleemaann 2010).

1.4 SRF and RDF

In Austria the Definition of recovered derived fuel (RDF) in the legally binding waste incineration ordinance as: “ waste that is used entirely or to a relevant extent for the purpose of energy generation and which satisfies the quality criteria laid down in this directive”. RDF, which originates from combustible waste like garbage, wastepaper and waste plastic, can be categorized as TDF (Tire Derived Fuels), SRF, or AF (Alternative Fuels). The RDF has been processed in accordance with guidelines and regulatory specifications to produce a high calorific value. RDF is suitable for use in cement kilns, thermoelectric power plants, etc. A few of the benefits of RDF include its considerable heating value, homogeneous physical-chemical composition, no difficulty for storage, handling and transportation and low pollutant emissions (Keum Park et al. 2008). Using raw MSW as a fuel is not popular because of high moisture content, low calorific value, high ash amount and also inhomogeneity of particle size. RDF has many advantages compare to raw MSW to use such as calorific value and lower emission (Bahareh Reza et al. 2013; Innes Deans et al. 2016). Several processes can be applied to MSW in order to create RDF, including:

- Separation at source,
- Sorting or mechanical separation,
- Size reduction,
- Screening,
- Blending,
- Drying and pelletizing,
- Packaging,
- Storage.

SRF are produced from high calorific fractions of non-hazardous waste. This type of fuel indicates as a refuse or waste derived fuels (Jörg Maier et al. 2011). Secondary fuels refined based on incoming waste like calorific value, particle size, moisture content, chemical properties etc. SRF represents a sub-group of RDFs. SRF is produced from non-hazardous, solid waste to utilize for energy recovery in incineration or co-incineration plants. In Europe SRF is produced from waste streams such as household waste (HHW), waste materials, construction and demolition waste (C&DW) and commercial and industrial waste (C&IW). Based on the research of Vlies et al. and Ionescu et al. (Costas Velis et al. 2012; Gabriela Ionescu et al. 2013). Mechanical treatment (MT) and Mechanical biological treatment (MBT) plants in Europe are used to produce SRF (Muhammad Nasrullah et al. 2014).

For sorting waste material to produce SRF these steps are essential, such as screening, shredding, magnetic separation and also NIR (Near-Infrared) sorting. All the mentioned steps used in MT plants. SRF and RDF will be use in different areas like Incineration plants that convert disposal to energy, Industrial sectors like cement industry and coal power plants (Renato Sarc et al. 2016).

1.4.1 Ash composition of combustible SRF

According to the sorting analyses, certain SRF samples contained traces of inert materials such as metals or glass in small quantities. However, due to the limited amount of these fractions available, they were not analyzed separately. Furthermore, as these materials were larger than 10mm and were only sorted from the screen overflow, it is improbable that they can be completely recycled and used in clinker phases. Generally, larger metal pieces are extracted from clinker through magnetic separators after the burning process. Hence, this study concentrates on examining the ashes derived from combustible and fine fractions. See figure 10 (Sandra Viczek et al. 2021).

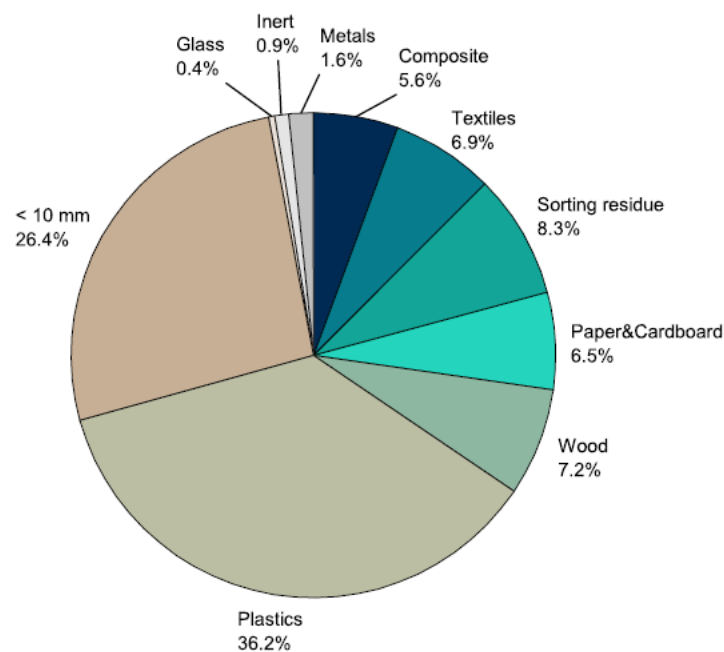


Figure 10: The typical composition of the solid recovered fuel (SRF) samples (Sandra Viczek et al. 2021).

1.4.2 SRF types

There are three different types of SRF that are used in incineration plants. The SRFs are classified by their particle size and lower calorific value. Table 7 shows characterization of low, medium and premium quality of SRF value (Renato Sarc et al. 2019).

Table 7: Characterization of SRF types (Renato Sarc et al. 2019).

SRF	Particle size(mm)	Lower calorific value (MJ/kg)	Purpose of usage
Low quality	≤120	3≤LHV≤12	WtE stationary bed incinerator
Medium quality	≤80	12≤LHV≤18	Secondary firing system of cement kiln
Premium quality	≤30	18≤LHV≤25	Primary firing system of cement kiln

Lower heating Value (LHV) and Higher heating value (HHV) was calculated from Equations below:

$$\text{HHV (MJ/kg)} = 0.336 \text{ C} + 1.419 \text{ H} + 0.94 \text{ S} - 0.145 \text{ O}$$

$$\text{HHV (MJ/kg)} = 0.3417 \text{ C} + 1.3221 \text{ H} + 0.1232 \text{ S} - 0.1198(\text{O} + \text{N}) - 0.0153 \text{ A}$$

$$\text{LHV (MJ/kg)} = \text{HHV (MJ/kg)} - 0.0244 (\text{W} + 9\text{H})$$

C (carbon), H (hydrogen), O (oxygen), S (sulfur), N (nitrogen), H (hydrogen content), W (water content) and A (ash) represent content percentage in weight (Nithikul Jidapa 2007).

1.4.3 Properties of SRF

1.4.3.1 External production of SRF low quality

For manufacturing of SRF low quality the input materials are household waste, bulky waste, construction waste and commercial waste which produce SRF low quality under external (by different suppliers) and internal (at the incineration plant) treatments. As shown in figure 11 processes and stages used to external production of SRF low quality consists of shredding steps, magnetic separation which used to reject Fe-metals, eddy-current separator for rejecting NON-Fe-metals and also sieving process (Renato Sarc et al. 2019; Karl E. Lorber et al. 2012).

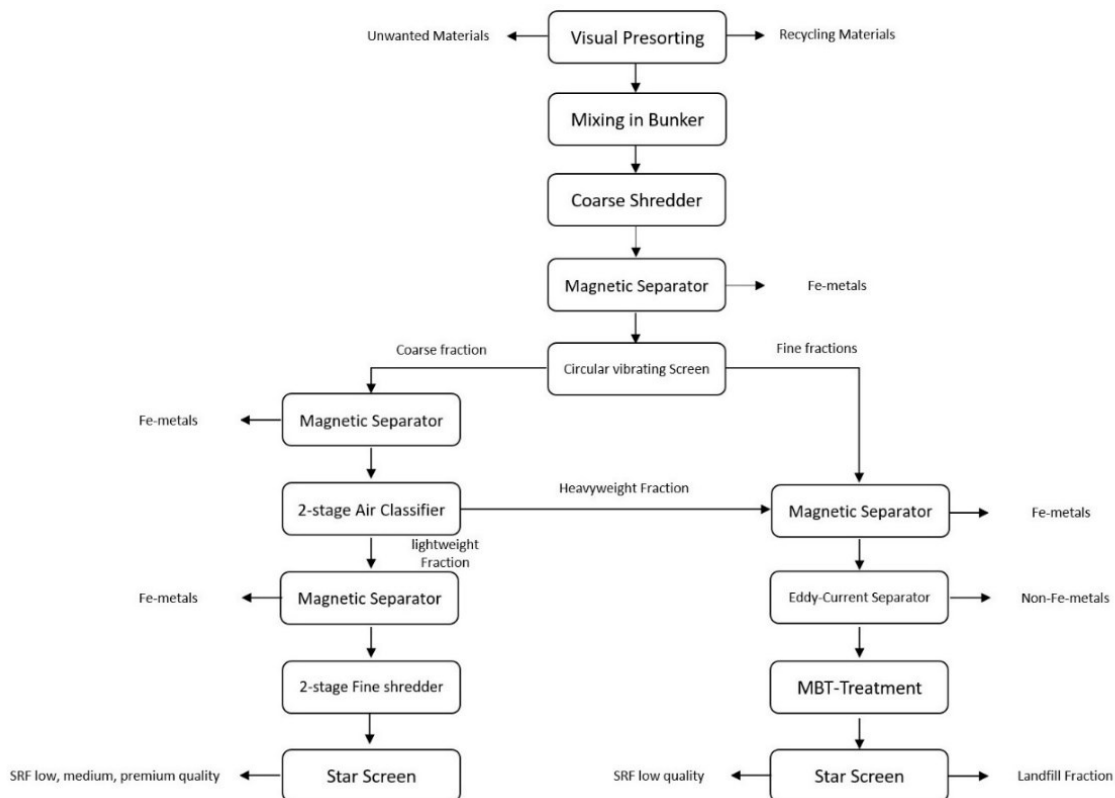


Figure 11: External production of SRF low quality (Renato Sarc et al. 2016).

