Master's Thesis in Environmental and Land Engineering

Polytechnic University of Turin

Department of Environmental and Land Engineering

Life cycle assessment of bottom ash valorisation into foam glass-ceramic

Supervisors:

Prof. Francesca Demichelis

Prof. Tonia Tommasi

Candidate:

Pouria Sedigh (s300775)

Academic year 2024-2025

To the nine pillars of my life;

My beloved Zahra, my parents, my sister,
Zahra's Parents, sister, and brother.

Table of Contents

Abstract **2**
Chapter 1: Introduction **4**
Chapter 2: Combustion plant **13**
2.1 Incineration process 13
2.2 Incineration plants in Europe 13
2.3 Bottom ashes and fly ashes: composition and current management 14
Chapter 3: Introduction to Life Cycle Assessment **17**
3.1 Description of the phases 17
3.2 Applicability 22
Chapter 4: Materials and methods **24**
4.1 Goal and scope 24
4.2 Inventory data 25
4.3 Impact assessment 37
Chapter 5: Results **38**
5.1 Environmental impacts of the process 38
5.2 Climate change impacts 39
5.3 Highest impact items and mitigation strategies 43
5.4 Comparison with literature 45
5.5 Comparison with conventional pathways 47
Conclusion **52**
References **54**

Abstract

The increasing generation of Municipal Solid Waste (MSW) and the need for sustainable management strategies present a critical environmental challenge. Among the residues from MSW incineration, bottom ash (BA) is the largest solid output by mass and poses long-term risks due to heavy metals and other pollutants. Conventional disposal methods like landfilling or low-grade reuse fail to address the environmental burden or resource potential of BA. In this context, thermal valorisation into high-value construction materials such as foam glass-ceramics has emerged as a promising solution.

This thesis aims to assess and compare the environmental performance of different BA conversion pathways through a Life Cycle Assessment (LCA) approach, following ISO 14040–44:2006 standards.

The functional unit of the study was 1 kg of BA, and the boundary conditions were from the grave to the gate, which included MSWI incineration, energy, and ashes (BA and fly ashes), and product productions. Inventory data were derived from peer-reviewed literature and adapted to Italian energy and waste composition contexts.

The study focuses on four product scenarios derived from two main technological routes. Product 1A represents the foam glass-ceramic route, in where BA is vitrified and foamed using minimal additives. In contrast, Products 2A, 2B, and 2C represent three variants of the foam glass-ceramic route, using 60%, 50%, and 40% bottom ash respectively, supplemented with various additives.

The environmental assessment was carried out using the ReCiPe 2016 Midpoint (H) method within SimaPro 9.6.0.1 and database Ecoinvent 3.5.0.1. The impact categories were: Global Warming Potential (GWP) and Human Toxicity, Non-Carcinogenic.

The results revealed that Product 1A, whose climate performance is largely influenced by the inclusion of steam from the incineration process and process credits during fly ash separation, outperformed the other scenarios across the GWP impact category, while it showed the highest human toxicity levels, highlighting the environmental benefits and challenges of modelling energy recovery and waste treatment in material valorisation. Among the 2-series products, Product 2A (with 60% BA content) showed the best performance, while Product 2C (40% BA) exhibited the highest environmental impacts, mainly due to the increased use of external materials, such as sodium phosphate, and reliance on grid electricity.

In conclusion, the thesis showed that the thermal conversion of bottom ash into foam glass-ceramic (as in Product 1A) can significantly reduce climate change impacts, primarily due to the inclusion of steam derived from incineration and the crediting of emissions avoided during fly ash separation. However, this environmental benefit comes with trade-offs, as Product 1A also exhibits the highest impacts in terms of human non-carcinogenic toxicity. These findings highlight the need to balance carbon efficiency with toxicity control in bottom ash valorisation strategies. The results further emphasize the critical role of careful material formulation and LCA modelling.

The analysis of the 2-series products suggests a clear trend: higher bottom ash content and reduced reliance on external additives are associated with lower overall environmental impacts, reinforcing the value of maximizing waste utilization in sustainable material design.

Future perspectives include extending the LCA to endpoint impact categories and assessing economic feasibility and scale-up potential.

Based on LCA results and the identified hotspots, further experimental work should be done to reduce the final environmental impacts.

Chapter 1: Introduction

The management of Municipal Solid Waste (MSW) poses one of the most pressing environmental challenges of our time. As societies strive toward sustainability and circular economy goals, the question is no longer whether to treat waste, but how to treat it responsibly. Among the various treatment technologies, incineration has emerged as a widely adopted solution for reducing the volume of waste while recovering energy. However, this apparent efficiency conceals a critical issue: the generation of large quantities of solid residues, particularly Bottom Ash (BA) and Fly Ash (FA), that remain after combustion. These residues are often overlooked in public discourse but represent a significant environmental liability due to their potential toxicity, volume, and complex composition. Effectively managing and valorising these by-products is not only essential for minimizing environmental risks but also for unlocking the full sustainability potential of waste-to-energy systems.

The challenge is further intensified by the rapidly growing quantities of waste. Urbanization, industrialization, and evolving consumption patterns continue to escalate MSW generation. According to the United Nations Environment Programme (UNEP), the global volume of MSW reached approximately 2.3 billion tonnes in 2023 and is projected to rise to 3.8 billion tonnes by 2050 [1]. Italy alone generated about 29.1 million tonnes of MSW in 2022, around 486 kg per capita, placing it slightly below the EU average of 513 kg per capita [2].

Incineration, also known as waste-to-energy (WtE), is a thermal treatment process in which MSW is combusted at high temperatures (typically 850–1100 °C) in specialized furnaces to reduce waste volume and recover energy. The incineration process consists of three main components: combustion, energy recovery, and air pollution control [3]. *Figure 1* shows a schematic diagram depicting the common MSW incineration process.

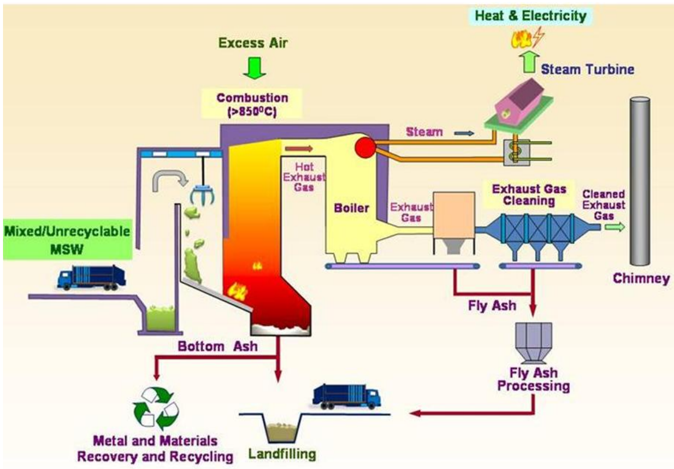

Figure 1. Schematic Diagram of the MSW incineration process [3]

The MSW is fed into the furnace continually for incineration. The temperature for incineration should be at least 850 °C with a residence time of more than two seconds. During the process, the air supply must be sufficient to ensure complete combustion of waste and to prevent the formation of dioxins and carbon monoxide. For energy recovery, the heat generated from waste is used to produce steam in the boiler. Then the steam drives the turbine to generate electricity. The excess heat generated can also be used for other purposes, e.g., heating for swimming pools. Air pollution is a major problem for incineration. In modern incinerators, an advanced pollution control system is designed to minimize the pollution and ensure compliance with environmental standards [3].

As a result of the incineration process, different solid and liquid residual materials as well as gaseous effluents are generated. Approximately one-fourth of the waste mass on a wet basis remains as solids. The volume of residues corresponds to one-tenth of the initial waste volume. Typical residues of MSWI by combustion are: Bottom ash, which consists primarily of coarse non-combustible materials and unburned organic matter collected at the outlet of the combustion chamber in a quenching/cooling tank. Grate siftings, including relatively fine materials passing through the grate and collected at the bottom of the combustion chamber. Grate siftings are usually combined with bottom ash, so that in most cases it is not possible to separate the two waste streams. Together bottom ash and grate siftings typically represent 20–30% by mass of the original waste on a wet basis. Boiler and economizer ash, which represent the coarse fraction of the particulate carried over by the flue gases from the combustion chamber and collected at the heat recovery section. This stream may constitute up to 10% by mass of the original waste on a wet basis. Fly ash, the fine particulate matter still in the flue gases downstream of the heat recovery units, is removed before any further treatment of the gaseous effluents. The amount of fly ash produced by an MSW incinerator is in the order of 1–3% of the waste input mass on a wet basis. Air pollution control (APC) residues, including the particulate material captured after reagent injection in the acid gas treatment units prior to effluent gas discharge into the atmosphere. This residue may be in a solid, liquid or sludge form, depending on whether dry, semi-dry or wet processes are adopted for air pollution control. APC residues are usually in the range of 2% to 5% of the original waste on a wet basis [4].

Along with the gradually increasing yield of the residues, appropriate management and treatment of the residues have become an urgent environmental protection problem. The lack of suitable landfill sites and the environmental impact of direct landfilling of waste boosted regional and national organizations toward more sustainable waste management strategies under the new term "circular economy", suggesting closing the loop of product lifecycle [5]. Recycling is not always an economically viable option, and other strategies like waste-to-energy recoveries are considered for sustainable waste management. There are different waste-to-energy technologies including biological treatment, thermal treatment, landfill gas utilization, and incineration [5].

To manage the increasing waste volume and reduce reliance on landfilling, waste-to-energy (WtE) incineration has emerged as a key technology. It reduces the waste volume by up to 70–90% and allows for the recovery of energy in the form of heat and electricity [6]. However, WtE processes generate significant quantities of solid residues, mainly fly ash and bottom ash, that require further treatment and management imposing tremendous strain on the urban living environment [7].

In several countries such as China, incineration is replacing landfilling as the preferred MSW treatment strategy. This shift is driven by land constraints and pollution risks associated with landfills (e.g., leachate, odors, and methane emissions), positioning incineration as a method that not only minimizes waste volume but also contributes to energy supply [8]. Nonetheless, the generation of solid residues such as fly ash and bottom ash imposes serious challenges to environmental safety and urban infrastructure.

At present, the conventional methods to treat MSWI fly ash include landfilling, solidification/stabilization, and resource recovery. Not only landfill cause the loss of valuable land resources, but also, they lead to environmental pollution over time. Therefore, this method is being phased out gradually across the world. Resource recovery is limited in scope due to its high cost; therefore, alternative methods are needed urgently. Recently, the use of waste to prepare glass-ceramics has become a popular solidification/stabilization method. Not only can this method effectively solve the problem of waste treatment, but also glass-ceramics are widely used in many fields, including construction, dentistry, electric power owing to its mechanical and physical properties [9].

Various treatment pathways have been developed to manage the solid residues generated by MSW incineration, particularly bottom ash (BA) and fly ash (FA). Among these, landfilling remains the most widely used method. Typically, BA is deposited in non-hazardous landfills, whereas FA, due to its high toxicity and heavy metal content, is directed to hazardous waste cells. While landfilling is straightforward and relatively cost-effective, it poses significant long-term environmental risks such as heavy metal leaching and groundwater contamination. These concerns have led countries like Italy and other EU member states to progressively reduce their reliance on landfilling in favour of more sustainable valorisation strategies [2].

One such alternative is Mechanical-Biological Treatment (MBT), which involves a two-stage process: first, the mechanical separation of recyclable materials such as metals, plastics, and inert components; and second, the biological stabilization of the remaining organic fraction via aerobic or anaerobic digestion. This method contributes to the reduction of the organic load and allows for partial energy and material recovery. However, MBT is relatively costly and proves largely ineffective in addressing the specific toxic constituents present in bottom ash, thereby limiting its direct applicability to incineration residues [10].

Metal recovery represents another important approach, aiming to extract valuable metals like iron, copper, and aluminium from BA. This is typically achieved through magnetic separation for ferrous metals and eddy current separation for non-ferrous metals. When applied effectively, this method can recover up to 10% of the bottom ash mass and significantly reduce its contamination level, especially in the coarser fractions. Nevertheless, metal recovery from finer fractions remains technically complex and may require more advanced techniques, such as wet separation, to be effective [11].

Thermal stabilization methods such as vitrification and sintering offer highly effective means of neutralizing the hazardous properties of incineration residues. In vitrification, bottom ash is subjected to extremely high temperatures (ranging from 1000 °C to 1500 °C), resulting in a molten glassy slag where heavy metals are chemically immobilized within a stable matrix [5]. While vitrification yields an inert product with minimal leaching potential, it is energy-intensive and demands robust emissions control. Sintering, in contrast, occurs at slightly lower temperatures (~1000–1160 °C) and transforms the ash into either lightweight or dense aggregates suitable for use in construction materials. Though both techniques improve the environmental stability and usability of BA, their high energy demand and operational complexity remain significant drawbacks [10, 12].

Another valorisation route is the incorporation of bottom ash into eco-materials, where pre-treated BA is used as a substitute for virgin raw materials in the production of construction products such as concrete, bricks, and ceramics. Research has shown that BA can replace up to 10–20 wt% of fine aggregates in these materials without compromising their mechanical performance. Glass-ceramic production, leverages BA as a primary feedstock, transforming a potentially hazardous waste into high-value, durable products. However, this pathway demands rigorous material characterization and quality control to address compositional variability and meet regulatory standards [13].

The choice of treatment strategy depends largely on the nature of the waste and the policy framework. For MSW, the overall aim is to reduce the quantity and hazard of landfilled material while recovering energy or materials when possible. As such, integrating residue treatment into the broader waste management chain is critical for meeting circular economy goals and minimizing long-term ecological impacts [4].

Europe’s waste-to-energy (WtE) infrastructure processes tens of millions of tonnes of MSW, yielding substantial amounts of incineration residues. In 2018, around 96 million tonnes of MSW were treated in European WtE plants, producing approximately 19 million tonnes of bottom ash (BA)

[14]. Fly ash (FA), though smaller in volume, remains a critical concern. The European Waste Framework Directive (2008/98/EC) mandates recovery over disposal, yet national policies vary, resulting in less than 50% of BA undergoing dedicated treatment despite growing circular economy ambition [14]. In 2024, the European Economic and Social Committee called for renewed policy support, urging Member States to treat WtE plants as resource hubs integrated with metal recovery and residue valorisation [15]. This regulatory momentum emphasizes minimizing landfill usage and realizing secondary resource recovery from incineration residues.

European countries have adopted an integrated approach to the management of solid residues from municipal solid waste incineration (MSWI), combining conventional disposal techniques with advanced valorization strategies. Landfilling, while considered a last resort, continues to be practiced for both bottom ash (BA) and fly ash (FA). FA is typically disposed of in hazardous waste cells due to its high toxicity, whereas BA is deposited in non-hazardous landfills. Although this method remains economically favorable, it results in the permanent loss of potentially valuable materials and poses long-term environmental hazards, including heavy metal leaching and land degradation [16].

To mitigate such impacts and promote material recovery, metal recovery from BA has become a core component of ash treatment systems across Europe. Mechanical separation technologies enable the recovery of approximately 10–12 weight percent of metals present in bottom ash. This includes ferrous metals, recovered at rates exceeding 70%, and non-ferrous metals such as aluminum and copper, which typically make up 2–5% of the ash. The environmental benefits of this process are significant: according to the Confederation of European Waste-to-Energy Plants (CEWEP), the recovery of metals from bottom ash contributes to annual greenhouse gas savings of nearly 3.8 million tons of CO_2-equivalent emissions [15].