1.4.3.2 Internal production of SRF low quality

The internal confectioning and homogenization process shown in figure 12 is crucial in improving the quality of SRF low quality. The use of a magnetic separator in this process is important in removing residual metals from the SRF low quality, ensuring that the feedstock quality is improved. Incorporating two stages of magnetic separation boosts the process efficacy and guarantees thorough extraction of residual metals. Maintaining high-quality feedstock is crucial for the optimal performance of an incinerator. Residual metals in the feedstock can cause damage to the incinerator and reduce its efficiency. By removing these metals, the internal confectioning and homogenization process helps to ensure that the incinerator operates efficiently and effectively. This can result in reduced emissions and improved energy recovery, which can contribute to the sustainability of the waste processing process (Renato Sarc et al. 2019; Karl E. Lorber et al. 2012; Renato Sarc et al. 2014).

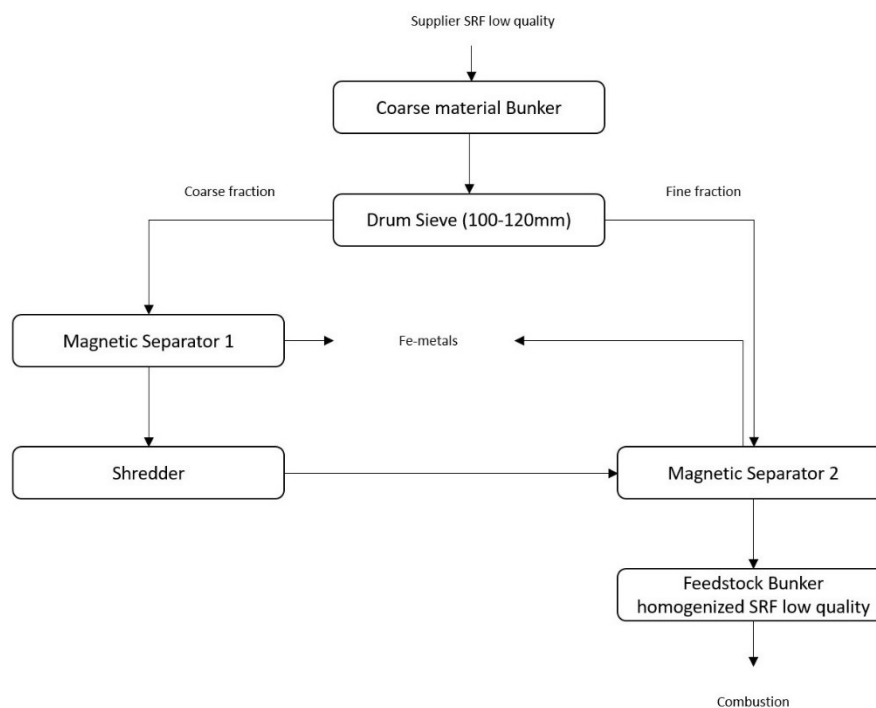


Figure 12: Internal confectioning and homogenization of SRF low quality (Renato Sarc et al. 2016).

1.4.3.3 Manufacturing SRF medium and premium quality of cement kiln

To produce SRF premium quality, it is important to have a multistage processing scheme in place. Figure 13 shows that the first stage involves shredding the materials into different particle sizes, followed by magnetic separation to remove Fe-metals. In the subsequent step, an eddy-current separator is utilized to eliminate NON-Fe metals and a sifting procedure is employed to enhance the SRF's quality even further. It is important to note that even with these processes in place, there may still be unwanted materials present in the waste stream, such as chlorine, antimony, mercury and chromium.

These materials must be controlled and removed in order to produce a high-quality SRF product. This can be achieved through the use of additional treatments and processes, such as chemical treatments or physical separations. Generating top-notch SRF offers various advantages, such as enhanced combustion efficiency, decreased emissions and improved energy recovery. This in turn can help to reduce the environmental impact of waste processing and make the process more sustainable. In addition, the production of high-quality SRF can also provide economic benefits, as it can increase the market value of the product and provide a new revenue stream for waste processing facilities. In conclusion, the multistage processing scheme to produce SRF medium quality with coarse materials and SRF premium quality with fine materials is a key step in ensuring the sustainability and efficiency of waste processing (Renato Sarc et al. 2019).

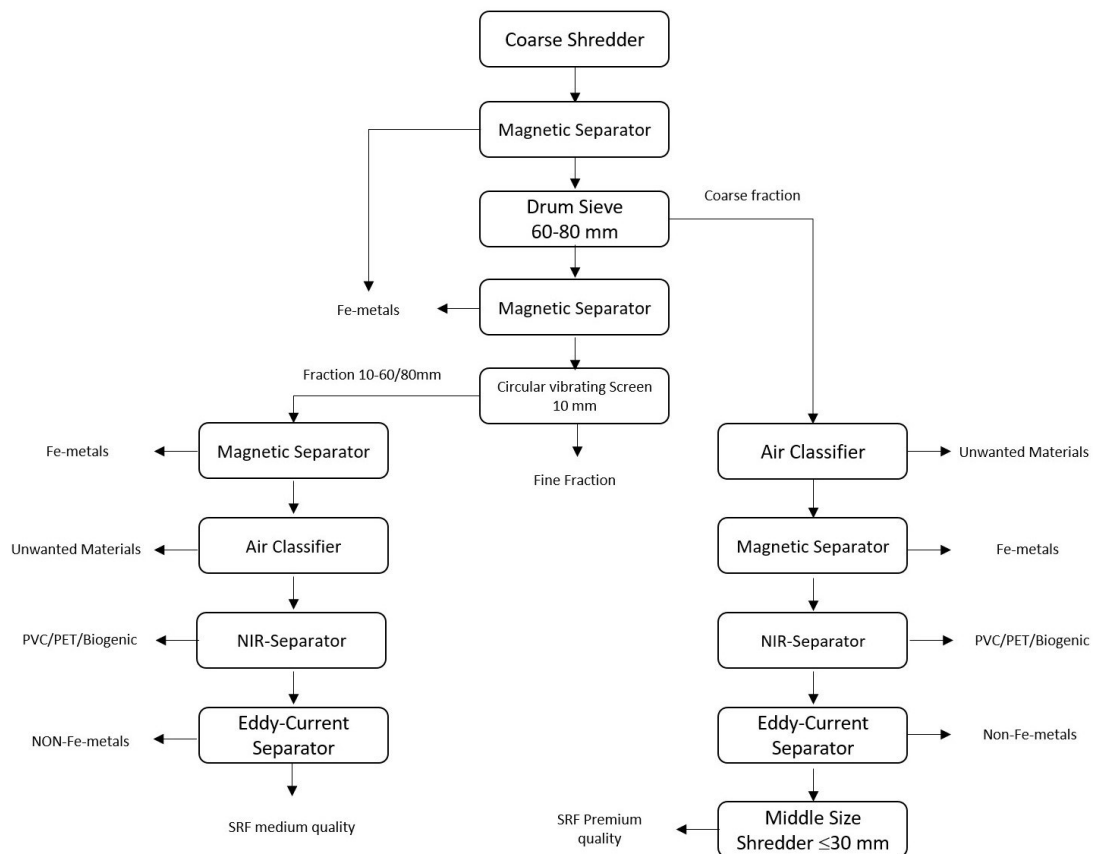


Figure 13: Multistage processing scheme for production of medium and premium SRF qualities (Renato Sarc et al. 2016).

1.4.3.4 Manual sorting analyses from SRF types

Sarc et al. (Renato Sarc et al. 2019) prepared an overview of SRF types from manual sorting analysis. The mean values are presented in table 8 from manual sorting, for low quality from two different processing plants, for SRF medium quality from seven different plants and for SRF premium derived from five different plants.

Table 8: Results from manual sorting analyses from all the three SRF types in percentage (Renato Sarc et al. 2016).

	Low Quality	Medium Quality	High Quality
Fine fraction	42.6 (<16mm)	26.1 (<11,2mm)	43.5 (<11.2mm)
Organic/biogenic waste	9.6	8.4	1.2
Paper, cardboard & cardboard packaging	6.8	16.0	9.5
Plastic & lightweight fraction	20.8	28.5	28.0
Composite materials	3.0	4.1	2.9
Textiles	5.1	7.6	11.9
Glass	1.0	1.4	0.1
Inert Materials	6.8	4.1	0.3
Metals	2.6	1.4	0.7
Hazardous household waste	0.2	0.2	0
Other	1.6	2.3	1.8

Table 9 illustrates how the proportion of high calorific fractions, including paper, cardboard, cardboard packaging, plastics, lightweight fraction, composite materials, and textiles, increases with the higher quality of SRF (such as premium), based on the manual sorting analyses. On the other hand, the percentage of inert impurities, such as glass, inert materials, metals, and hazardous household waste, decreases. The table also displays the distribution of PPCT (Paper, Plastic, Composite, and Textile), Fine Fraction, and INERT (Glass, Inerts, Metals, and Hazardous Waste) across all three types of SRF (Renato Sarc et al. 2016).