Beyond metal recovery, several European countries have implemented bottom ash processing plants aimed at producing construction-grade aggregates. These facilities typically follow either a dry or wet treatment route. For example, in Belgium, dry processing involves mechanical separation, ferrous/non-ferrous extraction, and aging to reduce reactivity, while wet processing adds washing stages that improve material quality but result in the landfilling of fine particles (<2 mm), which can account for nearly 50% of the total BA mass. Reuse rates vary significantly by region; in Flanders, for instance, only about 15% of processed BA is reused locally, while in other parts of Europe, the reuse rate exceeds 50%. Nevertheless, the strict regulations on material leaching and product certification often lead to the export of these secondary materials to countries with more permissive standards [16].

In parallel, thermal and chemical valorization technologies are gaining traction as part of the European Union’s push for circular economic solutions under initiatives such as the EU Green Deal.

Innovative treatments, including vitrification, ceramization, alkali activation, and chemical stabilization, seek not only to neutralize toxic elements in BA but also to create high-value products. Recent studies have explored alkaline pre-treatment methods, such as treating BA with sodium hydroxide (NaOH), which effectively immobilizes heavy metals while enabling the production of alternative construction materials. One such study demonstrated that replacing up to 30% of cement in concrete formulations with NaOH-treated bottom ash yielded products that satisfied both mechanical strength and leaching regulatory standards [17].

Although Europe has made considerable progress in establishing infrastructure for the management of incineration residues, several critical challenges remain unresolved. One major issue is the regulatory fragmentation caused by the classification of bottom ash (BA) as a "mirror entry" under the EU's List of Waste (LoW). This classification obliges each Member State to independently determine whether BA should be considered hazardous or non-hazardous, resulting in a patchwork of reuse thresholds, testing protocols, and legal interpretations across the continent. Consequently, some countries permit full recycling of BA, while others prohibit its use entirely [18].

Another significant challenge is the gap in treatment capacity. In 2018, it was estimated that about 19 million tons of bottom ash were generated across Europe, but only approximately 46% of this amount underwent formal treatment. The remainder, nearly 10 million tons, was still being sent to landfill, undermining resource recovery and circular economy goals [19]. Within this category, the fine fraction of bottom ash (particles smaller than 2 mm) presents a particular concern. These fines, which typically contain the highest concentrations of heavy metals and other contaminants, are seldom recycled and are frequently landfilled without further processing. This not only constitutes a lost opportunity for recovery but also raises ongoing environmental risks [16].

Even in cases where bottom ash is reused, insufficient or inappropriate pretreatment can result in the leaching of heavy metals and the release of other pollutants into the environment. These concerns are amplified in the case of fly ash, which, due to its high content of soluble toxic substances and persistent organic pollutants such as dioxins, remains a hazardous material unless subjected to proper stabilization techniques [20].

Despite these barriers, several promising opportunities for improvement and innovation are emerging. For instance, the recovery of ferrous and non-ferrous metals from bottom ash has demonstrated substantial environmental and economic benefits. In 2018 alone, approximately 1.15 million tons of ferrous metals and 0.18 million tons of non-ferrous metals were recovered in Europe, leading to significant reductions in greenhouse gas emissions, equivalent to several million tons of CO_2 avoided annually [19].

In addition, the utilization of processed BA as construction material is already well established in certain countries. In Denmark, the Netherlands, and Germany, more than 70–98% of bottom ash is reused as road base or aggregate, provided it meets quality and environmental standards [16]. Beyond traditional reuse, advanced valorization strategies are gaining momentum across Europe. Pilot projects exploring the conversion of bottom and fly ash into high-value materials, such as vitrified products, glass-ceramics, and technical ceramics, demonstrate the potential for fully circular and sustainable management of these residues [21].

Europe's incineration sector stands at a pivotal moment. While WtE remains effective for reducing waste volume and recovering energy, its by-products, BA and FA, present both challenges and opportunities. Transitioning from disposal toward valorisation necessitates harmonized regulations, investment in advanced treatment technologies, and market creation for secondary materials. Strengthening metal recovery, scaling up sustainable valorisation methods, and enhancing cross-border standardization will be crucial to transforming residues into valuable resources, making WtE a genuine pillar of the circular economy.

In recent years, the sustainable transformation of industrial and municipal solid wastes into environmentally friendly construction materials has gained significant momentum. This shift toward circular material strategies seeks to reduce reliance on finite natural resources while minimizing the environmental footprint of production in material-intensive industries [8]. Among these strategies, the synthesis of glass-ceramics from waste has emerged as a highly promising approach, largely due to their mechanical robustness, chemical resistance, and strong ability to immobilize heavy metals [8].

Glass-ceramics are hybrid materials that combine the shapability of glass with the structural resilience of ceramics. Their exceptional durability and thermal stability make them suitable for a wide array of applications, from building facades to high-tech uses in electronics and waste containment [22]. Closely related are ceramic foams, which are lightweight porous structures known for their insulation capacity and chemical resistance. These are commonly utilized in areas such as diesel engine filtration and wastewater treatment systems [23].

An increasingly adopted solution involves the production of glass-ceramics from hazardous wastes, which not only mitigates environmental risks but also creates economic value. These materials are especially useful in the construction sector as alternatives to natural stones like marble, providing relief from resource scarcity and contributing to waste diversion [24]. A specialized form, known as foam glass-ceramic, combines the strengths of glass-ceramics and ceramic foams, offering low density, thermal insulation, and chemical durability. Significantly, MSWI bottom ash, rich in oxides like SiO_2, Al_2O_3, and CaO, serves as an ideal raw material for foam glass-ceramic production, while simultaneously enabling the stabilization of heavy metals [25].

A key enabler of this process is vitrification, a high-temperature technique originally developed for the treatment of radioactive wastes. It involves melting materials to form a stable glass matrix that locks in hazardous components, reducing leachability. Though energy-intensive (requiring 1100–1500 °C), vitrification remains one of the most reliable methods for safely processing bottom ash, particularly when supplemented with waste glass cullet to improve melt quality [5].

Conventional treatments like landfilling and basic stabilization suffer from long-term environmental risks and missed resource recovery opportunities. In contrast, converting bottom ash into high-value glass-ceramic products offers a dual benefit: neutralizing the toxic potential of waste and contributing to sustainable material cycles. As a result, this approach is increasingly recognized as a viable and forward-looking solution for MSWI residue management [9].

The core aim of this thesis is to conduct a comprehensive Life Cycle Assessment (LCA) of the thermal valorization of municipal solid waste incineration (MSWI) bottom ash into foam glass-ceramic materials. This study begins by evaluating the environmental impacts of the conversion process using the LCA methodology, as structured in the ISO 14040 and 14044 standards. It proceeds with a detailed characterization of the bottom ash, focusing on its chemical composition and physical properties relevant to glass-ceramic synthesis. Furthermore, the thesis documents and analyzes the energy and material flows involved in the vitrification and sintering processes.

A critical component of the work is the comparison of environmental performance between the glass-ceramic products derived from bottom ash and more conventional treatment pathways, such as landfilling or use in construction aggregates. In addition, the thesis explores the potential of these innovative materials to function as substitutes for natural construction resources, thereby aligning with the broader objectives of the circular economy.

Through this multifaceted approach, the thesis aims to provide data-driven insights into the feasibility, environmental sustainability, and circularity potential of producing glass-ceramic and foam glass-ceramic materials from MSWI bottom ash, ultimately transforming a challenging waste stream into a valuable secondary resource.

A systematic review some studies in solid waste management highlights that most assessments are geographically concentrated in Europe and focus primarily on household or food waste, underscoring a critical research gap in valorisation of industrial residues like MSWI bottom ash [26]. This gap limits the ability to generalize findings across methodologies, technologies, or contexts, reinforcing the need for targeted studies such as this one to capture localized characteristics (e.g., ash composition, energy mix, process emissions).

Applying Life Cycle Assessment (LCA) to the production of glass-ceramic materials from bottom ash enables a comprehensive evaluation of the associated environmental burdens and benefits under real-world conditions. A recent study on porous glass-ceramics synthesized from MSWI fly ash, with bottom ash serving as a silica source, highlighted the feasibility of this valorization route. The study reported notably low environmental impacts, with CO_2 emissions of just 0.467 kg CO_2-eq per kg of product and energy requirements of approximately 9.3 MJ/kg. However, these insights were only made possible through a full life cycle perspective that captured the broader environmental trade-offs of the process [5].

In alignment with this approach, the LCA conducted in this thesis is designed to provide a case-specific yet replicable model based on dynamic, regionally relevant data, including actual bottom ash composition, the Italian energy mix, and industrial parameters for glass-ceramic manufacturing. Moreover, it facilitates a direct comparison between innovative grave-to-gate valorization strategies and conventional alternatives such as landfilling or reuse in low-grade aggregates [27].

The result is a robust, regionally contextualized LCA framework that not only benchmarks potential environmental gains of bottom-ash-to-glass-ceramic conversion but also offers adaptable insights for policymakers and waste management stakeholders seeking scalable, sustainable circular economy solutions.

Chapter 2: Combustion plant

2.1 Incineration process

Incineration stands out for its efficacy in solid waste disposal, offering advantages like substantial volume and mass reduction, energy recovery, and the destruction of pathogens and harmful contaminants. However, the process generates ash residues, particularly bottom ash and fly ash, which contains potentially harmful substances such as leachable heavy metals, dioxins, and other toxic substances [28].

Municipal solid waste incinerators (MSWIs) are key facilities in Waste-to-Energy (WtE) systems, designed to combust urban waste efficiently and recover energy while controlling emissions. The most common design is the moving-grate incinerator, which allows MSW to move continuously through the furnace, ensuring uniform combustion and enabling large throughputs [29].

The waste is first delivered into a storage bunker, from which it is transferred onto the moving grate by overhead cranes. Once on the grate, primary air is injected from beneath to initiate the sequential processes of drying, pyrolysis, and combustion. The grate's movement and continuous air supply yield a 70–85% mass reduction and 90–96% volume reduction. Temperatures in the primary zone must reach 850–1,100°C and maintain a residence time of ≥2 s with sufficient oxygen, following the "3T" rule (Temperature, Time, Turbulence) to ensure complete destruction of organic pollutants [30].

Above the primary grate lies a secondary combustion chamber, where secondary air (~50–80 m/s) is injected to mix flue gases and complete combustion. This step destroys remaining organics and prevents dioxin formation. The chamber is typically maintained at ≥ 850 °C with ≥2 s residence time, in compliance with the EU Waste Incineration Directive [30].

The heat released during combustion is used to produce high-pressure steam, typically around 400 °C and 40 bar, by heating water in boilers and superheaters. This steam drives turbines to generate electricity, and any excess heat can be used for district heating. When both electricity and heat are recovered in this way, the system's overall energy efficiency can reach or even exceed 80% [30].

2.2 Incineration plants in Europe

Europe boasts a well-established Waste-to-Energy (WtE) infrastructure, with hundreds of municipal solid waste incineration facilities playing a pivotal role in both waste management and renewable energy supply.

Number of WtE plants in 2020 figures, according to CEWEP, by 2020 there were 504 plants with a total incineration capacity of 61 Mt MSW/year [31]. Major operators include France (121 plants) and Germany (98 plants). Other countries with significant numbers are Italy (38 plants), Sweden (37 plants), Denmark (26 plants), and the Netherlands (12 plants) [32].

The high number of combustion plants and their capacity reflects significant bottom ash generation currents in Europe, providing ample feedstock for valorisation studies.

2.3 Bottom ashes and fly ashes: composition and current management

Bottom ash (BA) is the coarse, non-combustible material that settles at the bottom of the furnace during the incineration of municipal solid waste (MSW), typically accounting for about 15–25 wt% of the input waste [3]. It constitutes around 80–90 wt% of the total incineration residues [5, 7], with the remaining fraction being fly ash (FA) and air pollution control (APC) residues [8]. BA is generally classified as a non-hazardous waste, although it contains a mixture of heavy metals (such as Pb, Zn, Cu, Cr), glass particles, ceramics, mineral oxides like SiO_2, CaO, Al_2O_3, and Fe_2O_3, as well as unburned or partially burned organic matter [3, 33, 34]. The nature of BA is highly heterogeneous and granular, comprising broken glass cullet, ceramic fragments, sintered phases, and sometimes uncombusted material [28].

The incineration of one tonne of municipal waste typically results in the generation of about 300 kg of bottom ash and 30 kg of fly ash [35]. In Italy alone, this corresponds to an annual production of approximately 750,000 tonnes of bottom ash and 130,000 tonnes of fly ash [35]. In terms of morphology, bottom ash tends to be coarse and granular, while fly ash is much finer in particle size (micron scale), often highly glassy due to rapid quenching inside the boiler furnace [36].

While fly ash is considered hazardous due to the presence of toxic organic compounds and concentrated heavy metals, bottom ash, although non-hazardous, may still pose environmental concerns. If not properly treated, bottom ash can lead to issues such as heavy metal leaching into the soil and groundwater or airborne dust generation [37]. Landfilling of BA remains a common disposal method, yet it demands substantial land use and reflects a lost opportunity for material recovery [37].

Despite these risks, BA has significant potential for valorization due to its mineral-rich content. The high concentrations of silica, alumina, lime, and iron oxides make it an attractive candidate for secondary raw material applications [3]. Several studies have demonstrated the feasibility of extracting ferrous and non-ferrous metals from BA through magnetic and eddy current separation techniques, contributing to both resource recovery and reduced environmental impact [38]. Moreover, the mineral component of BA has been explored for use in construction materials such as road base, backfilling, concrete, bricks, and hybrid cements [53, 8].

In the European Union, over 19 million tonnes of bottom ash are generated each year, but only a portion is subjected to treatment or recycling processes [38]. This highlights the pressing need for innovative approaches to improve the management and utilization of BA streams. One of the most promising routes is thermal treatment, particularly vitrification, which transforms BA into a stable, inert glass-like phase. Vitrified bottom ash (VBA) can then be further processed into glass-ceramic products suitable for use in construction, filtration systems, and other industrial applications [37, 53].

The other incineration residues are fly ashes, which consist of the finer particles carried by the flue gases and captured by filtration systems such as baghouse filters or electrostatic precipitators. FA typically constitutes about 10–20% of the total ash, meaning that from the incineration of one ton of municipal solid waste, approximately 30 kg of fly ash is generated [35]. In Italy, this translates to an estimated 130,000 tonnes of FA annually [35], and globally, the figure reaches approximately 6.63 million tonnes per year [9]. The composition of fly ash can vary significantly depending on factors such as waste composition, combustion technology, and flue gas cleaning methods. However, it commonly contains soluble salts, high concentrations of heavy metals, and organic pollutants such as dioxins. While bottom ash may also contain heavy metals, the concentration in FA is significantly higher, which leads to its classification as hazardous waste in most countries. Commonly detected heavy metals in FA include Hg, Pb, Zn, Cd, As, Sb, Cu, Sn, Ni, Cr, and V [5].

FA is known for its fine particle size and relatively high glassy content, a result of the rapid cooling conditions within the boiler furnace. Despite undergoing complete combustion, fly ash often contains traces of residual carbon, sulphur, and a variety of toxic organic compounds, making it a considerable challenge in terms of environmental management [36]. If not properly managed, fly ash can pose significant environmental risks, particularly in terms of heavy metal leaching into soil and groundwater and the release of airborne pollutants [28]. Toxic pollutants such as dioxins and furans, in addition to heavy metals, can cause irreversible damage to ecosystems and human health [7].

Currently, several methods are employed for the treatment and disposal of MSWI fly ash. These include: (1) secure landfilling, often in dedicated hazardous waste cells; (2) use as raw material in cement, either through direct incorporation or after stabilization; (3) chemical or physical separation of heavy metals, using washing or extraction methods; and (4) thermal treatments such as vitrification [7]. However, each of these approaches has limitations. Landfilling and cement incorporation risk secondary pollution through long-term leaching of heavy metals [9]. Physical and chemical treatments often require additives and may generate secondary waste streams or residues [23].

Due to the environmental risks and the growing pressure for sustainable waste management, researchers have proposed more innovative solutions. Among them, the conversion of MSWI fly ash into high-value glass-ceramic materials has gained attention [22]. This approach not only offers a means of stabilizing toxic components through the formation of inert crystalline-glassy matrices but also generates economically valuable products with applications in construction and other industries. Nonetheless, the industrial-scale adoption of such technologies remains limited, primarily due to the high energy requirements and processing costs involved [22].

Chapter 3: Introduction to Life Cycle Assessment

The Society of Environmental Toxicology and Chemistry (SETAC), founded in 1979, played a foundational role in developing and formalizing Life Cycle Assessment (LCA) methodology. According to SETAC, LCA "addresses the environmental aspects and potential environmental impacts (e.g., resource use and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment and disposal (i.e. cradle-to-grave)" [40]. Originating in the late 1980s and early 1990s, SETAC workshops (e.g., Smugglers Notch 1990, Sesimbra 1993) introduced the technical framework, the SETAC triangle, comprising Goal & Scope, Inventory, Impact Assessment, and Improvement Analysis. This structure closely resembles, but predates, the ISO 14040–44 framework, which later adopted "Interpretation" as its final phase in place of SETAC's explicit "Improvement" stage [41].

This SETAC-originated definition and methodological structure underpins the approach adopted in this thesis, ensuring a rigorous and internationally recognized basis for the goal definition, boundary setting, inventory modelling, impact evaluation, and recommendations that follow. The technical robustness and transparency emphasized by SETAC provide credibility to subsequent chapters where these elements are applied to assess the bottom ash valorisation process.

3.1 Description of the phases

Definition of Goal and Scope.

The goal and scope definition phase represents the foundation of any Life Cycle Assessment (LCA), shaping the direction and boundaries of the entire study. As outlined in the ISO 14040 and 14044 standards, this phase serves to clarify the purpose of the analysis, define what is included and excluded, and ensure that the results are scientifically valid and useful for their intended application [42].

At the outset, the goal of the study must be clearly articulated. This includes identifying why the study is being carried out, who the intended audience is, and whether the findings will be used for public comparisons or internal decision-making [43]. In the context of this thesis, the goal is to evaluate and compare the environmental performance of two specific valorization routes for municipal solid waste incineration (MSWI) bottom ash, namely, the production of foam glass-ceramic materials from two different processes. These materials represent a high-value alternative to traditional bottom ash disposal methods, and the LCA aims to assess their environmental feasibility.

Equally important is the definition of the functional unit, which acts as a reference point for the entire life cycle model. All material and energy inputs, as well as the calculated environmental impacts, are related back to this unit [43]. For this study, the functional unit is defined as the treatment of 1 kilogram of bottom ash. This choice ensures consistency and comparability between different process scenarios, and it provides a scalable basis for evaluating environmental performance.

The system boundaries determine the extent of the life cycle that is analyzed. Depending on the objective, the system may be modeled from cradle to grave (i.e., from raw material extraction through to disposal), from cradle to gate, or even gate to gate [43]. This thesis adopts a grave-to-gate perspective: the system begins at the point where bottom ash is collected, treated as a by-product of incineration, and ends at the factory gate, where the valorized foam glass-ceramic product is ready for use. This boundary setting allows the study to focus specifically on the valorization phase, without attributing environmental burdens from the incineration or post-use phases, which are outside the scope.

This phase also involves the identification of assumptions and limitations. These include methodological decisions such as how to allocate impacts between co-products, how to handle data gaps, and which inputs may be excluded if they fall below a certain threshold [43]. In this thesis, secondary data from published literature is used to model the process flows, and allocation is avoided by framing the system around a single waste input, bottom ash, treated entirely within the valorization process.

Finally, the goal and scope definition serve as a safeguard for transparency and comparability. A well-documented scope allows other researchers or stakeholders to understand the assumptions made, to replicate the study, or to compare its outcomes against other systems [43]. This is particularly important in studies like the present one, where alternative waste treatment scenarios are being compared and robust, reproducible results are critical for supporting sustainability-oriented decisions. Thus, the goal and scope phase are far more than a formality [42].

Life Cycle Inventory (LCI).

The Life Cycle Inventory (LCI) phase represents the analytical core of any Life Cycle Assessment and is crucial for translating a system's physical operations into quantifiable environmental inputs and outputs. In this phase, all relevant data are collected and compiled to represent the flows of materials, energy, emissions, and waste associated with each stage of the product system under study [43]. For this thesis, the LCI specifically focuses on the valorization of municipal solid waste incineration (MSWI) bottom ash into foam glass-ceramic products.

The inventory begins with data collection on material inputs, including the bottom ash itself, any additives (e.g., glass cullet, borax, sodium carbonate), water, and fuels or electricity used throughout the process. These flows are tracked from the point where bottom ash is collected (after combustion) through transport, pre-treatment, thermal processing (such as vitrification or sintering), and final product shaping. Additionally, energy inputs, particularly electricity and thermal energy consumed during heating, drying, melting, and cooling operations, are quantified in detail. In many cases, the energy demand of these processes, especially high-temperature stages, significantly influences the overall environmental impact and therefore requires precise measurement or modeling [57, 58].

Equally important is the identification and quantification of outputs, including direct emissions to air (such as CO_2, NO_x, and particulates), potential leachates, process residues, and by-products [43]. For example, steam emissions during drying, gas-phase pollutants from sintering, and solid residues from dust collection systems are all accounted for. These emissions are vital for assessing impact categories such as global warming potential and toxicity. Where direct measurement is not possible, secondary data from peer-reviewed literature or environmental databases (e.g., Ecoinvent) are used to estimate flow magnitudes, with transparent documentation of all assumptions.

This phase also encompasses the definition of data quality requirements and the temporal, geographical, and technological representativeness of the data [43]. In the present study, every effort is made to ensure that the inventory reflects real or region-specific conditions, for example, by aligning electricity consumption data with the Italian national energy mix, and using composition data from bottom ash streams documented in the literature or previous LCA case studies relevant to European contexts.

An essential feature of the LCI phase is the systematic modeling of each unit process, often represented in flow diagrams that depict material and energy connections between stages. These flowcharts guide the structure of the model in LCA software such as SimaPro, where each process is input as a module connected by shared flows. Consistency in units (e.g., per 1 kg of bottom ash) is maintained throughout to ensure coherent aggregation and comparison [57, 58].

Ultimately, the accuracy and completeness of the Life Cycle Inventory heavily influence the reliability of the entire LCA. Poor or missing data at this stage can undermine the conclusions drawn from the impact assessment [42].

Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase plays a pivotal role in the overall Life Cycle Assessment (LCA) framework, as it enables the transformation of raw inventory data, such as emissions, energy use, and material flows, into meaningful environmental impact indicators. While the inventory phase provides the quantitative backbone of a system's inputs and outputs, it is through LCIA that this information becomes interpretable in terms of environmental relevance, helping to answer not just "how much was emitted," but also "what does it mean for the environment?" [57, 58].

This translation process relies on a series of characterization models that group inventory flows into specific impact categories based on their environmental mechanisms. For instance, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are aggregated under the Global Warming Potential (GWP) category, where they are converted into CO_2-equivalents based on their relative heat-trapping effect over a standard time frame (typically 100 years) [42]. Other important categories include acidification (linked to SO_2 and NOx emissions), photochemical ozone formation, terrestrial and aquatic ecotoxicity, human toxicity, eutrophication, and resource depletion (both fossil and mineral) [42].

Each impact category reflects a distinct environmental mechanism, and thus the selection of categories should be aligned with the study's goal and scope. For example, in the assessment of waste valorization processes, human toxicity and ecotoxicity are especially relevant due to potential emissions of heavy metals and persistent organic pollutants from thermal processes. Similarly, GWP is critical when evaluating the net climate impact of energy-intensive processes like vitrification or sintering.

A crucial factor influencing the LCIA phase is the choice of impact assessment method. Several internationally recognized LCIA models are available, including ReCiPe, TRACI, and ILCD, each with different methodological assumptions, regional relevance, and indicator frameworks [43]. For example, ReCiPe 2016, used in this thesis, offers both midpoint and endpoint modeling approaches and allows the practitioner to select from different perspectives—individualist, hierarchist, and egalitarian—based on time horizon and risk preference [42]. The midpoint level, applied here, focuses on problem-oriented indicators (e.g., kg CO_2-eq for GWP) and is preferred for its greater level of detail and lower uncertainty, making it more suitable for comparative assessments of specific waste management technologies.

Another dimension of LCIA is normalization and weighting, which can be optionally applied to help interpret the relative magnitude of impact categories or aggregate them into a single score. However, these steps involve value choices and regional benchmarks and are not always included in comparative LCA studies unless justified by the goal [42].

The LCIA phase serves as the interpretive bridge between raw process data and environmental meaning. By linking emissions and resources used to broader ecological consequences through scientifically derived models, it allows for the objective evaluation and comparison of different processes or products [43]. In the context of this thesis, LCIA quantifies the environmental impacts related in converting BA into foam glass-ceramic materials.

Interpretation

The interpretation phase represents the final and integrative step of the Life Cycle Assessment, where the results from the inventory and impact assessment phases are critically analyzed and contextualized. Its primary aim is to ensure that the conclusions drawn from the study are both scientifically sound and practically meaningful. At this stage, the assessment identifies key contributors to environmental impacts, commonly referred to as hotspots, which may include specific materials, energy sources, or process stages that disproportionately influence the overall results [42].

In addition to pinpointing these hotspots, the interpretation phase incorporates sensitivity and uncertainty analyses to evaluate the robustness of the findings. Sensitivity analysis explores how variations in certain input parameters (such as energy use or emissions data) might affect the outcomes, while uncertainty analysis addresses the reliability of the data and methodological assumptions used throughout the study. These tools are critical for distinguishing between real environmental differences and those that might arise from data limitations or modeling choices [57, 58].

The interpretation process also involves checking for consistency with the originally defined goal and scope of the study and examining whether the results support clear, transparent recommendations. In doing so, it ensures that the LCA not only fulfills academic rigor but also delivers actionable insights that can inform decision-making in industrial practice, policy development, or further research [43]. Ultimately, this phase transforms the complex technical outputs of the LCA into conclusions that are robust, well-justified, and aligned with the intended applications of the study [42].

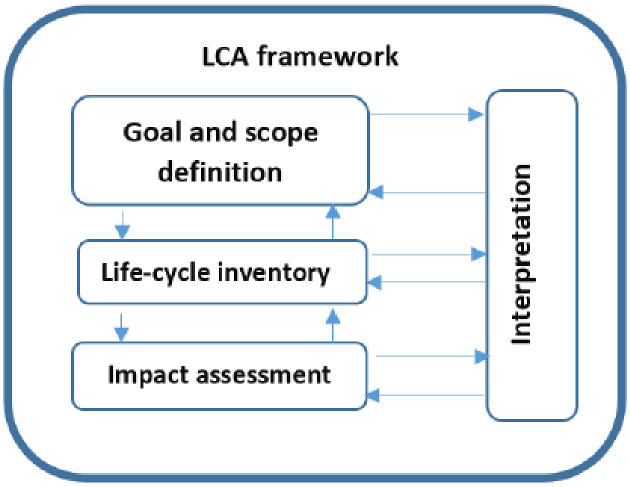

Figure 2. Different phases of LCA according to ISO 14040:2006 [43]

3.2 Applicability

The Life Cycle Assessment (LCA) method is particularly well-suited for evaluating novel waste valorisation strategies, such as converting municipal solid waste incineration (MSWI) BA into foam glass-ceramic materials. LCA provides a structured framework that captures the full spectrum of environmental impacts, from resource extraction through production, use, and disposal, making it ideal for assessing the sustainability of circular economy interventions [44].

Recent systematic reviews highlight LCA's strengths in waste management: it enables quantitative comparison of diverse scenarios (e.g., landfilling vs. valorisation), uncovers environmental hotspots, and facilitates decision-making for cleaner production and resource efficiency. Yet, these reviews also caution practitioners about limitations such as data scarcity, region-specific variability, the need for temporal and spatial context, and methodological harmonization. Addressing these issues requires transparency, robust inventory data collection, and a sensitivity analysis, all integral parts of this thesis's LCA study.

International case studies, from both developed and developing contexts, demonstrate LCA's versatility in comparing conventional versus innovative waste treatments, identifying environmental trade-offs, and supporting policy-making for sustainable waste systems [45]. Specifically, the valorisation of hazardous ashes via vitrification and glass-ceramic synthesis has been assessed using LCA to quantify benefits such as reduced heavy metal leaching and avoided production of primary materials [5].

By applying LCA to the experimental conversion of bottom ash into high-value materials, this thesis will quantify and compare environmental profiles, enabling a robust decision-support tool. It also addresses key research gaps identified in literature, including standardized methodology, localized inventory data, and complete impact and sensitivity analysis. The goal is to produce a credible and replicable environmental assessment that both aligns with global sustainability standards and provides actionable insights for integrating bottom ash valorisation into circular economy strategies

Chapter 4: Materials and methods

4.1 Goal and scope

The goal of this thesis is to conduct an environmental evaluation of two valorisation pathways for municipal solid waste incineration (MSWI) bottom ash (BA): the production of foam glass ceramic materials through two different processes. These materials are increasingly regarded as sustainable alternatives to landfilling and low-grade aggregate use, offering both environmental and economic advantages in line with circular economy principles. The assessment follows the Life Cycle Assessment (LCA) methodology as outlined in ISO 14040-44:2006 standards, and is implemented using the SimaPro 9.6.0.1 software environment and databases Ecoinvent 3.0 and Agri-Footprint were employed.

The functional unit of the study is defined as the treatment and conversion of 1 kg of bottom ash into the final foam glass-ceramic product. This unit provides a consistent basis for comparing environmental burdens associated with each treatment scenario. The functional unit is selected to reflect the typical scale of residue treatment and to allow for scalability of results in future industrial applications.

In this study, the system boundaries are defined differently for the two products. For both products, the boundaries are set as grave-to-gate, but for one of them it is starting from the point where bottom ash is received as a raw material, assuming the environmental impacts from the incineration process have already been accounted for. The analysis then follows the valorization steps up to the finished foam product, ready to leave the factory.

For the other product, however, the system boundaries explicitly include the incineration phase. This means the assessment begins from the waste input before incineration, capturing the environmental impacts of the incineration process itself, along with the subsequent valorization stages such as pretreatment, vitrification or sintering, shaping, drying, and all the energy and materials involved in converting the bottom ash into the final product.

This approach allows a comprehensive comparison by treating bottom ash as a by-product excluded from the system boundary in one case, while including the full life cycle from incineration for the other product.