Table 9: Summarized results from manual sorting analyses of SRF types (Renato Sarc et al. 2016).

Fractions	SRF Low quality	SRF Medium quality	SRF High quality
PPCT	35.6	56.2	52.4
INERT	10.6	7.1	1.1
fine fraction and Organic	53.8	36.7	46.5

1.4.3.5 Chemical-Physical properties of SRF

As the quality of SRF (low, medium, premium) increases, so does the energy value parameter (LHV), while the moisture and ash content parameters decrease. When comparing medium and premium quality SRF in terms of LHV and PPCT content, it becomes clear that the increased amount of paper, cardboard, and cardboard packaging in medium quality SRF is a major contributor to its water content. Another notable observation is that the higher the SRF quality, the greater the amounts and ratios of procedural parameters such as chlorine and sulfur content. Additionally, higher quality SRF types have higher fossil CO₂ emissions due to the increased presence of fossil components in fractions such as textiles and fine fractions < 11.2 mm that are generated through energy recovery. See Table 10 (Renato Sarc et al. 2016).

Table 10: The chosen findings from the physical-chemical analyses of all three SRF types (Renato Sarc et al. 2016).

Parameter	SRF low quality	SRF medium quality	SRF high quality
Moisture Content (%)	26.5	25.0	15.1
Lower heating value (MJ/kg)	8.9	15.5	19.3
Lower heating value (MJ/kg)	14.3	21.2	25.0
Ash content (%)	29.6	12.7	12.4
Chlorine content (g/kg)	9.2	10.8	13.8
Sulphur content (g/kg)	2.9	3.4	3.3
Ratio Chlorine/Sulphur	3.2	3.2	4.2
Total carbon content (w%)	-	46.9	52.8
Fossil CO ₂ emission factor (g/MJ)	-	34.5	43.2

2 Aim of the work

Substitute fuels are an important source of energy for energy-intensive processes especially in the cement industry. Since their use in the manufacturing industry has an impact on products, the pollutants they contain are a particularly important issue, examples for pollutants being chlorine and heavy metals. Even though during the production of SRF the waste undergoes a range of mechanical treatment steps, these steps are often insufficient to remove all relevant pollutants. Consequently, further treatment options may be required to produce quality assured SRF with low concentrations of pollutants. Various hydrothermal and steam-based methods for waste treatment are described in literature, usually in connection with dehalogenation/dechlorination of waste. This thesis aims to describe the state of the art of hydrothermal treatment in waste management, design a laboratory setup to test superheated steam treatment of SRF and to report the effect of the superheated steam treatment on chlorine and pollutant concentrations and its potential for simultaneously drying the waste.

3 Material and methods

The aim of the experiment was to study the behaviour of SRF in the reactor and the effect of the addition of PVC on the chlorine removal through steam treatment. The experiment was carried out by subjecting the samples to steam treatment at a temperature of 150 degrees Celsius for 60 minutes. For this experiment, the SRF “premium quality” samples were taken by following the ÖNORM S 2127 guidelines. Ten subsamples were taken from the pile and combined to produce the composite sample. To ensure accurate measurements, the SRF samples used in the experiment were analysed in accordance with the ÖNORM EN 13656:2002-12 standard for total content and the ÖNORM 14582:2016-11 standard for calorimetric content, dry residue calculated in accordance with ÖNORM EN 14346:2007-03. ICP-MS analysis (in accordance with EN 15411 and EN ISO 17294-2) was conducted on the washed SRF, the washing residue, the PVC sample and the samples after superheated steam treatment. Prior to analysis, microwave-assisted acid-digestion with hydrofluoric acid (HF), nitric acid (HNO₃), and hydrochloric acid (HCl) according to ÖNORM EN 13656 was performed to determine the concentrations of lithium (Li), beryllium (Be), sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), phosphorus (P), potassium (K), calcium (Ca), titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), selenium (Se), strontium (Sr), molybdenum (Mo), palladium (Pd), silver (Ag), cadmium (Cd), tin (Sn), antimony (Sb), tellurium (Te), barium (Ba), tungsten (W), mercury (Hg), thallium (Tl) and lead (Pb). The chlorine (Cl) content of the samples was measured through ion chromatography (in accordance with EN ISO 10304-1), following calorimetric digestion (ÖNORM EN 14582).

Solid residue was dried at 105°C, comminuted to a particle size under 0.5 mm and then analyzed. The liquid was evaporated and the evaporation residue was also analyzed. This information is important because the properties of the fuel can significantly impact the results of the experiment. By using a high-quality, uniform SRF sample, the experiment can be more controlled and the results can be more reliable. The characteristics of unwashed SRF and washed SRF residue along with PVC are displayed in table 11. The mass of the washed SRF was 1.23563 kg, while the mass of the residue was 0.02589 kg.

Table 11: Concentration of washed, unwashed and residue SRF. Units in mg/kg except for dry residue.

	Washed SRF	Washed SRF residue	Unwashed SRF	PVC
Dry residue	100%	100%	100%	100%
Cl	5860	12700	6000	351000
Li	1.7	22	2.1	0.5
Be	2.5	2.5	2.5	2.5
Na	3570	79000	5100	39





Mg	2080	10200	2200	0.86
Al	11800	5860	12000	2.5
Si	19200	17200	19000	28
P	330	5400	430	2.5
K	830	37000	1600	2.5
Ca	37400	647000	50000	50
Ti	3140	1090	3100	0.9
V	2.5	9.4	2.6	0.25
Cr	55	50	55	0.5
Mn	80	410	87	0.5
Fe	1830	3980	1900	4.4
Co	5.5	9.3	5.6	0.25
Ni	48	45	48	0.52
Cu	73	160	75	0.5
Zn	1050	650	1000	2.5
As	2.5	2.5	2.5	2.5
Se	2.5	2.5	2.5	2.5
Sr	44	160	46	0.25
Mo	3.6	18	3.9	2.4
Pd	0.25	0.25	0.25	0.25
Ag	2.9	9.5	3	0.25
Cd	2	1.8	2	0.25
Sn	16	28	16	800
Sb	34	9.9	34	0.25
Te	0.5	0.5	0.5	0.5
Ba	270	140	270	23
W	20	35	20	0.25

Hg	0.46	0.87	0.47	0.25
Tl	0.25	0.25	0.25	0.25
Pb	21	22	21	0.25

The experiment setup requires a kettle and a hot plate to heat up deionized water to a temperature of 150 degrees Celsius. To produce steam, a PTFE tube is used to connect the kettle and steam heater. The PTFE tubing used in the experiment is a product from Rotilabo®, with an inside diameter of 10mm and an outside diameter of 12mm. The choice of PTFE tubing is important because it is made from non-hazardous materials and has a melting point of 260 degrees Celsius, which is appropriate for the experiment. PTFE tubing is commonly used in laboratory experiments that involve high temperatures, corrosive chemicals, and/or high pressure. PTFE is a type of fluoropolymer that is known for its excellent resistance to heat, chemicals and electrical insulation. It is also non-reactive with most chemicals and has a low coefficient of friction, making it ideal for use in applications where purity is important. Additionally, the high melting point of PTFE ensures that the tubing can withstand the high temperatures required for the experiment without melting or degrading.

The Superheater used in the experiment was connected to a glass reactor, with steam flowing into the reactor via three transition pieces with straight hose from Carl Roth®. The main part of the reactor was an extraction attachment for solid from Duran®, with a volume of 250ml. The components of the reactor are depicted separately in table 12.

Table 12: The reactor components.

			
Upper transition piece. Carl Roth®(Carl Roth)	Transition piece. Carl Roth®(Carl Roth)	Extraction attachment for solid. Carl Roth®(Carl Roth)	Transition piece with straight tubing. Carl Roth®(Carl Roth)

The Superheater used in the experiment was the Superheater s2000, which was manufactured by Ghidini Benvenuto Srl®. The machines are fitted with a start switch and a thermostat to regulate temperature from 100°C to 300°C. The Superheater was designed to superheat water steam or compressed air and had a heating power of 2000-Watts with ΔT up to 50°C with maximum 72 kg/h of continuous steam. In this experiment, the Superheater was connected to an external source of steam, which was produced in the kettle. To ensure that the steam did not leak and that the temperature of the reactor remained constant, a glass wool

and temperature band were used around the reactor. The glass wool insulation helps to maintain the temperature of the reactor, while the temperature band avoids any temperature reduction.

In the experimental setup, a thermoelement was placed in the reactor to monitor the temperature. The temperature of the reactor was closely monitored using a K-type thermometer that was linked to a temperature controller. The thermometer used in the experiment had an accuracy of $\pm 3\%$ deviation, with a temperature range of -50°C to 999°C .

This high level of precision in temperature measurement is essential for ensuring the accuracy and reliability of the experimental results. All of the connections between the superheater, kettle, washing bottles and extraction were secured using non-toxic cable ties and parafilm with a width of 100mm. These measures ensured that the connections remained tight and prevented any potential leaks, which could compromise the experimental results.

In the experiment, the aim was to reach a temperature of 150°C , which was achieved using temperature bands. The use of temperature bands allowed for precise control of the temperature and ensured that the temperature remained constant throughout the duration of the experiment. Two washing bottles with filter plates with a volume of 250 ml each were used. The washing bottles were made from Duran®.