This study is conducted to explore and evaluate sustainable pathways for managing and valorizing bottom ash, a significant by-product of waste incineration. As waste generation continues to grow globally, finding environmentally responsible and economically viable methods to treat incineration residues is increasingly critical. By assessing the life cycle environmental impacts of converting bottom ash into valuable products, such as foam glass-ceramic materials, this research aims to provide a comprehensive understanding of the benefits and trade-offs associated with different valorization strategies.

The applicability of this study lies in its potential to inform decision-makers, waste management companies, and policymakers about the environmental implications of integrating incineration and post-incineration treatment processes. Specifically, it addresses the gap in evaluating the full grave-to-gate impacts when the incineration phase is included versus when it is excluded, thereby offering insights into the true sustainability of these valorization routes. Ultimately, this research supports the advancement of circular economy principles by demonstrating how industrial by-products like bottom ash can be transformed into high-value materials, reducing landfill use and promoting resource efficiency.

4.2 Inventory data

The Life Cycle Inventory (LCI) phase of this study volves the collection and structuring of all input and output flows required for the environmental modelling of the two valorisation pathways assessed: the production of glass ceramic foam and various formulations of foamed glass ceramic from municipal solid waste incineration (MSWI) bottom ash. The inventory data for these processes were entirely sourced from peer-reviewed scientific literature, ensuring a reliable and standardized basis for comparative environmental analysis.

For the first product, the foam glass ceramic (1A), the input and output flows were adapted from the article by Francesco Barracco et al. (2023). This inventory included mass and energy flows associated with vitrification, shaping, firing, and emissions, and was normalized per 1 kg of bottom ash, matching the functional unit defined in this study.

For the second product, the foam glass ceramic (2A, 2B, 2C), inventory data were extracted from the work of Marcus H.N. Yio et al. (2021). In this case, three sub-scenarios (2A, 2B, 2C) were modelled, each differing in the mass of glass and additives used per kg of BA. The input materials included glass, borax, sodium phosphate, calcium carbonate, polyethylene glycol, and water, along with electricity used in various stages such as slurry preparation, drying, disc pressing, and firing. Outputs included both useful products and emissions such as wastewater, vapor, andCO_2. This inventory was normalized per 1 kg of bottom ash, matching the functional unit defined in this study.

The full process flow diagrams for each product, including all relevant material and energy streams, are presented in the *figures 3,4,5,6*. These diagrams visually represent the structure of the modeled systems and were derived directly from the process schemes described in the original papers.

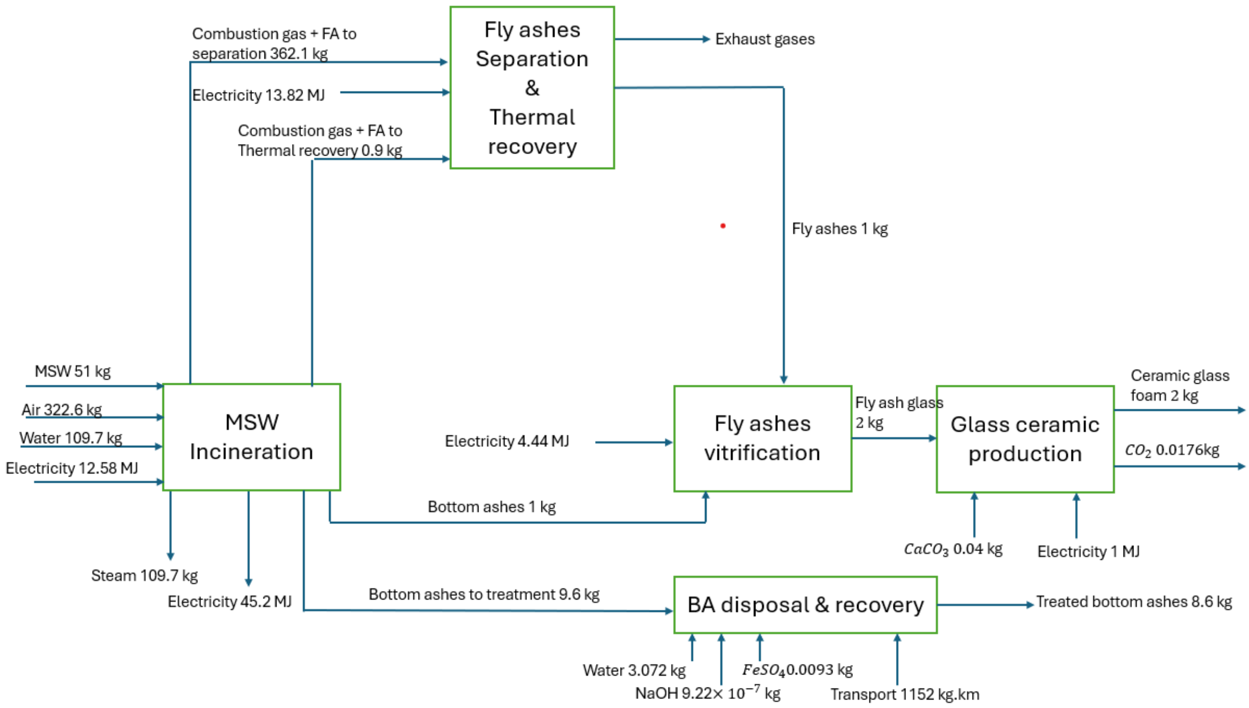

Figure 3. Foam glass ceramic (first product, 1A) flow diagram

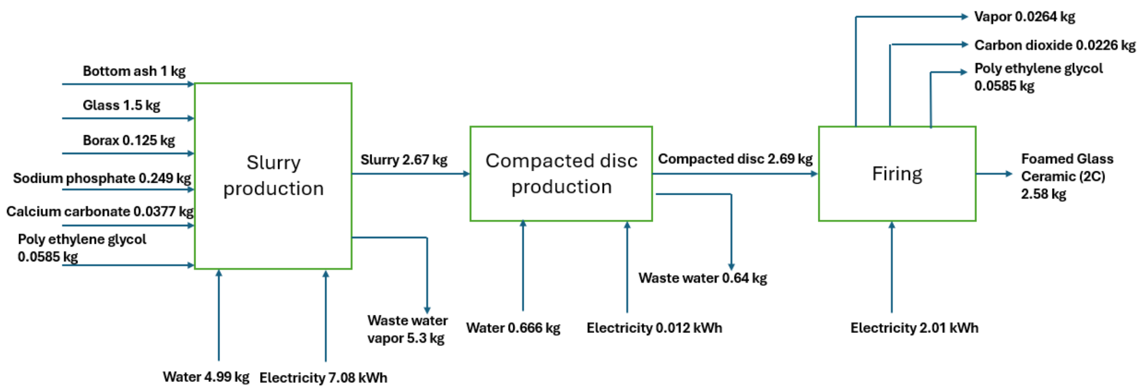

Figure 4. Foam glass ceramic (second product, 2A)

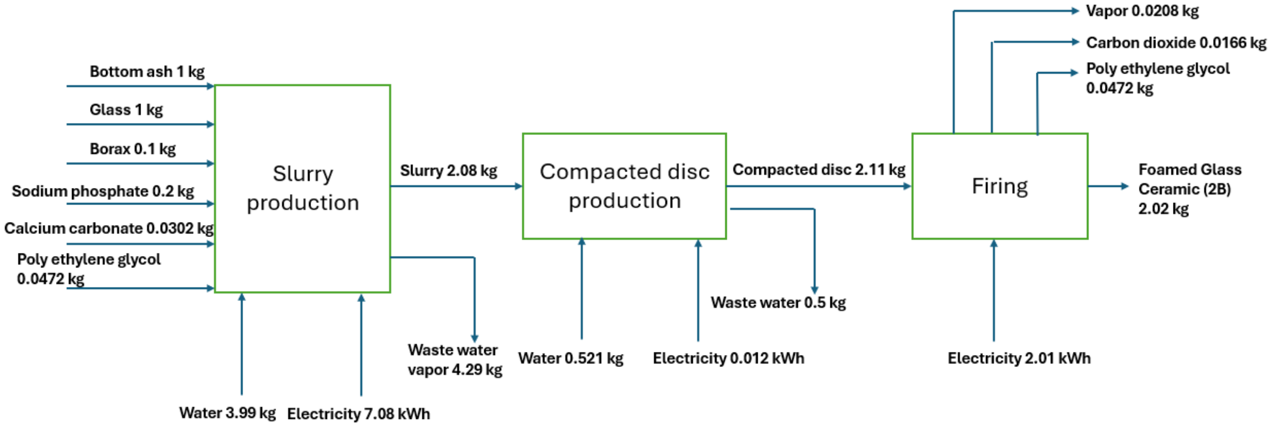

Figure 5. Foam glass ceramic (second product, 2B)

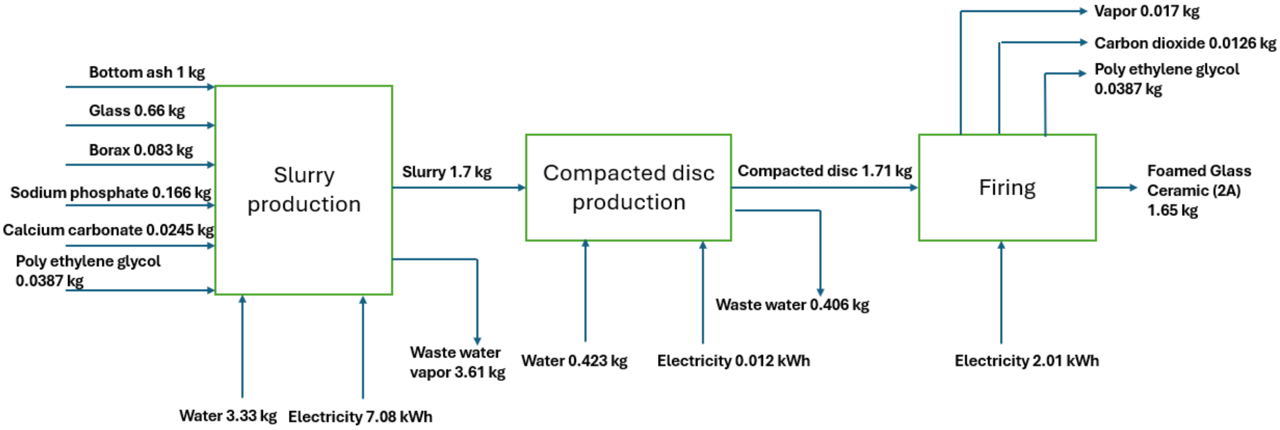

Figure 6. Foam glass ceramic (second product, 2C)

The inventory data are organized in tables that detail each step of the processes for incineration and the production of products 1A, 2A, 2B, and 2C. Each table includes the name of the process step, inputs and outputs associated with that step, their quantitative values, units of measurement, flow types, and the corresponding flow names as defined in the Ecoinvent database. These structured tables provide a clear and comprehensive overview of the mass and energy balances used in the life cycle assessment.

Table 1. Inventory data

0) Combustion				
Step0: raw material collection				
Input	**Value**	**Unit of measure**	**Type of flow**	**Ecoinvent**
Municipal solid waste	51	kg	zero burden	
transport	100	km kg	Transportation	Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, S
Output				
Transported MSW	51	kg	Product of step 0	
Step1: MSW Incineration				
Input				
Transported MSW	51	kg	Product of step 0	
Air	322.6	kg	Natural resource	Air
Water	109.7	kg	Natural resource	
Electricity	12.58	MJ	Technosphere flow	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Bottom ash	1	kg	Product of step 1	
Gas of combustion+Fly ashes to separation	362.1	kg	Product of step 1	
Gas combustion+Fly ash to thermal recovery	0.9	kg	Product of step 1	
Steam	109.7	kg	Avoided product	Steam, in chemical industry

				{GLO}| market for steam, in chemical industry | Cut-off, S
Electricity	45.2	MJ	Avoided burden	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Waste bottom ashes	9.6	kg	inert waste	Hazardous waste, incineration
Control: input = output	0	ok		
Step 2: Fly ash separation & Thermal recovery				
Input				
Gas combustion+Fly ash to seperation	362.10	kg	Product of step 1	
Gas combustion+Fly ash to thermal recovery	0.90	kg	Product of step 1	
Electricity	13.82	MJ	Technosphere flow	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Fly ashes	1.0000	kg	Product of step 2	
Carbon monoxide	0.0136	kg	Emission of step 2	Carbon monoxide
Sulphur oxides, IT	0.0448	kg	Emission of step 2	Sulfur oxides, IT
Nitrogen oxides	0.0882	kg	Emission of step 2	Nitrogen oxides, IT
Wood (dust)	0.9500	kg	Emission of step 2	Wood (dust)
Ammonia	0.5400	kg	Emission of step 2	Ammonia, TT
Dioxin, 1,2,3,4,6,7,8-heptachlorodibenzo-p-	0.0007	kg	Emission of step 2	Dioxins (TEQ)
Mercury (II)	0.0258	kg	Emission of step 2	Mercury (II)
Carbon dioxide, fossil	20.4000	kg	Emission of step 2	Carbon dioxide, fossil
Carbon dioxide, biogenic	30.6000	kg	Emission of step 2	Carbon dioxide, biogenic
Hydrogen fluoride	39.4000	kg	Emission of step 2	Insert Ecoinvent flow
Hydrochloric acid	0.3950	kg	Emission of step 2	Chlorine
Hydrogen	0.0224	kg	Emission of step 2	Hydrogen

Clean gas (steam)	269.51	kg	Emission of step 2	Clean gas
Control: input = output	0.0	ok		
Step 3: Vitrification				
Input	Value	Unit of measure	Type of flow	Ecoinvent
Fly ash hot	1.000	kg	Product of step 2	
Bottom ash	1.000	kg	Product of step 1	
Electricity	4.440	MJ	Technosphere flow	Electricity medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Flay ash glass	2.000	kg	Product of step 3	
Control: input = output	0	ok		
Step 4: Glass ceramic foam production				
Input				
Flay ash glass	2	kg	Product of step 3	
$CaCO_3$	0.04	kg	Technosphere flow	Calcium carbonate, precipitated {RoW}| market for calcium carbonate, precipitated | Cut-off, S
Electricity	1	MJ	Technosphere flow	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
ceramic glass	2	kg	Product of step 4	
CO_2, almost pure	0.04	kg	Emission to air	Carbon dioxide
Control: input = output	0	ok		
2A) Foamed glass ceramic production				
Step 0: Raw material collection				
Input	**Value**	**Unit of measure**	**Type of flow**	**Ecoinvent**
Bottom ash	1.00	kg	Product of step 1	
Glass	0.67	kg	Technosphere flow	Glass cullet, sorted {RoW}| market

				for glass cullet, sorted | Cut-off, S
Borax	0.08	kg	Technosphere flow	Borax, anhydrous, powder {GLO}| market for borax, anhydrous, powder | Cut-off, S
Sodium phosphate	0.17	kg	Technosphere flow	Sodium phosphate {RoW}| market for sodium phosphate | Cut-off, S
Calcium carbonate	0.02	kg	Technosphere flow	Calcium carbonate, precipitated {RoW}| market for calcium carbonate, precipitated | Cut-off, S
Output				
0-Raw material	1.94	kg	Product of step 0	
Control: input = output	0	ok		
Step 1: Slurry production				
Input				
Raw material	1.94	kg	Product of step 0	
Water	3.33	kg	Natural resource	Water, completely softened {RoW}| market for water, completely softened | Cut-off, S
PEG 6000	0.04	kg	Technosphere flow	Ethylene glycol {RER}| market for ethylene glycol | Cut-off, S
Electricity	7.08	kWh	Technosphere flow	Electricity , medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Slurry	1.70	kg	Product of step 1	
Waste water vapor	3.61	kg	Emission to air	Clean gas