To prepare the samples for the experiment, 10 grams of SRF with a particle size under 0.5 mm were carefully weighed and placed into tea bags. Three of the samples were supplemented with 1 gram of PVC pellets with sizes under 5 mm. The addition of PVC was an important variable in the study, as it allowed for the evaluation of the effect of PVC on chlorine release from SRF during the steam treatment. The use of tea bags for sample preparation ensured that the SRF and PVC particles remained contained during the experiment and did not scatter, which could have compromised the accuracy of the results. The tea bags were made from a high-quality, heat-resistant material that did not react with the SRF or PVC during the experiment.

The experiment was conducted for one hour at a temperature of 150°C , which was carefully controlled and monitored throughout the duration of the experiment. The SRF and PVC samples utilized in the experiment are illustrated in figure 14, providing a visual representation of the samples and their composition.

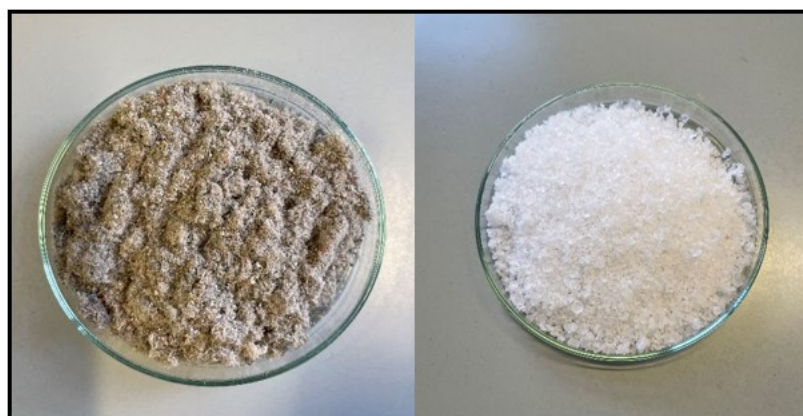


Figure 14: SRF premium quality with particle size lower than 0.5 mm (Left), PVC with particle size around 3mm (Right)

After the steam treatment, the samples were removed from the reactor and allowed to cool to room temperature. This step is important to prevent any further chemical or physical changes from occurring due to the high temperature.

4 Result and discussion

4.1 Literature review of on hydrothermal treatment

The composition of MSW varies greatly depending on the location, with factors playing a significant role such as culture, living standards, development level, and MSW disposal regulations. Despite this variation, MSW typically contains biomass, such as wood and paper, which can be utilized as a valuable resource through waste-to-energy (WTE) treatments (Liang Lu et al. 2011).

While thermal treatments, particularly combustion, are advantageous for MSW utilization due to the reduction in waste volume (Ruth Lawrence 1998; Ligang Liang et al. 2008) and destruction of toxic organic compounds, the high moisture content of MSW makes it challenging to recover enough energy from the combustion process (Ligang Liang et al. 2008). Hydrothermal treatment (HT) is a process that combines water and heat to convert waste to usable products. HT uses pressure and heat in an aqueous medium to directly disintegrate waste inside the hydrothermal reactor, eliminating the need for sorting and crushing processes (Kunio Yoshikawa and Pandji Prawisudha 2014). As HT uses water as a reaction medium, high moisture content waste can be processed without the need of drying and the hot water can act as a solvent, reactant and catalyst for the raw material (Mark Crocker 2010).

HT technology is categorized by processing temperature:

- Supercritical processing uses supercritical water at temperatures above 374°C and pressures above 22.1 MPa (critical point and pressure) to completely convert organic materials into carbon dioxide, water and nitrogen (Seifeddine Jomaa et al. 2003; Motonobu Goto et al. 2004; Peter Kritzer 2000).
- Subcritical processing, on the other hand, employs temperatures below the critical point and pressure (Vincent Rivasseau 2007).
- Waste autoclave technology uses saturated steam at 160°C to sterilize waste. Then the waste pulp is separated through screens, trommels and magnets to remove steel, aluminium and rigid plastics. Afterward, a washing process is conducted to eliminate sand and glass. The washed pulp is subsequently dried to prepare it for thermal conversion into synthetic gas (Kunio Yoshikawa and Pandji Prawisudha 2014).
- Waste converter technology utilizes superheated steam at 150°C and it operates in the atmospheric pressure range. The process can pasteurize organic waste, sterilize pathogenic or biohazard waste and grind and pulverize refuse. However, the waste converter employs a vacuum pump and superheated steam to dehydrate the waste product and it does not offer the advantage of rapidly dehydrochlorinating PVC like the hydrothermal process (Kunio Yoshikawa and Pandji Prawisudha 2014).

Additional studies have demonstrated that the hydrothermal method induces swift dehydrochlorination of PVC at temperatures ranging from 250 °C to 350 °C, leading to the generation of polyene and hydrochloric acid (HCl) (Katsuki Kusakabe et al. 2022). This outcome distinguishes the hydrothermal approach favourably from traditional techniques for treating waste. Nevertheless, waste autoclaves and converters lack this advantage as they operate at temperatures lower than 250 °C (Yukitoshi Takeshita et al. 2004; Kunio Yoshikawa and Pandji Prawisudha 2014).

The primary difference between the newly developed hydrothermal treatment and other hydrothermal methods lies in the operational conditions, as illustrated in figure 15. The developed hydrothermal treatment is operated at lower temperatures and pressures compared to subcritical and supercritical hydrothermal processes, making it easier to construct. While it requires higher temperatures and pressures than waste autoclaves and waste converters, the developed hydrothermal treatment having the benefit of waste dechlorination. This is necessary to consider product as a viable alternative solid fuel (Kunio Yoshikawa and Pandji Prawisudha 2014).

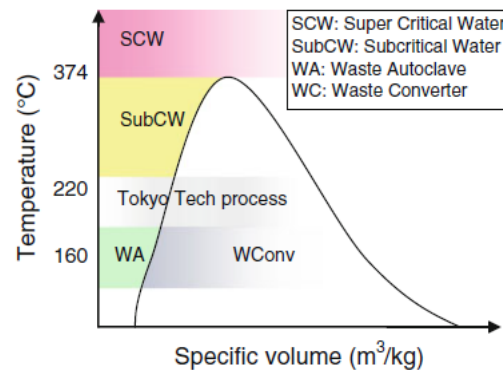


Figure 15: Operational condition of different hydrothermal treatments (Kunio Yoshikawa and Pandji Prawisudha 2014).

MSW treatments based on the hydrothermal principle have been developed, but only some are designed to obtain solid fuel and are commercially available due to high pressure and temperature requirements or the need for a catalyst (Abdallah Shanbaleh 1998; Yasuyuki Ishida et al. 2009). Tokyo Tech has developed a hydrothermal treatment process that converts high moisture content solid wastes into uniform pulverized coal-like solid fuel with low energy consumption. The system has the capability to transform various waste materials, including food waste, sewage sludge, animal manure, agricultural residue, high-moisture solid waste, and municipal solid waste (MSW), into either organic fertilizer or a uniformly dried and pulverized coal-like solid fuel. The commercial plant for hydrothermal treatment is already operating in Hokkaido, Japan, where it processes waste from nearby medical facilities (Kunio Yoshikawa and Pandji Prawisudha 2014).

The hydrothermal treatment plant comprises a reactor, a boiler, and auxiliary equipment such as a steam condenser and water treatment. The process starts with loading raw material (MSW) into the reactor and injecting saturated steam at around 200 °C and 2 MPa. To achieve homogeneous waste reactions with steam, the reactor has blades rotated by a 30 kW motor unit (Kunio Yoshikawa and Pandji Prawisudha 2014). When the temperature and pressure reach the mentioned values, the process conditions are maintained for a specific period. Once the process is complete and the steam is discharged, the reactor yields a wet uniform material that shows significantly improved drying performance and turns into powdery dried products. Figure 16 shows a scale plant in Japan which is treated by the waste collected from nearby medical facilities (E. U. Franck 1984).

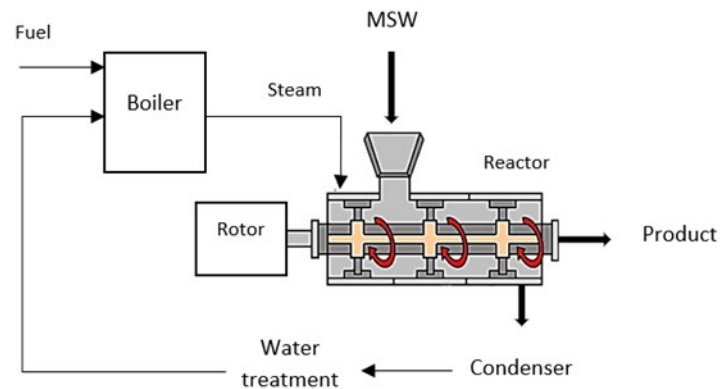


Figure 16: An example of hydrothermal treatment plant in Japan (Kunio Yoshikawa and Pandji Prawisudha 2014; E. U. Franck 1984; Pandji Prawisudha et al. 2018).