Control: input = output	0	ok		
Step 2: Compacted disc production				
Input				
Slurry	1.71	kg	Product of step 1	
Water	0.42	kg	Natural resource	Water, completely softened {RoW}| market for water, completely softened | Cut-off, S
Electricity	0.01	kWh	Technosphere flow	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Compacted disc	1.71	kg	Product of step 2	
Water	0.41	kg	Emission to water	Water IT
Control: input = output	0.0	ok		
Step 3: Firing				
Input				
Compacted disc	1.710	kg	Product of step 2	
Electricity	2.010	kWh	Technosphere flow	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Foamed Glass ceramic	1.650	kg	Product of step 3	
Vapor	0.017	kg	Emission to air	Clean gas
CO2	0.013	kg	Emission to air	Carbon dioxide
PEG 6000	0.030	kg	Hazardous waste	Not hardous wate recovery
Control: input = output	0	ok		
2B) Foamed glass ceramic production				
Step 0: Raw material collection				
Input	**Value**	**Unit of measure**	**Type of flow**	**Ecoinvent**
Bottom ash	1.00	kg	Product of step 1	

Glass	1.00	kg	Technosphere flow	Glass cullet, sorted {RoW}| market for glass cullet, sorted | Cut-off, S
Borax	0.10	kg	Technosphere flow	Borax, anhydrous, powder {GLO}| market for borax, anhydrous, powder | Cut-off, S
Sodium phosphate	0.20	kg	Technosphere flow	Sodium phosphate {RoW}| market for sodium phosphate | Cut-off, S
Calcium carbonate	0.03	kg	Technosphere flow	Calcium carbonate, precipitated {RoW}| market for calcium carbonate, precipitated | Cut-off, S
Output				
Raw material	2.33	kg	Product of step 0	
Control: input = output	0	ok		
Step 1: Slurry production				
Input				
Raw material	2.33	kg	Product of step 0	
Water	3.99	kg	Natural resource	Water, completely softened {RoW}| market for water, completely softened | Cut-off, S
PEG 6000	0.05	kg	Technosphere flow	Ethylene glycol {RER}| market for ethylene glycol | Cut-off, S
Electricity	7.08	kWh	Technosphere flow	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				

Slurry	2.08	kg	Product of step 1	
Waste water vapor	4.29	kg	Emission to air	Clean gas
Control: input = output	0	ok		
Step 2: Compacted disc production				
Input				
Slurry	2.08	kg	Product of step 1	
Water	0.52	kg	Natural resource	Water, completely softened {RoW}| market for water, completely softened | Cut-off, S
Electricity	0.01	kWh	Technosphere flow	Electricity , medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Compacted disc	2.11	kg	Product of step 2	
Water	0.50	kg	Emission to water	Water IT
Control: input = output	0.00	ok		
Step 3: Firing				
Input				
Compacted disc	2.110	kg	Product of step 2	
Electricity	2.010	kWh	Technosphere flow	Electricity , medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Foamed Glass ceramic	2.020	kg	Product of step 3	
Vapor	0.020	kg	Emission to air	Clean gas
CO2	0.017	kg	Emission to air	Carbon dioxide
PEG 6000	0.047	kg	Hazardous waste	Not hardous wate recovery
Control: input = output	0.01	ok		
2C) Foamed glass ceramic production				
Step 0: Raw material collection				

Input	Value	Unit of measure	Type of flow	Ecoinvent
Bottom ash	1.00	kg	Product of step 1	
Glass	1.50	kg	Technosphere flow	Glass cullet, sorted {RoW}| market for glass cullet, sorted | Cut-off, S
Borax	0.12	kg	Technosphere flow	Borax, anhydrous, powder {GLO}| market for borax, anhydrous, powder | Cut-off, S
Sodium phosphate	0.25	kg	Technosphere flow	Sodium phosphate {RoW}| market for sodium phosphate | Cut-off, S
Calcium carbonate	0.04	kg	Technosphere flow	Calcium carbonate, precipitated {RoW}| market for calcium carbonate, precipitated | Cut-off, S
Output				
Raw material	2.91	kg	Product of step 0	
Control: input = output	0.00	ok		
Step 1: Slurry production				
Input				
0-Raw material	2.91	kg	Product of step 0	
Water	4.99	kg	Natural resource	Water, completely softened {RoW}| market for water, completely softened | Cut-off, S
PEG 6000	0.06	kg	Technosphere flow	Ethylene glycol {RER}| market for ethylene glycol | Cut-off, S
Electricity	7.08	kWh	Technosphere flow	Electricity, medium voltage {IT}| market for electricity,

				medium voltage | Cut-off, S
Output				
Slurry	2.67	kg	Product of step 1	
Waste water vapor	5.30	kg	Waste to air	Clean gas
Control: input = output	0.00	ok		
Step 2: Compacted disc production				
Input				
Slurry	2.67	kg	Product of step 1	
Water	0.67	kg	Natural resource	Water, completely softened {RoW}| market for water, completely softened | Cut-off, S
Electricity	0.01	kWh	Technosphere flow	Electricity , medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Compacted disc	2.69	kg	Product of step 2	
Water	0.64	kg	Emission to water	Water IT
Control: input = output	0.00	ok		
Step 3: Firing				
Input				
Compacted disc	2.69	kg	Product of step 2	
Electricity	2.01	kWh	Technosphere flow	Electricity , medium voltage {IT}| market for electricity, medium voltage | Cut-off, S
Output				
Foamed Glass ceramic	2.58	kg	Product of step 3	
Vapor	0.026	kg	Emission to air	Clean gas
CO2	0.022	kg	Emission to air	Carbon dioxide
PEG 6000	0.058	kg	Hazardous waste	Not hardous waste recovery
Control: input = output	0.00	ok		

4.3 Impact assessment

The impact assessment phase of this study was performed using the ReCiPe 2016 Midpoint (H) method, which is one of the most comprehensive and scientifically established life cycle impact assessment (LCIA) frameworks currently available. It is implemented within the SimaPro 9.6.0.1 software environment and widely applied in environmental studies involving waste valorization, resource recovery, and materials processing [46].

ReCiPe 2016 builds upon its predecessor, ReCiPe 2008, and was developed by the National Institute for Public Health and the Environment (RIVM) in the Netherlands, in collaboration with Radboud University and PRé Sustainability [46]. It links life cycle inventory results to environmental impact indicators through a structured cause-effect model. ReCiPe offers two modeling perspectives: Midpoint (problem-oriented) and Endpoint (damage-oriented) [46]. In this thesis, the Midpoint approach is adopted, as it provides higher resolution and specificity in impact characterization and is less sensitive to subjective assumptions than Endpoint modeling [46].

Two Midpoint impact categories were selected in accordance with the specific nature of the study, i.e., the treatment of bottom ash and its transformation into foam glass-ceramic materials:

- Global Warming Potential (GWP): Quantifies emissions of greenhouse gases such as CO_2, CH_4, and N_2O, expressed in kg CO_2-equivalents. This indicator reflects the climate change impacts associated with energy consumption and combustion-related emissions.
- Human Toxicity, Non-Carcinogenic Effects: Assesses the chronic health risks to humans from exposure to substances with non-carcinogenic properties. This category is especially relevant to the valorization of ash, given its potential to release pollutants through air emissions or leachates [47].

The "H" in ReCiPe 2016 Midpoint (H) stands for the Hierarchist perspective, which represents a scientifically consensus-based view using a 100-year time horizon and is aligned with common policy frameworks and the ISO 14040/44 standards. This perspective is commonly adopted in LCA studies aiming to inform public decision-making and long-term environmental planning [46].

By selecting ReCiPe 2016 Midpoint (H), this study benefits from a harmonized, transparent, and widely accepted impact characterization method that enables consistent and comparable environmental analysis between the two modeled scenarios: production of foam glass ceramic from MSWI bottom ash through two different processes.

Chapter 5: Results

5.1 Environmental impacts of the process

The results show clear differences in environmental performance among the four scenarios. In *Table 2* the quantitative environmental impacts of the four products across the two Impact Categories are reported.

Table 2. Environmental impacts of the four products across the two Impact Categories

Impact category	Unit	Foam glass ceramic (1A)	Foam Glass ceramic (2A)	Foam glass ceramic (2B)	Foam glass ceramic (2C)
Global warming	kg CO2 eq	-15.67	4.16	4.38	4.57
Human non-carcinogenic toxicity	kg 1,4-DCB	629.18	3.27	3.71	4.26

In terms of Global Warming Potential (GWP), Product 1A stands out with the lowest impact, making it the most climate-efficient option among the four. This is largely attributed to the inclusion of the incineration phase, which not only treats the waste but also provides enough recovered energy (in the form of electricity) to power the entire life cycle of the product. This offsets the need for grid electricity and significantly reduces greenhouse gas emissions. By contrast, Products 2A, 2B, and 2C rely entirely on external energy sources and do not benefit from energy recovery, leading to higher GWP values. As the bottom ash content decreases and more additives are introduced (from 2A to 2C), the carbon footprint increase, with Product 2C showing the highest GWP due to its lower ash content and greater demand for materials and processing.

However, this environmental advantage of Product 1A is not observed in the other category, Human Non-Carcinogenic Toxicity, where it exhibits the highest impact values. This is likely due to the intrinsic chemical composition of incineration residues, which can contain elevated levels of heavy metals and persistent inorganic pollutants. Even though vitrification stabilizes these elements within a glassy matrix, their presence in the life cycle inventory contributes significantly to toxicity-related indicators. In contrast, Products 2A, 2B, and 2C, which do not include incineration and often dilute ash content with inert or less toxic additives, show lower human toxicity scores. These results suggest a trade-off: while Product 1A performs better in terms of climate impact, it may pose a higher risk in categories related to toxic substance management, depending on the specific formulation and stabilization efficiency of the product.

In the 2-series products (2A, 2B, and 2C), a clear trend is observed where Human Non-Carcinogenic Toxicity impact increases as the percentage of bottom ash decreases and the proportion of additive materials rises. While formulations with lower BA content may be pursued for technical or processing reasons, they result in the use of more industrial additives, such as borax or sodium phosphate, which introduce their own environmental burdens due to upstream energy use and chemical processing. Furthermore, when the proportion of bottom ash is reduced, the resulting material may become less effective at stabilizing and locking in toxic elements through vitrification [48]. This weaker immobilization can potentially lead to greater release or leaching of pollutants during the product's life cycle, thus increasing toxicity impacts. In this context, higher BA content not only enhances waste recovery, aligning with circular economy goals, but also appears to contribute to lower toxicity impacts, making it both environmentally and strategically favourable.

5.2 Climate change impacts

Global warming, driven by greenhouse gas (GHG) emissions, remains one of the most critical impact categories in environmental assessments. In this study, Global Warming Potential (GWP) was analysed for the four bottom ash valorisation scenarios (1A, 2A, 2B, and 2C) expressed in kg CO_2-equivalent per kg of product. The results provide insight into the climate-related implications of different material formulations, energy sources, and system boundaries.

According to *Figure 7*, the main contributor to Product 1A GWP is Step 2, Fly ash separation and thermal recovery. Within this stage, the environmental impact is mainly shaped by two contrasting flows: the production of fly ash, which contributes +20.4 kg CO_2-eq, and the gas of combustion with fly ash sent to separation, which provides a significant environmental credit of –37.89 kg CO_2-eq. The notably low GWP of the gas of combustion with fly ash sent to separation is primarily driven by the inclusion of steam as an input to its process, as reported in the Sankey diagram of *Figure 8*. This steam is modelled as a by-product of incineration-based heat recovery and is assigned a negative GWP (–34.7 kg CO_2-eq) due to the avoided burden of fossil-based steam production. Consequently, the large climate credit embedded in this input substantially reduces the overall GWP of Product 1A.

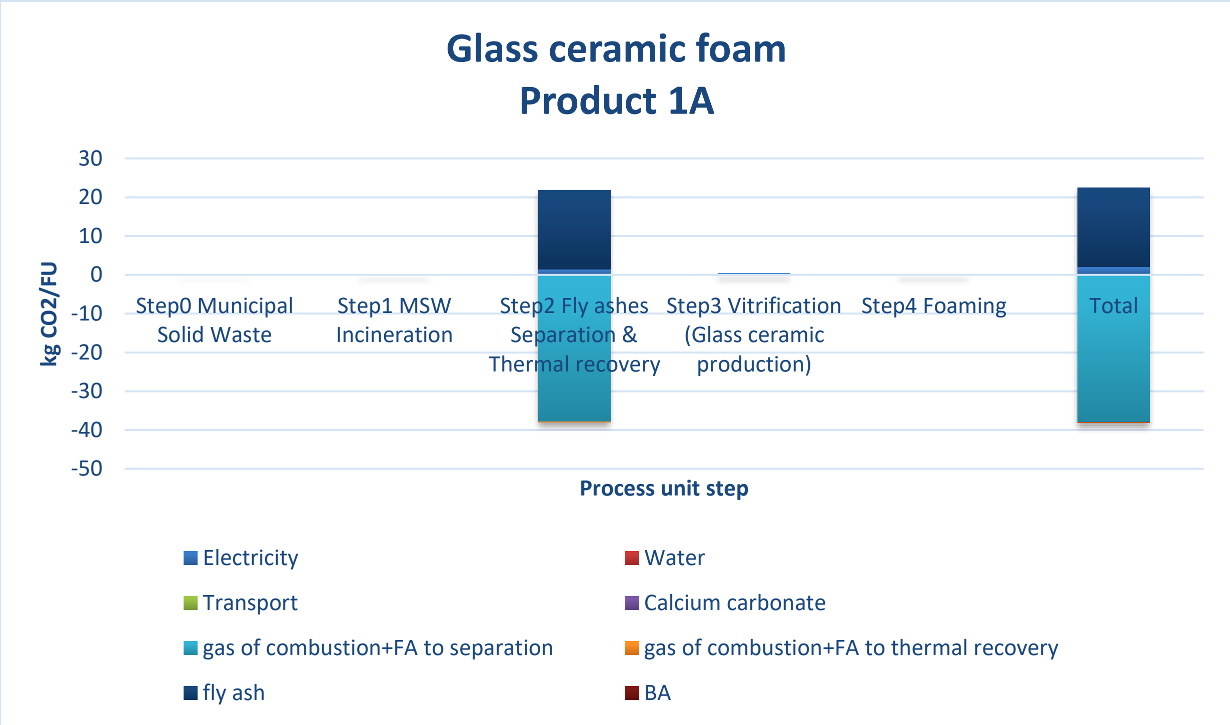

Figure 7. The contribution of individual life cycle stages to overall climate impact of Product 1A

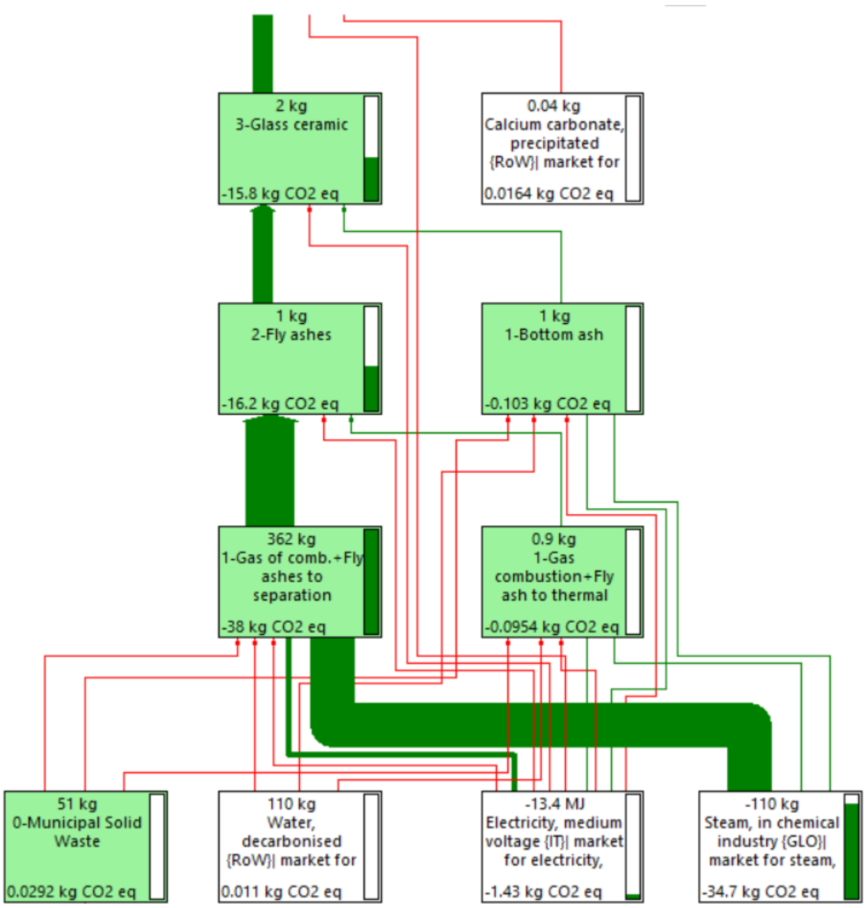

Figure 8. Sankey diagram of Global Warming impact of Product 1A (from Step 0 to Step 3)

For Products 2A, 2B, and 2C, *Figures 9 to 11* show a progressive increase in GWP, largely due to the higher use chemical additives as the bottom ash content decreases. This confirms that lower ash content correlates with higher environmental burden, mainly due to additive-related emissions. In Products 2-series, the electricity demand is the most critical hotspot, accounting for the majority of the CO_2-equivalent emissions, followed by inputs like borax**,** sodium phosphate, and glass cullets, which are associated with high embodied energy.

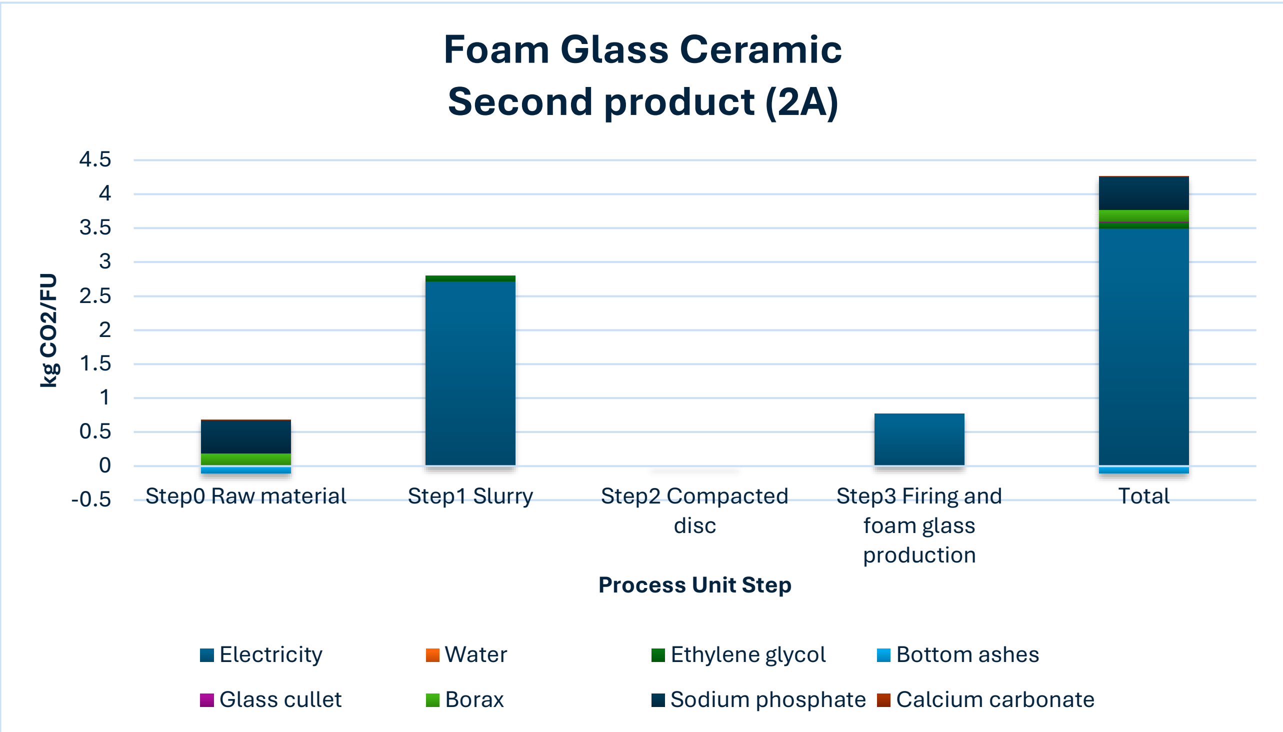

Figure 9. The contribution of individual life cycle stages to overall climate impact of Product 2A

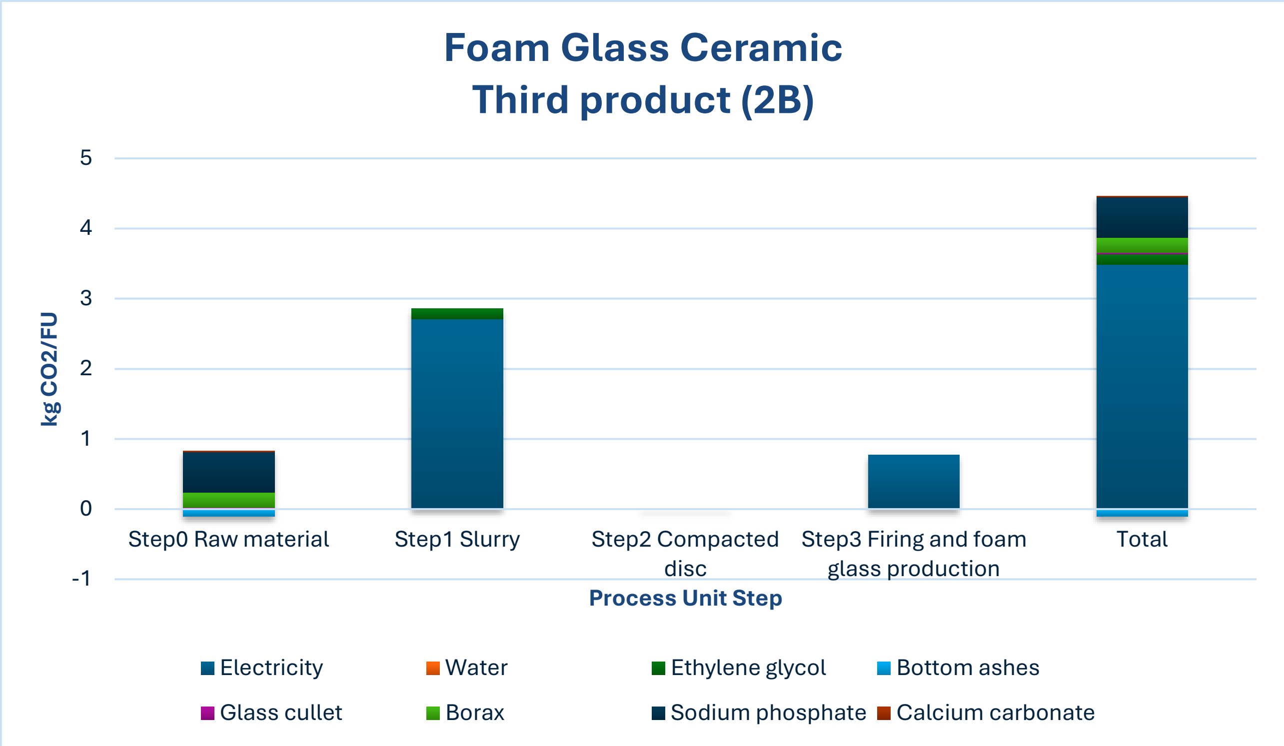

Figure 10. The contribution of individual life cycle stages to overall climate impact of Product 2B

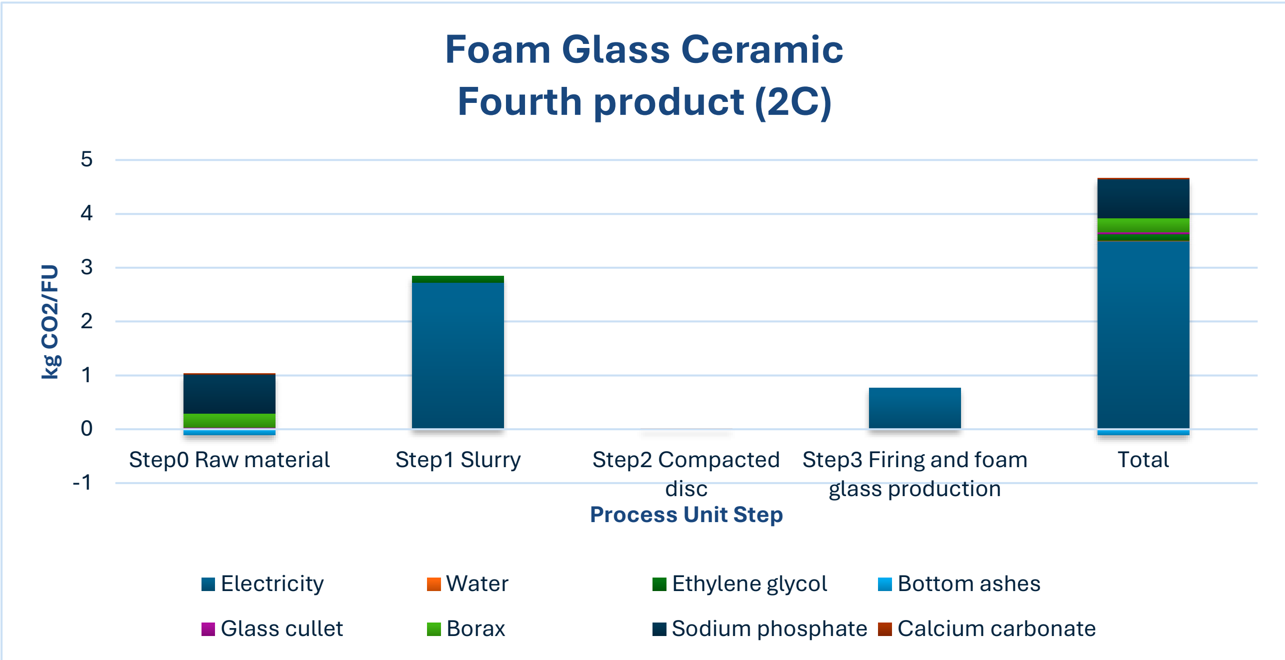

Figure 11. The contribution of individual life cycle stages to overall climate impact of Product 2C

In summary, the climate change analysis reinforces the advantage of utilizing internal process inputs with strong environmental credits, particularly steam recovered from incineration. Product 1A, by incorporating steam as a by-product in the gas separation stage and reducing reliance on external energy sources, achieves the lowest carbon footprint. In contrast, Products 2A, 2B, and 2C, lacking this internal energy advantage and relying increasingly on virgin additives, exhibit higher GWP values. The climate performance of 2-series products deteriorates as ash content decreases, suggesting that beyond a certain threshold, substitution with additives negates the environmental benefits of valorisation. These results underline the importance of material efficiency and accurate modelling of co-product energy flows in the design of future bottom ash recycling technologies.

5.3 Highest impact items and mitigation strategies

Understanding which processes and materials contribute most to environmental impacts is essential for improving the sustainability of bottom ash valorisation.

The breakdown of GWP for Product 1A indicated in *Figure 7* reveals that Step 2, Fly ashes separation and thermal recovery is the dominant contributor to the overall climate performance. Interestingly, this step does not contribute positively to emissions; rather, it introduces a large negative GWP, primarily due to the inclusion of steam as an input, which is modelled as a by-product of the incineration process. As a result, this credit significantly outweighs the emissions of other life cycle stages. By contrast, other phases such as incineration, vitrification, and foaming contribute marginally to the total GWP, underlining the extent to which system expansion via co-product substitution can dominate climate results in LCA modelling.

For Products 2A, 2B, and 2C, the analysis of the GWP contributions across life cycle stages shows that the electricity consumption is the dominant environmental hotspot in all three scenarios. This is particularly evident in the two most critical steps: Slurry production, and Firing and foam glass production, as highlighted in *Figures 9 to 11*. These two phases consistently contribute the highest share to the total GWP in each scenario.

In the slurry production step, electricity is used for preparing and mixing the bottom ash with the required additives to create the homogeneous slurry needed for forming. This phase is highly energy-dependent due to prolonged mixing and potentially heating operations. The firing and foam glass production step is also energy-intensive, as it involves high-temperature treatment to create the foamed structure, requiring sustained thermal input, mostly supplied by electricity.

Across all three products scenarios of 2-series, the amount of electricity consumed per process step was assumed constant, regardless of the bottom ash content. As a result, as the bottom ash percentage decreases (moving from 2A to 2C), the environmental burden increases because the proportion of external additives increases, which are often associated with higher upstream emissions. However, the electricity demand per kilogram of product remains the most influential factor, especially because the Italian electricity mix still carries a significant carbon intensity.

Figures 9 to 11 also show that the contribution of raw material inputs (mainly additives like borax, sodium phosphate, and glass powder) becomes more significant as bottom ash content decreases. This effect is especially pronounced in Product 2C, where the additive share is the highest. While the material-related GWP contribution is not as large as that of the electricity-intensive steps, it becomes a secondary hotspot that should not be overlooked, particularly in low-ash formulations.

In contrast, other stages, such as forming and disc pressing, drying, and transport, contribute minimally to the overall GWP in all three scenarios. These stages, though necessary, are less energy-demanding and involve lower-emission processes.

Considering the identified environmental hotspots, several targeted strategies can be proposed to reduce the overall climate impact of BA conversion processes and improve the sustainability of the product system.

One of the most effective approaches is to maximize the content of bottom ash in the formulation. By increasing the share of this waste-derived material, the need for external, carbon-intensive additives can be significantly reduced. The results clearly indicate that products with higher bottom ash content, such as Product 2A, consistently perform better in terms of global warming potential than formulations like Product 2C, which rely more heavily on supplementary materials. From an environmental standpoint, material optimization should aim to maintain or exceed a 60% ash content, wherever feasible, without compromising product functionality.

Another mitigation strategy involves using process-integrated by-products such as steam from waste incineration. The modelling results for Product 1A demonstrate that the use of steam, produced as a by-product of thermal recovery, can significantly reduce the overall carbon footprint when applied strategically within the process, particularly in high-energy stages such as gas separation or thermal treatment. To replicate this benefit, future valorisation systems should consider direct integration with municipal waste-to-energy plants, enabling access to low-carbon process heat. This approach not only enhances energy circularity but also allows for system-level synergy where heat recovered from waste incineration is reinvested into the production cycle, reducing reliance on external, carbon-intensive thermal energy sources.