The process involves feeding the waste into a reactor and exposing it to medium-pressure saturated steam at 2 MPa for about 1 hour while being stirred. The reactor is then maintained at the target temperature for a set period. After the hydrothermal reaction is completed, the products are removed from the reactor and the pressurized steam is released to a condenser. The water from the condenser is sent to a water treatment facility and recycled back to the boiler for steam generation, forming a closed-loop water system. By increasing the size and number of reactors the plant capacity will increase (Wenzhi He et al. 2008).

In figure 17, the result of the energy balance calculation shows that the hydrothermal treatment process is self-sustaining and able to produce net solid fuel products with energy content close to quarter of the energy required to run the process. Most of the energy required for the process is utilized for heating the reactor and the raw MSW, as well as for maintaining the temperature during the holding period. The energy loss is due to the condenser and the water content in the product. The physical and chemical properties of both the raw MSW and the hydrothermally treated products were analyzed. The results suggest that the process is viable for generating solid fuel from municipal solid waste, and the dried products can be utilized as fuel.

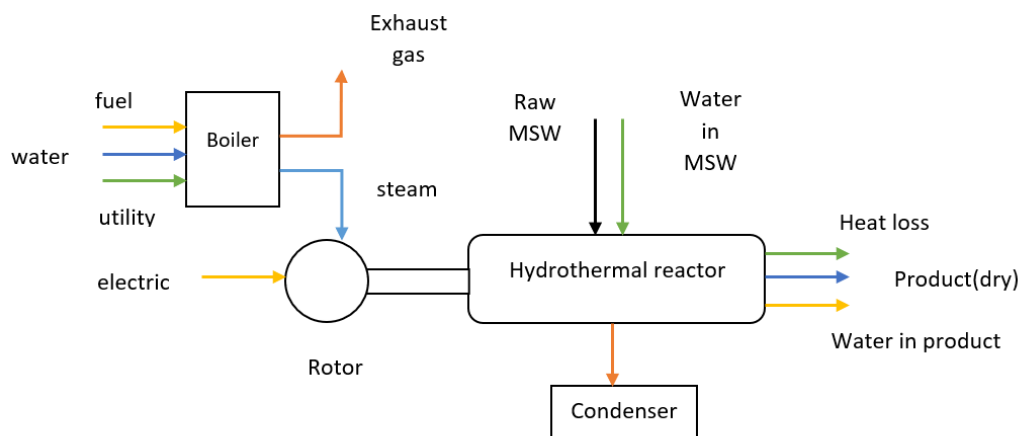


Figure 17: Total energy balance of hydrothermal treatment (Pandji Prawisudha et al. 2012).

When dry steam receives additional heat energy, its temperature increases and it becomes known as "superheated steam". This type of steam is at a higher temperature than saturated steam at the corresponding pressure. The energy added to dry steam to raise its temperature is referred to as sensible heat. Before achieving superheated steam, it is necessary to evaporate all the entrained water within the steam. One way to produce steam that is several hundred degrees higher than the saturation temperature is to utilize a steam superheater (Carey Merritt 2022).

The existing literature on heat transfer and drying behavior of MSW using steam treatment is insufficient. However, Hase et al. have conducted experiments on the continuous drying of waste with a moisture content of approximately 75% using superheated steam. Their study does not include any information on dechlorination. Therefore, a basic model of heat and mass transfer of municipal waste using superheated steam was created to establish a groundwork for utilizing superheated steam as a substitute for hot air in the RDF drying process (Tomoya Hase et al. 2014a).

Superheated steam drying utilizes superheated steam as a drying medium and has several advantages such as the absence of oxygen or carbon dioxide in the process. Which makes it easy to collect exhaust gas through condensation and increased drying rate above the inversion temperature compared to hot air drying. During the initial stage of drying, the low initial temperature of the material causes condensation to occur on the material surface, followed by evaporation into the superheated steam. This phenomenon is known as the "reverse process" and can affect the material quality and drying process by quickly heating the interior of the material and temporarily increasing its moisture content. When a material is exposed to superheated steam at a temperature lower than the saturated temperature (100°C in the case of atmospheric pressure), the steam contacting the material is cooled and condenses onto the material surface, resulting in a mass increase. Later, as the temperature of the material rises, the condensed water on the material surface evaporates, and the mass of the material continues to decrease (Hiroyuki Iyota et al. 2001).

Hase et al. introduced three assumptions for model creation of steam treatment: (Tomoya Hase et al. 2014a)

1. Heat transfer and drying of the sample using superheated steam take place at atmospheric pressure. If the sample temperature is below 373 K (the boiling point of water), there will be no drying from the sample surface due to condensation heat transfer. At exactly 373 K, there is constant drying rate that only dries from the sample surface. If the temperature exceeds 373 K it causes a decrease in drying rate not only from surface but also from inside.
2. The sample should be flat and has no temperature distribution.
3. The heat transfer and drying mechanisms are assumed to be the same in each of the condensation heat transfer, constant drying rate, and decreasing drying rate periods, and the heat transfer coefficients for each period are assumed to be constant.

The paper by hase et al. (Tomoya Hase et al. 2014b) provides a detailed treatment process used for the RDF sample. The RDF was crushed with a blender and dried at 383 K for 24 h, as shown in figure 18. The sample was then suspended in a treatment chamber. The superheated steam generated from ion-exchanged water was introduced to the chamber at a given temperature. The steam temperature, sample and chamber were measured using K-

type thermocouples. The RDF sample was placed on a wire-woven net in the form of a bowl and hung in the chamber for treatment.

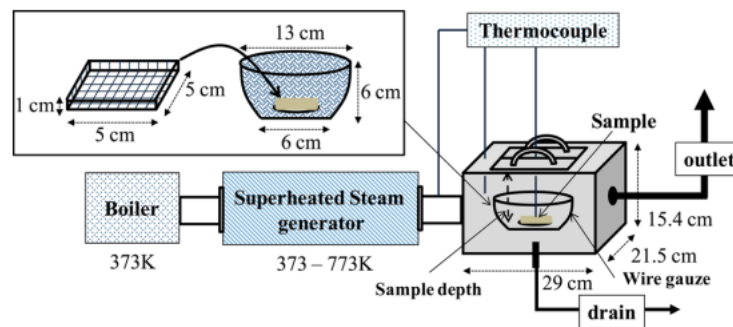


Figure 18: An experimental setup design used by Hase et al. (Tomoya Hase et al. 2014b).

During the decreasing drying rate phase, moisture evaporates from the interior of the sample, causing sample temperature rise and the concurrent evaporation of water in the sample. The apparatus is loaded with a sample at room temperature placed on a 0.08m diameter mesh, preheated to the set temperature, and then subjected to overheated water vapor at predetermined temperatures of 423, 473, and 523 K. The moisture content and the sample temperature were measured at predetermined intervals during the 40-minute treatment period.

Based on a study by Hase et al. figure 19 illustrates the changes in sample temperature over time at superheated steam temperatures of 423 K, 473 K, and 523 K. The changes in sample temperature can be categorized into three stages: a condensation heat transfer period below 373 K, a constant-drying rate period at 373 K and a falling drying rate period above 373 K. As the superheated steam temperature rises, the duration of each period decreases. Moreover, this accelerates the increase rate of the sample temperature. Figure 19 shows an increase in the discrepancy between the sample temperature and the calculated outcomes as the temperature of superheated steam rises. This may be attributed to the higher rate of decrease in moisture content at higher temperatures and the non-uniformity of the RDF sample, leading to errors. In terms of total chlorine content, there was a slight change at 473 K, but 40% decrease was observed at 523 K after 60 minutes of treatment. This change might be due to the thermal decomposition of organic chlorine. The organic chlorine content decreased by about 90% when the sample temperature reached 523 K, leading to a 40% decrease in dry matter yield. However, even if all the organic chlorine in the sample is thermally decomposed, the dry matter yield is not decreased by about 40% (Tomoya Hase et al. 2014a).

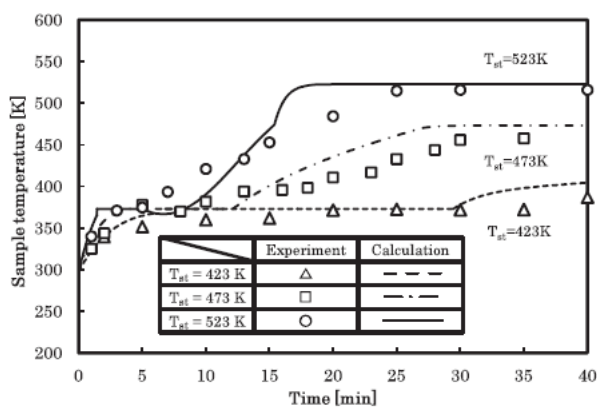


Figure 19: The changes in sample temperature over time in three different experiment (Tomoya Hase et al. 2014a).

The drying behaviour of the samples at superheated steam temperatures of 423 K, 473 K, and 523 K is shown in figure 20. The graph indicates that as the superheated steam temperature increases, the drying rate increases. This is shown the decrease of the moisture content. During the constant drying rate period, the rate of decrease in moisture content remained consistently high, but it gradually decreases during the falling drying rate period.

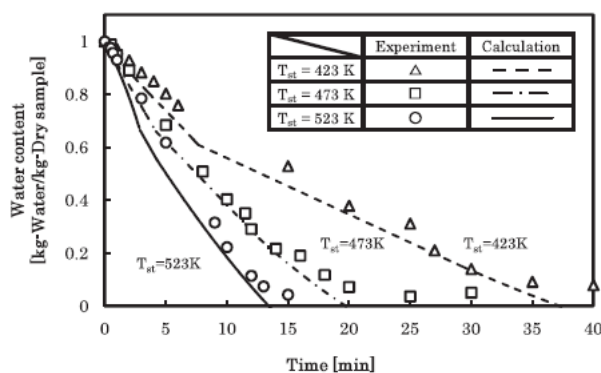


Figure 20: The water content's temporal change in three different experiments (Tomoya Hase et al. 2014a).

The simplified heat and mass transfer model for drying using superheated steam was confirmed to be valid by comparing the experimental and predicted curves in figures 19 and 20.

PVC degradation occurs in two stages: the first stage happens at a temperature range from 473K to 623 K and the second stage occurs above 623 K (Rosa Miranda et al. 1999; Shogo Kumagai and Toshiaki Yoshioka 2016). During the initial stage, dehydrochlorination occurs, leading to the creation of HCl and a solid residue that possesses a polyene structure. During the second stage, polyenes break down to form aromatic hydrocarbons. There are two categories of dechlorination methods based on the number of reaction chambers (Yusaku Sakata et al. 2003). The first method involves simultaneous dehydrochlorination and dechlorination at the same location using of a catalyst and/or adsorbent. This results in dechlorinated products such as metallic chlorides. The second method involves decomposing PVC through dehydrochlorination at one reaction chamber. Then, chlorine is removed from the degradation products (i.e. chlorine-containing gas and oil) using a catalyst/adsorbent. These products are stored in another reaction chamber (Haruka Nishibata et al. 2020).

In conclusion, the literature review on steam treatment for MSW drying has shown that superheated steam can be a viable alternative to hot air in drying process. The use of superheated steam has several advantages, such as increased drying rates above the inversion temperature and the absence of oxygen or carbon dioxide in the process, which makes it easy to collect exhaust gas through condensation. However, the existing literature on the heat transfer and drying behaviour of MSW using steam treatment is insufficient. Steam treatment can increase the mass of a specific material by contacting it with steam, but as time passes and the temperature rises, the mass of the material will decrease. To ensure a successful steam treatment, Hase et al. (Tomoya Hase et al. 2014a) identified three fundamental assumptions: the temperature must exceed 373K (100°C), the material should be flat to facilitate even steam distribution, and a constant rate of heat is required. As the temperature increases during the treatment, the drying rate also increases, leading to a decrease in moisture content. Two main methods are known for removing chlorine: using a catalyst to dechlorinate and decomposing PVC through dehydrochlorination.

4.2 An experimental design

In order to perform experiments using superheated steam on SRF, an experimental setup was designed. The final setup is depicted in figure 21. Utilizing a comprehensive literature review of hydrothermal treatment methodologies, diverse techniques have been analysed to discern the optimal approach for assessing SRF samples via steam treatment. Evidently, steam serves as the foundational prerequisite. To generate steam, deionized water is placed within a kettle atop a heated plate. The subsequent step necessitates a proper transfer of steam into the reactor, for this reason the hose clamp used at the connection between kettle and tube. As previously specified within the materials and methods section, PTFE tube represents an efficacious selection for facilitating thermal transfer between the kettle, superheater, and the reactor.

The Superheater was connected to a glass reactor and steam goes to the reactor. The reactor consists of four parts which of three transition pieces with straight tubing and the main part is extraction attachment for solid. To reduce the risk of steam leakage and minimize heat loss, a layer of glass wool and a temperature band have been applied around the reactor. At the end, two washing bottles were improvised. After 60 minutes of the experiment runs, the first washing bottle following the reactor was filled with water due to steam entering the reactor.

However, the amount of water inside the second bottle was unspecified. The water inside of first washing bottle had a pH between 4 and 5, indicating slightly acidic water. To be able to measure the real temperature inside of reactor, the thermoelement was placed from top until the center of the reactor. As mentioned before, all the connections between the superheater and the kettle as well as the extraction were tightened with cable ties and parafilm which are non-toxic, as well. In the study, the aim was to reach 150°C which was accomplished while using temperature bands.

Because of the initial uncertainty about the amount of the present chlorine, PVC was introduced into our SRF samples. Therefore, PVC was deliberately infused into the three samples to ensure that there was a certain amount of chlorine that we could subsequently remove.

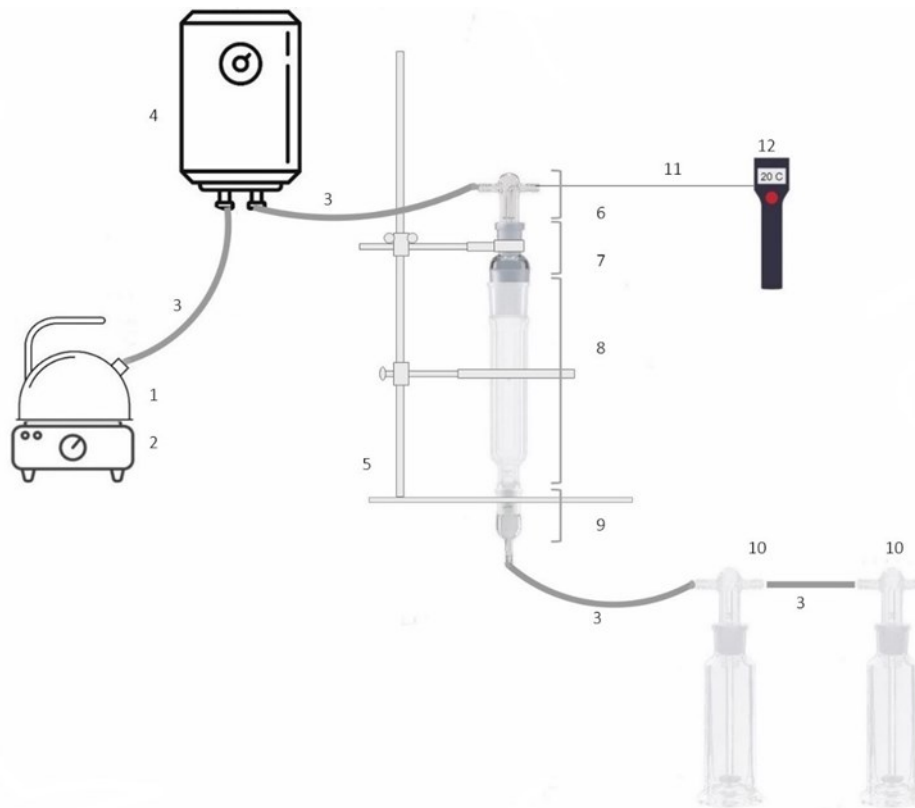


Figure 21: Setup design.

- | | |
|----------------------|---|
| 1.Kettle | 7.Transition piece |
| 2.Hot plate | 8.Extraction attachment for solid |
| 3.PTFE tube | 9.Transition piece with straight tubing |
| 4.Steam heater 2000w | 10.Washing bottle |
| 5.Lab stand | 11.Thermoelement |
| 6. Transition piece | 12.Thermometer |

As previously mentioned, three of the samples were filled with 1 gram of PVC, which is a commonly used thermoplastic with high chlorine content. The experiment was conducted for one hour at 150 °C.

4.3 Experimental results

Tables 13 and 14 show an overview of SRF chemical characteristics after the experiment and effect of the experiment of the samples with and without PVC. The mean, median and standard deviation of samples calculated separately for each group and the concentration change for each element is displayed. The initial concentrations of the SRF sample containing PVC were determined based on the composition of the sample bag, which consisted of 10 grams of washed SRF and 1 gram of PVC. The concentration of washed SRF (as shown in table 11) was utilized for the samples containing washed SRF without PVC.

Table 13: Chemical component overview of the samples containing washed SRF and PVC. Units in mg/kg except for dry residue, temperature and duration.

	Washed SRF+PVC	After Experiment						Effect of treatment					
		S2	S4	S5	mean	median	standard deviation	S2	S4	S5	mean	median	standard deviation
Temperature (°C)	150	150	150	150	-	-	-	150	150	150	-	-	-
Duration (min)	60	60	60	60	-	-	-	60	60	60	-	-	-
Dry residue (%)	-	99.7	99.8	99.8	99.77	99.8	-	-	-	-	-	-	-
Cl	37236.4	49400	45000	36800	43733.33	45000	6394.79	+33%	+21%	-1%	+17%	+21%	+17%
Li	1.6	1.6	1.5	1.6	1.57	1.6	0.06	+1%	-6%	+1%	-2%	+1%	+4%
Be	2.5	2.5	2.5	2.5	2.50	2.5	0.00	0%	0%	0%	0%	0%	0%
Na	3249.0	2840	3050	2900	2930.00	2900	108.17	-13%	-6%	-11%	-10%	-11%	+3%
Mg	1891.0	1790	1820	1660	1756.67	1790	85.05	-5%	-4%	-12%	-7%	-5%	+4%
Al	10727.5	16900	12200	11700	13600.00	12200	2868.80	+58%	+14%	+9%	+27%	+14%	+27%
Si	17457.1	17000	16800	17100	16966.67	17000	152.75	-3%	-4%	-2%	-3%	-3%	+1%
P	300.2	330	290	310	310.00	310	20.00	+10%	-3%	+3%	+3%	+3%	+7%
K	754.8	820	770	780	790.00	780	26.46	+9%	+2%	+3%	+5%	+3%	+4%
Ca	34004.5	24300	24900	30200	26466.67	24900	3247.05	-29%	-27%	-11%	-22%	-27%	+10%
Ti	2854.6	3070	2470	2580	2706.67	2580	319.43	+8%	-13%	-10%	-5%	-10%	+11%