Another critical mitigation pathway involves improving energy efficiency and sourcing. Electricity consumption was found to be the dominant contributor to GWP across all scenarios, particularly in the slurry preparation and firing stages. Therefore, reducing the energy demand in these steps, through process optimization, better insulation, or refined operating conditions, can substantially lower emissions. Additionally, transitioning to low-carbon or renewable electricity sources would reduce the carbon intensity of the energy input. Where feasible, implementing on-site energy recovery systems or integrating processes with existing waste-to-energy infrastructure, as successfully demonstrated in Product 1A, can further decouple the process from fossil-based grid energy.

A fourth avenue for impact reduction lies in the selection and optimization of additives. Certain high-impact components, such as borax and sodium phosphate, carry considerable upstream environmental burdens. Where technically possible, these materials could be substituted with recycled or lower-impact alternatives, or their use could be minimized by fine-tuning the foaming or sintering conditions. Optimizing the additive-to-ash ratio through process experimentation may allow the production of glass-ceramic materials with lower environmental impacts, without compromising the mechanical or chemical performance of the final product.

Lastly, while transportation is not a major contributor to the overall GWP, it still offers a potential for incremental improvements. Sourcing raw materials and additives from local suppliers can help reduce emissions associated with long-distance transport. In large-scale implementations, even these small savings can accumulate meaningful reductions in the overall carbon footprint.

Together, these strategies point toward a more climate-resilient and circular approach to bottom ash valorization, prioritizing waste utilization, energy integration, and smart material design to lower the environmental burden of glass-ceramic production.

5.4 Comparison with literature

The life cycle assessment conducted in this thesis provides a detailed comparison of four bottom ash valorisation scenarios, offering valuable insights into the environmental trade-offs associated with different process routes and material formulations. The results confirm that the inclusion of steam generated from incineration as an internally credited input in key processing stages, as in Product 1A, is a key factor in achieving low climate impacts, while also revealing that product formulations with higher bottom ash content generally perform better across all environmental categories.

The favourable climate performance of Product 1A, which demonstrates a net negative GWP, is in line with the findings of Barracco et al. (2023), whose LCA framework formed the basis of the present study [5]. While their analysis emphasized the importance of integrating energy recovery to reduce climate impacts, this thesis has further clarified that the primary contributor to the negative GWP in Product 1A is the inclusion of steam, generated through incineration and credited as an internal input in the gas separation stage. This element, though present in the original model, plays a far more decisive role than previously highlighted, significantly offsetting the product's carbon footprint. Similarly, Yio et al. (2021) noted that maximizing bottom ash content and minimizing external raw material use can enhance the environmental competitiveness of glass-ceramic products, a trend that is also confirmed in the present results [23].

In this study, the FA separation and thermal recovery phase emerged as the most significant contributor to the gross GWP of Product 1A. This finding aligns with the conclusions of Arena (2012), who emphasized that energy recovery processes in waste-to-energy systems are often the most energy-intensive, but can offer substantial offsets when properly integrated [6].

For Products 2A, 2B, and 2C, the most critical contributors to climate impact were identified as the electricity consumption in slurry production and firing/foaming steps, which is in line with prior studies such as Zhang et al. (2021), where the energy intensity of high-temperature processes was found to dominate the carbon footprint of glass-ceramic production [33]. The increasing use of additives in low-ash products, particularly in Product 2C, significantly raised the environmental burden, a trend also reported by Rabelo Monich et al. (2019), who showed that the choice of fluxing agents and chemical additives can considerably influence the total environmental impact of glass-based materials [39].

The trend observed in this thesis, where higher bottom ash content correlates with lower climate impacts, also mirrors the conclusions of Bruno et al. (2021), who demonstrated that maximizing waste-derived input and minimizing virgin material use is essential for achieving favorable LCA outcomes in waste valorization processes [38].

One of the most interesting trade-offs highlighted by this study is that Product 1A, while performing best in climate change impact, shows higher values in human toxicity (non-carcinogenic) category. This observation is consistent with the challenges discussed by Zhang et al. (2021), who noted that while energy recovery can offer carbon savings, the presence of heavy metals and persistent inorganic pollutants in incineration residues can still contribute to toxicity-related impacts [33].

In contrast, Products 2A, 2B, and 2C, despite showing higher GWP, generally exhibited lower toxicity impacts, suggesting that additive-driven formulations might dilute or better immobilize hazardous elements, although at the cost of higher upstream emissions from material production.

This balance between climate benefits and toxicity trade-offs is a well-known complexity in waste management LCAs, as also emphasized in the broader review by Arena (2012), where system boundary choices and impact category prioritization were shown to heavily influence the final interpretation of waste treatment technologies [6].

5.5 Comparison with conventional pathways

One of the other pivotal objectives of this thesis is to benchmark the environmental performance of valorised bottom-ash products against traditional disposal or reuse pathways such as landfilling and aggregate use in construction. This comparative analysis places our findings in a broader context and highlights the true value of the developed glass-ceramic solutions.

The use of fly ash into lightweight aggregate (LWA) production delivered a GWP of approximately 275 kg CO_2-eq per ton (0.275 kg CO_2-eq /kg) compared to 420 kg CO_2-eq per ton (0.420 kg CO_2-eq/kg) for landfilling [49, 50]. In our study, Product 1A shows a net GWP of –15 kg CO_2-eq/kg, reflecting significant climate benefits due to the inclusion of steam generated through incineration and credited as an internal input. This negative result starkly outperforms landfill options by nearly 60 times more negative in absolute terms. Products 2A, 2B and 2C show positive GWP values, ranging roughly from +3 to +8 kg CO_2-eq/kg. These values are higher than those reported for landfill and aggregate scenarios, indicating that while these valorisation routes avoid landfilling, they may not offer climate benefits over conventional treatments unless the process energy and additive sourcing are optimized, particularly when bottom ash content is reduced.

Regarding the Human Non-carcinogenic Toxicity, the LWA reuse scenario reported by [49] yields an HTP of approximately 0.248 kg 1,4-DCB-eq/kg bottom ash and the CEWEP Waste-to-Energy analysis [52] reports an HTP value of 0.53 kg 1,4-DCB-eq per kg of MSW for landfilling. To enable fair comparison with bottom ash-based systems, this figure must be normalized to the typical yield of bottom ash from MSW incineration, commonly assumed to be around 25% by mass. Applying this correction results in an adjusted value of approximately 2.12 kg 1,4-DCB-eq/kg bottom ash, which remains significantly lower than the value obtained for Product 1A in this study (629.18 kg 1,4-DCB/kg). Similarly, Products 2A, 2B, and 2C, with HTP values ranging from 3.27 to 4.26 kg 1,4 DCB per kg of bottom ash, significantly exceed the HTP levels commonly associated with landfilling or aggregate reuse scenarios.

The exceptionally high Human Non-carcinogenic Toxicity Potential (HTP) value obtained for Product 1A in this study, measured at 629.18 kg 1,4-DCB per kg of bottom ash treated, is primarily attributed to the "Fly Ashes Separation & Thermal Recovery" stage, as identified through contribution analysis using a Sankey diagram, as shown in *Figure 12*. This stage alone contributes nearly the entire HTP impact (≈629 kg 1,4-DCB-eq/kg), indicating it is the dominant hotspot in the life cycle. A detailed examination of the life cycle inventory for this phase reveals numerous emissions to air that carry high characterization factors under the ReCiPe 2016 Midpoint (H) method. These include fossil and biogenic carbon dioxide, carbon monoxide, sulphur oxides, nitrogen oxides, ammonia, chlorine, hydrogen fluoride, and particularly mercury, which is known for its significant toxicity weighting. Many of these emissions, especially heavy metals and acidifying gases, are potent contributors to human toxicity impacts due to their potential for inhalation exposure and long-term persistence in the environment. It is likely that the inventory dataset used to model this process represents an uncontrolled or partially controlled emission scenario for fly ash treatment, which may not reflect the actual air pollution control technologies typically used in modern MSWI plants. As a result, the HTP score in this study may reflect a conservative or worst-case assumption regarding emission intensities.

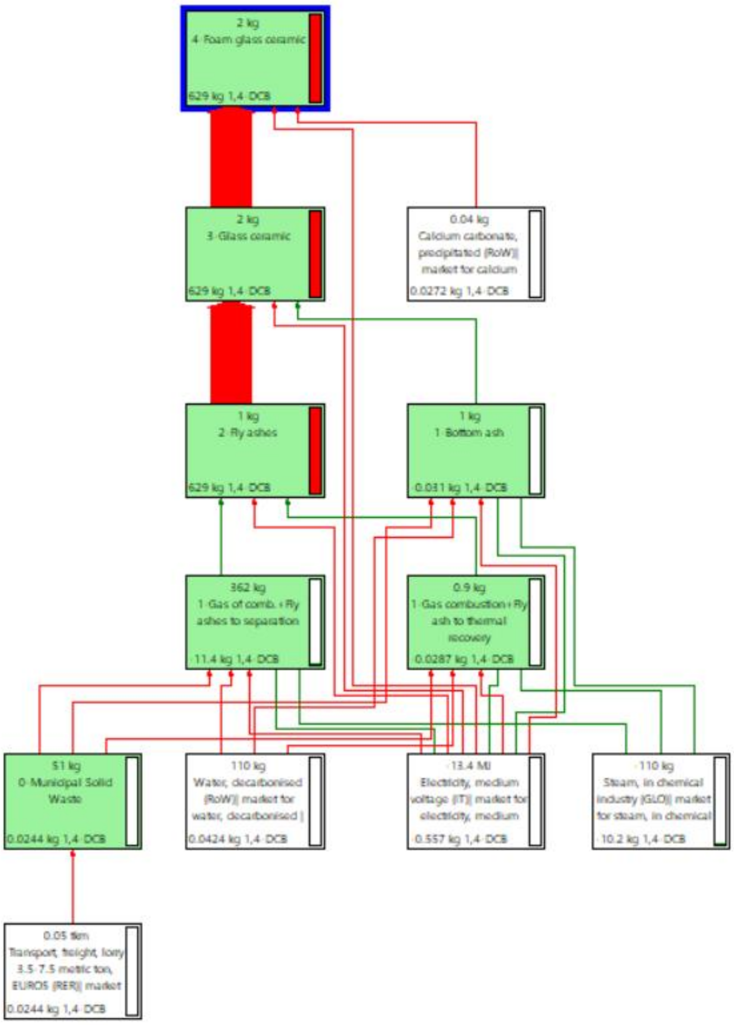

Figure 12. Sankey diagram of Human Non-carcinogenic Toxicity of Product 1A

The Human Non-carcinogenic Toxicity Potential (HTP) values obtained for Products 2A, 2B, and 2C in this study, ranging from 3.27 to 4.26 kg 1,4-DCB per kg of bottom ash treated, are significantly lower than for Product 1A but remain considerably higher than typical toxicity benchmarks reported for conventional treatment routes. For example, in Product 2A, contribution analysis revealed that the dominant sources of toxicity were the use of sodium phosphate (contributing approximately 1.7 kg 1,4-DCB/kg) and electricity from the Italian grid mix (approximately 1.36 kg 1,4-DCB/kg). Sodium phosphate, a commonly used fluxing or foaming agent in glass-ceramic formulations, is associated with toxicity impacts due to emissions linked to its production, such as heavy metals, phosphates, and energy-intensive precursors. Meanwhile, electricity consumption contributes substantially to HTP primarily due to emissions from fossil-based power generation in the Italian energy mix, which includes sulphur dioxide, nitrogen oxides, and trace heavy metals emitted during combustion. These compounds are weighted heavily in the ReCiPe 2016 characterization model for their adverse effects on human health through inhalation and accumulation in ecosystems. The relatively high HTP values observed in the 2-series products reflect the environmental cost of additive sourcing and energy intensity, particularly for materials like sodium phosphate that are chemically active and for grid electricity that lacks decarbonization. This finding suggests that even in the absence of fly ash processing, the material and energy inputs in the formulation of glass-ceramics can carry substantial toxicity burdens if not carefully selected or substituted with cleaner alternatives.

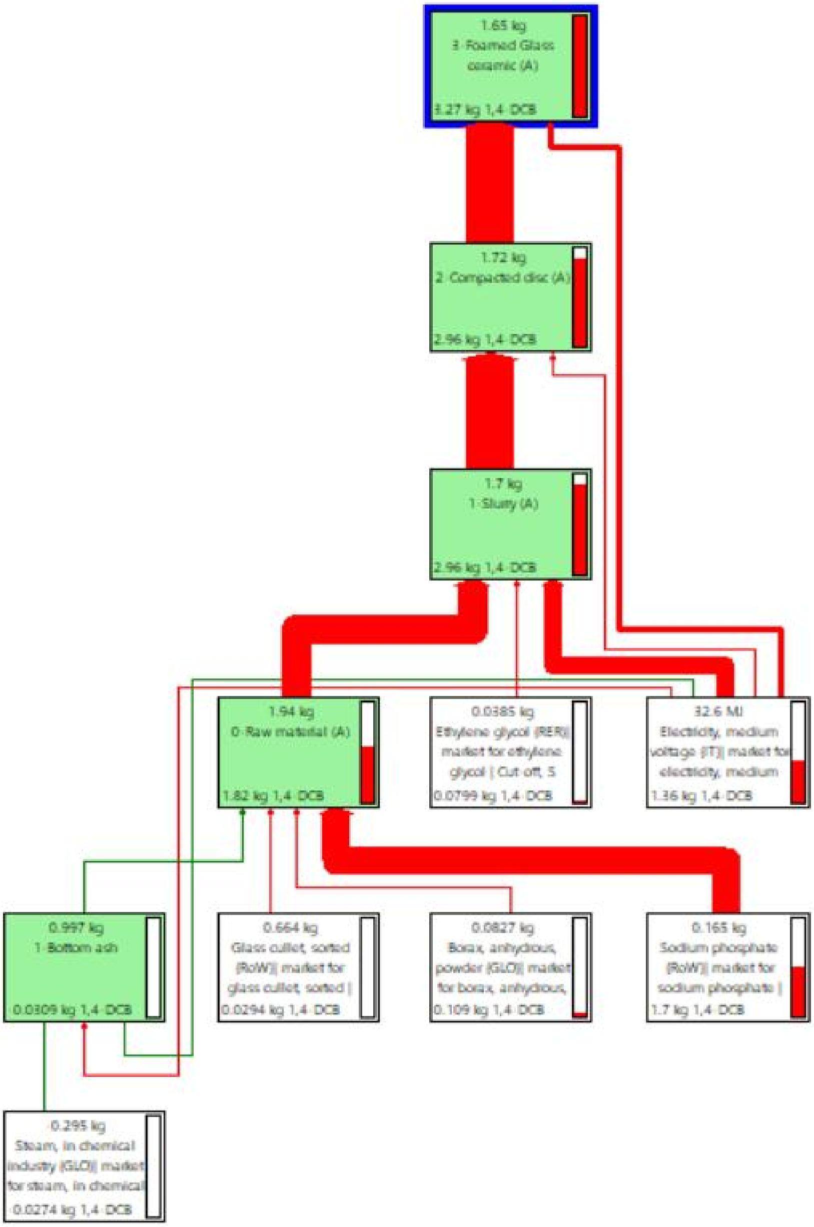

Figure 12. Sankey diagram of Human Non-carcinogenic Toxicity of Product 2A

In conclusion, valorizing bottom ash into glass-ceramic products offers a clear climate advantage, especially with the integration of steam derived from incineration as a credited process input. However, the current forms of these products, particularly Product 1A, pose critical human health risks due to high toxicity potentials. The moderate improvements seen in Products 2A, 2B and 2C are insufficient to match the low-toxicity performance of conventional reuse or landfill disposal.