V	2.3	2.9	2.9	2.6	2.80	2.9	0.17	+26%	+26%	+13%	+22%	+26%	+8%
Cr	50.0	75	48	45	56.00	48	16.52	+50%	-4%	-10%	+12%	-4%	+33%
Mn	72.8	62	62	55	59.67	62	4.04	-15%	-15%	-24%	-18%	-15%	+6%
Fe	1664.0	2100	1930	2100	2043.33	2100	98.15	+26%	+16%	+26%	+23%	+26%	+6%
Co	5.0	4.2	2.9	3.4	3.50	3.4	0.66	-16%	-42%	-32%	-30%	-32%	+13%
Ni	43.7	34	24	32	30.00	32	5.29	-22%	-45%	-27%	-31%	-27%	+12%
Cu	66.4	70	66	55	63.67	66	7.77	+5%	-1%	-17%	-4%	-1%	+12%
Zn	954.8	250	290	240	260.00	250	26.46	-74%	-70%	-75%	-73%	-74%	+3%
As	2.5	2.5	2.5	2.5	2.50	2.5	0.00	0%	0%	0%	0%	0%	0%
Se	2.5	2.5	2.5	2.5	2.50	2.5	0.00	0%	0%	0%	0%	0%	0%
Sr	40.0	44	36	37	39.00	37	4.36	+10%	-10%	-8%	-3%	-8%	+11%
Mo	3.5	5	3.2	2.9	3.70	3.2	1.14	+43%	-8%	-17%	+6%	-8%	+33%
Pd	0.3	0.25	0.25	0.25	0.25	0.25	0.00	0%	0%	0%	0%	0%	0%
Ag	2.7	2.6	1.9	2.1	2.20	2.1	0.36	-2%	-29%	-21%	-17%	-21%	+14%
Cd	1.8	2.1	1.6	1.6	1.77	1.6	0.29	+14%	-13%	-13%	-4%	-13%	+16%
Sn	87.3	42	160	130	110.67	130	61.33	-52%	+83%	+49%	+27%	+49%	+70%
Sb	30.9	44	36	45	41.67	44	4.93	+42%	+16%	+45%	+35%	+42%	+16%
Te	0.5	0.5	0.5	0.5	0.50	0.5	0.00	0%	0%	0%	0%	0%	0%
Ba	247.5	300	230	270	266.67	270	35.12	+21%	-7%	+9%	+8%	+9%	+14%
W	18.2	12	6.4	9.8	9.40	9.8	2.82	-34%	-65%	-46%	-48%	-46%	+15%
Hg	0.4	0.29	0.25	0.25	0.26	0.25	0.02	-34%	-43%	-43%	-40%	-43%	+5%

Tl	0.3	0.25	0.25	0.25	0.25	0.25	0.00	0%	0%	0%	0%	0%	0%
Pb	19.1	27	20	16	21.00	20	5.57	+41%	+5%	-16%	+10%	+5%	+29%

Table 14: Chemical component overview of the samples containing washed SRF. Units in mg/kg except for dry residue, temperature and duration.

	Washed SRF	After Experiment						Effect of treatment					
		S1	S3	S6	mean	median	standard deviation	S1	S3	S6	mean	median	standard deviation
Temperatur (°C)	-	150	150	150	-	-	-	150	150	150	-	-	-
Duration (min)	-	60	60	60	-	-	-	60	60	60	-	-	-
Dry residue (%)	100	99.6	99.8	99.8	99.7	99.8	-	-	-	-	-	-	-
Cl	5860	11200	9500	24200	14966.7	11200.0	8041.35	91%	62%	313%	155%	91%	+137%
Li	1.7	2.5	1.7	1.6	1.9	1.7	0.49	47%	0%	-6%	14%	0%	+29%
Be	2.5	2.5	2.5	2.5	2.5	2.5	0.00	0%	0%	0%	0%	0%	0%
Na	3570	4590	3150	2840	3526.7	3150.0	933.83	29%	-12%	-20%	-1%	-12%	+26%
Mg	2080	2410	1920	1960	2096.7	1960.0	272.09	16%	-8%	-6%	1%	-6%	+13%
Al	11800	14300	13400	17100	14933.3	14300.0	1929.59	21%	14%	45%	27%	21%	+16%
Si	19200	21300	17800	17900	19000.0	17900.0	1992.49	11%	-7%	-7%	-1%	-7%	+10%
P	330	340	330	370	346.7	340.0	20.82	3%	0%	12%	5%	3%	+6%
K	830	1020	800	820	880.0	820.0	121.66	23%	-4%	-1%	6%	-1%	+15%
Ca	37400	16000	35200	36600	29266.7	35200.0	11510.57	-57%	-6%	-2%	-22%	-6%	+31%
Ti	3140	3340	3040	3290	3223.3	3290.0	160.73	6%	-3%	5%	3%	5%	+5%

V	2.5	3.7	3.3	3.4	3.5	3.4	0.21	48%	32%	36%	39%	36%	+8%
Cr	55	95	90	51	78.7	90.0	24.09	73%	64%	-7%	43%	64%	+44%
Mn	80	97	81	64	80.7	81.0	16.50	21%	1%	-20%	1%	1%	+21%
Fe	1830	2660	1990	2120	2256.7	2120.0	355.29	45%	9%	16%	23%	16%	+19%
Co	5.5	4	3.7	3.7	3.8	3.7	0.17	-27%	-33%	-33%	-31%	-33%	+3%
Ni	48	33	40	30	34.3	33.0	5.13	-31%	-17%	-38%	-28%	-31%	+11%
Cu	73	66	68	68	67.3	68.0	1.15	-10%	-7%	-7%	-8%	-7%	+2%
Zn	1050	241	230	320	263.7	241.0	49.10	-77%	-78%	-70%	-75%	-77%	+5%
As	2.5	2.5	2.5	2.5	2.5	2.5	0.00	0%	0%	0%	0%	0%	0%
Se	2.5	2.5	2.5	2.5	2.5	2.5	0.00	0%	0%	0%	0%	0%	0%
Sr	44	45	48	44	45.7	45.0	2.08	2%	9%	0%	4%	2%	+5%
Mo	3.6	8	3.5	3.7	5.1	3.7	2.54	122%	-3%	3%	41%	3%	+71%
Pd	0.25	0.25	0.25	0.25	0.3	0.3	0.00	0%	0%	0%	0%	0%	0%
Ag	2.9	2.6	2.2	2.3	2.4	2.3	0.21	-10%	-24%	-21%	-18%	-21%	+7%
Cd	2	2	1.9	2.6	2.2	2.0	0.38	0%	-5%	30%	8%	0%	+19%
Sn	16	12	24	12	16.0	12.0	6.93	-25%	50%	-25%	0%	-25%	+43%
Sb	34	39	41	38	39.3	39.0	1.53	15%	21%	12%	16%	15%	+4%
Te	0.5	0.5	0.5	0.5	0.5	0.5	0.00	0%	0%	0%	0%	0%	0%
Ba	270	270	410	280	320.0	280.0	78.10	0%	52%	4%	19%	4%	+29%
W	20	14	10	17	13.7	14.0	3.51	-30%	-50%	-15%	-32%	-30%	+18%
Hg	0.46	0.37	0.25	0.38	0.3	0.4	0.07	-20%	-46%	-17%	-28%	-20%	+16%

TI	0.25	0.25	0.25	0.25	0.3	0.3	0.00	0%	0%	0%	0%	0%	0%
Pb	21	17	17	18	17.3	17.0	0.58	-19%	-19%	-14%	-17%	-19%	+3%

4.3.1 Chlorine removal

Table 15 shows the changes in chlorine content in each sample after the experiment, relative to the chlorine content present in the washed SRF utilized in the experiment. The percentage variation was determined using the chlorine content in washed SRF samples without PVC (5860 mg/kg) for samples 1, 3 and 6, and washed SRF samples with PVC (37236.4 mg/kg) for samples 2, 4 and 5. As evidenced by table 14, the chlorine concentration in samples without PVC had a noteworthy increase compared to the washed SRF.

Although no additional chlorine was introduced through steam treatment, our experimental findings revealed an increase in chlorine content. This might be caused by different reasons. One of which would be the loss of a certain constituent of the samples during the steam treatment process. The use of tea bags to encase the samples within the reactor could also be an optional explanation for the sample loss as we observed the presence of particles of the samples within the first washing bottle which caused a reduction in the mass of the samples. Moreover, we did not document the precise mass of the samples after the experiments which could potentially impact our results. Referring to table 15, it can be observed that Sample 1 experienced a 91% increase in chlorine content after the experiment. If we assume that the mass reduction had a proportional effect on the change of chlorine content, then the sample's post-experiment mass would be approximately two times smaller than its initial mass. However, the laboratory data sheet indicates that the sample's mass was around 10 grams, and therefore the assumption of mass reduction cannot be applied to this case and can be rejected. The second hypothesis pertains to the potential inhomogeneity of the SRF sample, which could have led to chlorine content fluctuations in the samples utilized in this experiment. However, our findings would still need further experiments to prove this assumption, as the number of samples was very limited in the present study. Thus, further experimentation is warranted for those interested in obtaining more comprehensive insights into the matter. In conclusion, due to the high fluctuation of chlorine content observed after the steam treatment process, we would recommend conducting several experiments with a much larger number of samples to ensure reliable outcomes and intensifying the analysis of the untreated SRF to obtain consistent results regarding chlorine concentration.

Table 15: Chlorine content change after experiment. AE (After Experiment)

	Temperature and Duration	Content	Chlorine content AE (mg/kg TS)	Δ (%)
Sample 1	150 °C – 60 min	10 gr SRF	11200	+91%
Sample 2	150 °C – 60 min	10 gr SRF + 1 gr PVC	49400	+33%
Sample 3	150 °C – 60 min	10 gr SRF	9500	+62%
Sample 4	150 °C – 60 min	10 gr SRF + 1 gr PVC	45000	+21%
Sample 5	150 °C – 60 min	10 gr SRF + 1 gr PVC	36800	-1%
Sample 6	150 °C – 60 min	10 gr SRF	24200	+313%

4.3.2 Effect of steam treatment on other elements

Two sets of samples were analysed for concentration changes, where one set contained PVC and the other set did not. There are four categories of elements based on their concentration changes.

- Elements with unchanged concentration.
- Elements with increased concentration.
 - Slightly increased (under 50%).
 - Significantly increased (above 50%).
- Elements with decreased concentration.
 - Slightly decreased (under 50%).
 - Significantly decreased (above 50%).
- Elements with fluctuating concentration.

Samples with PVC:

- Elements with increased concentration:

A slight increase was observed in the concentration of Al, Sb, V, K and Fe. There was not notable increase observed for this particular group.

- Elements with decreased concentration:

A slight decrease was observed in the concentration of the elements Na, Ag, Mg, Si, Ca, Mn, Co, Ni, W and Hg. The concentration of Zn decreased significantly.

- Elements with unchanged concentration.

The concentration of Be, As, Se, Pd, Te and Tl remained equivalent to their initial concentration.

- Elements with fluctuating concentration:

Some elements exhibit varying changes across different samples. Li, Ti, Cu, P, Cr, Sr, Mo, Sn, Ba, Cd, Pb and Cl are among the examples of such elements. Their concentrations do not adhere to a specific pattern, as they may either significantly increase or decrease in different samples.

Samples without PVC:

- Elements with increased concentration:

A slight increase was observed in the concentration of Al, V, Fe, Sb, Sr, and P. Nonetheless, there was a significant increase in the concentration of Cl.

- Elements with decreased concentration:

The concentration of elements Ca, Co, Ni, Cu, Ag, W, Hg, and Pb exhibited a slight decrease. However, a significant decrease was observed in the concentration of Zn.

- Elements with unchanged concentration:

The concentration of Be, As, Se, Pd, Te, and Tl remained equivalent to their initial concentration.

- Elements with fluctuating concentration:

The concentration of elements Li, Na, Mg, Si, K, Ti, Cr, Mn, Mo, Cd, Sn, Cr, Mn and Ba exhibited both increases and decreases across the samples, without any discernible pattern.

4.3.3 Drying effect of steam treatment

In the next phase of the experiment, 14 additional washed SRF samples (10 gr) which were completely dried in accordance with EN 14346 as previously mentioned, were soaked in ion-exchanged water and their weights were measured after soaking. The experiment time was altered to identify the specific duration required for the samples to dry completely. A total of fourteen experiments were conducted to evaluate the effectiveness of steam treatment in drying wet samples. The experimental protocol comprised four trials with a duration of 60 minutes, one trial for 45 minutes, three trials for 30 minutes, one trial for 20 minutes, one trial for 15 minutes, one trial for 10 minutes, one trial for 5 minutes, one trial for 2 minutes and one trial for 1 minute. For one 45-minute experiment and three 30-minute experiments, SRF samples were enriched with one gram of PVC. It should be noted that all the experiments were conducted at 150°C.

Figure 22 shows an overview of the drying process and detailed information provided in table 16. The water content in the diagram is the weight difference of sample weight before and after experiment. Using ion-exchanged water can ensure uniform experimental conditions. According to the findings, samples that were subjected to experiments lasting 15 minutes or longer were observed to be fully dried. However, a decrease in experiment duration resulted in the retention of water content in the samples. It should be noted that in the 45-minute experiment, the weight of the sample before and after the procedure was identical. The experiment conducted for two minutes revealed that the water content inside the sample had been completely eliminated. However, the ten-minute experiment did not yield any significant drying effect on the sample. It is important to note that the two-minute experiment result cannot be generalized, as it was only applicable for a specific setting (temperature, steam flow and duration of the experiment). To obtain more accurate results, it is recommended that each experiment with a specific duration be conducted at least four times in future studies.

As mentioned earlier, four samples were supplemented with PVC to evaluate its impact on the drying process. Despite the increased mass of the samples due to PVC addition, our results indicate that the drying process remained unaffected, and all samples were able to dry completely. However, it is important to note that further investigation may be necessary to determine any potential long-term effects of PVC on the drying process.

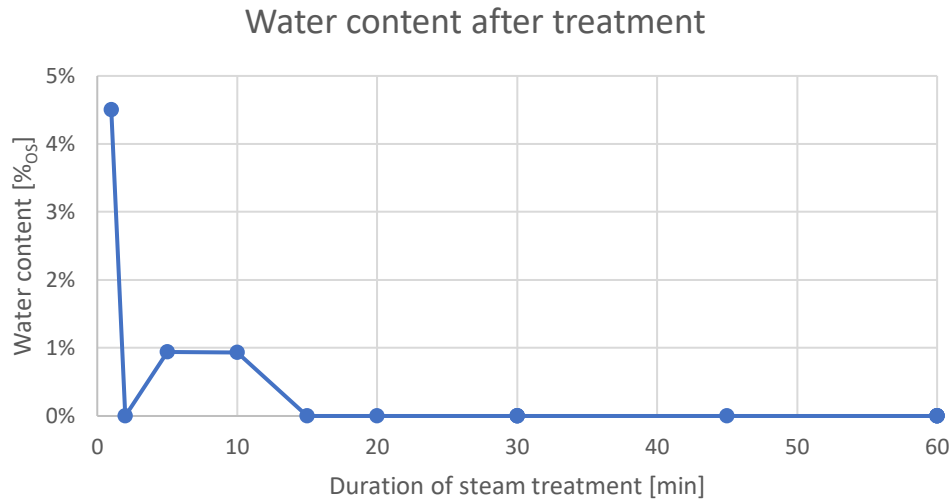


Figure 22: Water content after steam treatment.

Table 16: Detailed information of the experiments. BE (Before Experiment), AE (After Experiment)

Experiment duration (min)	Temperature (°C)	Weight BE (gr)	Weight after soaking in water (gr)	Weight AE (gr)	Δ (weight BE-weight AE)	Water content (%)
60	150	10.6	13.5	10.5	-0.1	0
60	150	10.5	13.6	10.4	-0.1	0
60	150	10.6	14.1	10.5	-0.1	0
60	150	10.6	13.9	10.5	-0.1	0
45	150	11.5	14.2	11.5	0	0
30	150	11.6	14.6	11.5	-0.1	0
30	150	11.6	14.2	11.5	-0.1	0
30	150	11.6	14	11.5	-0.1	0
20	150	10.6	13.7	10.4	-0.2	0
15	150	10.5	13.2	10.3	-0.2	0
10	150	10.6	14.1	10.7	0.1	0.9
5	150	10.5	12.8	10.6	0.1	0.9
2	150	10.6	13.4	10.5	-0.1	0
1	150	10.6	13.1	11.1	0.5	4.5

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5.4 List of abbreviation

MSW – Municipal Solid Waste

RDF – Recovered Derived Fuel

WtE – Waste to Energy

GHG – Greenhouse Gas

TCC – Total Chlorine Content

SRF – Solid Recovered Fuel

C&DW – Construction and Demolition Waste

HP – Hazardous Properties

TOC – Total Organic Carbon content

MBP – Mechanical Biological Pre-treatment

SW – Solid Waste

BAWP – Bundes-Abfallwirtschaftsplan

MW – Municipal Waste

MBT – Mechanical Biological Treatment

IW – Industrial Waste

IEA – International Energy Agency

CHP – Combined Heat and Power

ATT – Advanced Thermal Treatment

MBT – Mechanical Biological Treatment

BMW – Biodegradable Municipal Waste

MRF – Material Recovery Facilities

ABT – Advanced Biological Treatment

EfWs – Energy from Waste plants

TDF – Tire Derived Fuel

AF – Alternative Fuel

HHW – Household Waste

C&IW – Commercial and Industrial Waste

CW – Construction Waste

DW – Demolition Waste

LHV – Lower Heating Value

HHV – Higher Heating Value

PPCT – Paper, Plastic, Composite, Textile

WIO – Waste Incineration Ordinance

PTFE – Poly Tetra Fluoro Ethylene

HT – Hydrothermal Treatment

PVC – Polyvinyl Chloride