Future work must focus on enhancing stabilization techniques, applying health risk assessments, or targeting non-sensitive applications for these materials to safely integrate them into circular economic models.

Conclusion

The primary objective of this thesis was to evaluate the environmental performance of converting municipal solid waste incineration (MSWI) bottom ash (BA) into value-added materials, specifically foam glass-ceramic products. Through a comprehensive Life Cycle Assessment (LCA), the study aimed to quantify the potential environmental benefits and trade-offs associated with BA valorization, with a particular focus on climate change and human toxicity. The study intended to benchmark these innovative valorization routes against conventional treatment pathways such as landfilling and aggregate reuse, contributing to the broader goals of sustainable waste management and circular economy.

To achieve this, four distinct scenarios were modelled and analysed: Product 1A, a foam glass-ceramic pathway that included the use of steam generated during the incineration phase as a credited input; Product 2A, a valorisation route with 60% bottom ash content, excluding energy recovery; Product 2B, a formulation with 50% bottom ash content, also without internal energy credits; and Product 2C, a product with 40% bottom ash content, again excluding energy recovery. These scenarios enabled a comparison between two process strategies: one benefiting from internal process integration and credited co-products (such as steam), and others focusing on different material formulations without such system-level benefits.

The LCA results demonstrated that Product 1A offers substantial climate benefits, achieving a net negative Global Warming Potential (GWP) of approximately –15 kg CO_2-eq/kg. This favorable outcome is primarily driven by the inclusion of steam modeled as a by-product of the incineration process which carries a significant environmental credit when used in downstream processing stages. Additionally, Product 1A's high bottom ash content enhances material efficiency by reducing the need for virgin additives and further supports its overall environmental performance.

However, this environmental gain in the climate category came at a significant cost: Product 1A exhibited exceptionally high values in Human Toxicity Potential (HTP), driven by the concentration of heavy metals and persistent inorganic contaminants within the vitrified ash matrix. In comparison, Products 2A, 2B, and 2C, while less efficient in terms of climate impact, demonstrated lower toxicity values, though still substantially higher than conventional landfill and lightweight aggregate reuse pathways. These scenarios illustrated that reducing bottom ash content can dilute toxicity, but at the cost of increased material and energy demand.

The comparative analysis with the literature confirmed the trade-offs inherent to bottom ash valorization: while significant climate benefits are achievable, toxicity remains a critical environmental challenge. The results also highlighted the importance of system boundary choices and the need to balance multiple impact categories when evaluating the sustainability of waste valorization strategies.

The outcomes of this thesis suggest some interesting new paths of research. Firstly, improving the chemical stabilization of heavy metals in glass-ceramic matrices is crucial to reduce human toxicity to levels comparable with or superior to conventional disposal methods. Secondly, investigating the long-term environmental behavior and leaching potential of these glass-ceramic products under field conditions would help validate their safety and support their acceptance in regulatory frameworks and practical applications.

By addressing these research gaps, future studies can help advance the safe, sustainable, and economically viable valorization of bottom ash, reinforcing its potential as a key contributor to circular economy strategies and low-impact materials engineering.

References

1. United Nations Environment Programme. (2024). *Global Waste Management Outlook 2024: Beyond an age of waste – Turning rubbish into a resource*. Nairobi, Kenya. Retrieved from https://www.unep.org/ietc/resources/report/global-waste-management-outlook-2024
2. Chen, D., Zhang, Y., Xu, Y., Nie, Q., Yang, Z., Sheng, W., & Qian, G. (2022). *Municipal solid waste incineration residues recycled for typical construction materials—a review*. RSC Advances, 12(10), 6279–6291. https://doi.org/10.1039/d1ra08050d
3. Lam, C. H. K., Ip, A. W. M., Barford, J. P., & McKay, G. (2010). *Use of Incineration MSW Ash: A Review*. Sustainability, *2*(7), 1943-1968. https://doi.org/10.3390/su2071943
4. Sabbas, T., Polettini, A., Pomi, R., Astrup, T., Hjelmar, O., Mostbauer, P., Cappai, G., Magel, G., Salhofer, S., Speiser, C., Heuss-Assbichler, S., Klein, R., & Lechner, P. (2003). *Management of municipal solid waste incineration residues.* Waste Management, 23(1), 61–88. https://doi.org/10.1016/S0956-053X(02)00161-7
5. Barracco, F., Demichelis, F., Sharifikolouei, E., Ferraris, M., Fino, D., & Tommasi, T. (2023). *Life cycle assessment for the production of MSWI fly-ash based porous glass-ceramics: scenarios based on the contribution of silica sources, methane-aided, and energy recoveries*. Waste Management, 157, 301–311. https://doi.org/10.1016/j.wasman.2023.05.005
6. Arena, U. (2012). *Process and technological aspects of municipal solid waste gasification. A review.* Waste Management, 32(4), 625–639. https://doi.org/10.1016/j.wasman.2011.09.025
7. Zhang, H., Deng, X., Zhao, Y., Wang, H., Wang, L., & He, P. (2022). *Hierarchically porous glass–ceramics by alkaline activation and crystallization from municipal solid waste incineration ashes*. Journal of Cleaner Production, 364, 132693. https://doi.org/10.1016/j.jclepro.2022.132693
8. Zhang, Z., Wang, J., Liu, L., Ma, J., & Shen, B. (2020). *Preparation of additive-free glass-ceramics from MSW incineration bottom ash and coal fly ash*. Construction and Building Materials, 254, 119345. https://doi.org/10.1016/j.conbuildmat.2020.119345
9. Li, C., Zhang, P., Zeng, L., Yu, L., & Li, D. (2023). *Study on preparation of glass-ceramics from municipal solid waste incineration (MSWI) fly ash and chromium slag*. Journal of Building Engineering, 68, Article 106080. https://doi.org/10.1016/j.jobe.2023.106080
10. Sanito, R. C., Bernuy-Zumaeta, M., You, S.-J., & Wang, Y.-F. (2022). *A review on vitrification technologies of hazardous waste*. Journal of Environmental Management, 316, Article 115243. https://doi.org/10.1016/j.jenvman.2022.115243
11. Šyc, M., Simon, F. G., Hykš, J., Braga, R., Biganzoli, L., Costa, G., Funari, V., & Grosso, M. (2020). *Metal recovery from incineration bottom ash: State-of-the-art and recent developments*. Journal of Hazardous Materials, 393, Article 122433. https://doi.org/10.1016/j.jhazmat.2020.122433
12. Han, Y., Cao, Y., Wang, H., Xu, Y., Liu, R., Xu, Y., Zhang, Y., & Yang, X. (2020). *Lightweight aggregate obtained from municipal solid waste incineration bottom ash sludge (MSWI-BAS) and its characteristics affected by single factor of sintering mechanism.* Journal of the Air & Waste Management Association, 70(2), 180–192. https://doi.org/10.1080/10962247.2019.1674753

13. Stabile, P., Bello, M., Petrelli, M., Paris, E., & Carroll, M. R. (2019). *Vitrification treatment of municipal solid waste bottom ash*. Waste Management, 95, 250–258. https://doi.org/10.1016/j.wasman.2019.06.021
14. Bruno, M., Abis, M., Kuchta, K., Simon, F.-G., Grönholm, R., Hoppe, M., & Fiore, S. (2021). *Material flow, economic and environmental assessment of municipal solid waste incineration bottom ash recycling potential in Europe*. Journal of Cleaner Production, 317, Article 128511. https://doi.org/10.1016/j.jclepro.2021.128511
15. European Commission. (2025, January 23). *Commission Implementing Decision (EU) 2025/107 of 23 January 2025 refusing protection in the Union of the Appellation of Origin "Emmentaler" registered in the International Register of Appellations of Origin and Geographical Indications of the Geneva Act*. Official Journal of the European Union, L 107, 24 January 2025. Retrieved June 26, 2025, from https://eur-lex.europa.eu/eli/dec_impl/2025/107/oj/eng
16. Joseph, A. M., Snellings, R., Van den Heede, P., Matthys, S., & De Belie, N. (2018). *The use of municipal solid waste incineration ash in various building materials: A Belgian point of view.* Materials, 11(1), Article 141. https://doi.org/10.3390/ma11010141
17. Poranek, N., Łaźniewska-Piekarczyk, B., Lombardi, L., Czajkowski, A., Bogacka, M., & Pikoń, K. (2022). *Green Deal and circular economy of bottom ash waste management in building industry—Alkali (NaOH) pre-treatment*. Materials, 15(10), 3487. https://doi.org/10.3390/ma15103487
18. Calderón, M., Alcalá, M., & Zornoza, E. (2022). *A study on the classification of a mirror entry in the European list of waste: Incineration bottom ash from municipal solid waste.* Sustainability, 14(16), 10352. https://doi.org/10.3390/su141610352
19. Morf, L. S., Zieger, L., & Hellweg, S. (2021). *Material flow, economic and environmental assessment of municipal solid waste incineration bottom ash recycling potential in Europe*. Journal of Cleaner Production, 297, 128511. https://doi.org/10.1016/j.jclepro.2021.128511
20. Venkatraman, K., Wilcox, S., Verheyen, V., & Panther, B. (2022). *The challenges of utilising bottom ash from waste to energy plant.* International Journal of Energy, Environment and Economics, 28(4), 305–333. https://doi.org/10.13140/RG.2.2.32034.29120
21. SCHOTT AG. (2024, April 23). *SCHOTT launches pilot projects on glass-ceramics and specialty glass for a more circular economy*. Retrieved June 05, 2025, from https://www.schott.com/en-dk/news-and-media/media-releases/2024/schott-launches-pilot-projects-on-glass-ceramics-and-specialty-glass-for-a-more-circular-economy
22. Chen, X., Tan, Y., Yan, H., Shi, J., Wu, J., & Ding, B. (2024). *A review of cleaner production of glass-ceramics prepared from MSWI fly ash.* Journal of Environmental Management, 370, 122855. https://doi.org/10.1016/j.jenvman.2024.122855
23. Yio, M. H. N., Yue Xiao, Ji, R., Russell, M., & Cheeseman, C. (2021). *Production of foamed glass-ceramics using furnace bottom ash and glass*. Ceramics International, 47(6), 8697–8706. https://doi.org/10.1016/j.ceramint.2020.12.193
24. Li, C., Zhang, P., & Li, D. (2022). *Study on low-cost preparation of glass–ceramic from municipal solid waste incineration (MSWI) fly ash and lead–zinc tailings.* Construction and Building Materials, 356, 129231. https://doi.org/10.1016/j.conbuildmat.2022.129231

25. Liu, B., Yang, Q.-W., & Zhang, S.-G. (2019). *Integrated utilization of municipal solid waste incineration fly ash and bottom ash for preparation of foam glass–ceramics.* Rare Metals, 38(3), 914–921. https://doi.org/10.1007/s12598-019-01314-2
26. Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Christensen, T. H., & Hauschild, M. Z. (2014). *Review of LCA studies of solid waste management systems—Part I: Lessons learned and perspectives.* Waste Management, 34(3), 573–588. https://doi.org/10.1016/j.wasman.2013.10.045
27. Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Hauschild, M. Z., & Christensen, T. H. (2014). *Review of LCA studies of solid waste management systems—Part II: Methodological guidance for a better practice*. Waste Management, 34(3), 589–606. https://doi.org/10.1016/j.wasman.2013.12.004
28. Yuan, Q., Zhang, J., Robert, D. J., Mohajerani, A., Tran, P., Zhang, G., & Pramanik, B. K. (2024). *Life cycle assessment of ceramic tiles manufactured using industrial waste fly ash*. Journal of Building Engineering, 97, Article 110775. https://doi.org/10.1016/j.jobe.2024.110775
29. Abubakar, S., Oumarou, M. B., Jummah, A. M. E., & Abubakar, A. B. (2021). *Development and performance evaluation of a small scale municipal solid waste incineration plant.* American Journal of Energy Research, 9(2), 75–83. https://doi.org/10.12691/ajer-9-2-1
30. Oumarou, M. B., Abubakar, A. B., & Abubakar, S. (2018). *Municipal solid waste incinerator design: Basic principles*. Sustainable Energy, 6(1), 11–19. https://doi.org/10.12691/rse-6-1-2
31. CEWEP. (2019, June). *Circular economy still needs residual waste treatment in 2035*. Confederation of European Waste-to-Energy Plants. Retrieved June 26, 2025, from https://www.cewep.eu/cewep-capacity-calculations/
32. Tsekeris, G., & Anastassakis, G. N. (2022). *Municipal solid waste-to-energy in EU-27 towards a circular economy*. Reciklaza i održivi razvoj, 15(1), 83–96. https://doi.org/10.5937/ror2201085T
33. Zhang, H., Zhao, Y., & Wang, H. (2021). *Characteristics and environmental risk of MSWI bottom ash: A review*. Journal of Hazardous Materials, 402, 123544. https://doi.org/10.1016/j.jhazmat.2020.123544
34. Sorlini, S., Abbà, A., & Collivignarelli, M.C. (2017). *Leaching behaviour of municipal solid waste incineration bottom ash: From column tests to modelling*. Waste Management, 62, 147–158 https://doi.org/10.1016/j.wasman.2017.02.037
35. Appendino, P., & Ferraris, M. (2004). *Production of glass–ceramic bodies from the bottom ashes of municipal solid waste incinerators.* Journal of the European Ceramic Society, 24(13), 2113–2118. https://doi.org/10.1016/S0955-2219(03)00264-4
36. Vu, D. H., Wang, K.-S., Chen, J.-H., Bui, X. N., & Bui, H. B. (2012). *Glass–ceramic from mixtures of bottom ash and fly ash*. Waste Management, 32(12), 2306–2314. https://doi.org/10.1016/j.wasman.2012.05.040
37. Rincón, A., Romero, M., & Rawlings, R.D. (2018). *Utilisation of vitrified MSWI bottom ash for the production of glass–ceramics*. Waste Management, 76, 241–248 https://doi.org/10.1016/j.wasman.2018.03.008
38. Bruno, G., Bianco, C., & Mollea, C. (2021). *Material flow, economic and environmental analysis of bottom ash treatment technologies*. Resources, Conservation & Recycling, 173, 105719 https://doi.org/10.1016/j.resconrec.2021.105719

39. Rabelo Monich, P., et al. (2019). *Glass–ceramics from vitrified bottom ash of municipal solid waste incineration: Influence of crystallization heat treatment*. Journal of Cleaner Production, 235, 1555–1566. https://doi.org/10.1016/j.jclepro.2019.07.327
40. Srinivas, H. (Ed.). (n.d.). *Defining Life Cycle Assessment*. Global Development Research Center. Retrieved June 26, 2025, from https://gdrc.org/uem/lca/lca-define.html
41. Klöpffer, W. (1997). *Life cycle assessment: From the beginning to the current state*. Environmental Science and Pollution Research, 4(4), 223–228. https://doi.org/10.1007/BF02986351
42. Baumann, H., & Tillman, A.-M. (2004). *The hitch hiker's guide to LCA: An orientation in life cycle assessment methodology and application*.
43. International Organization for Standardization. (2006). *ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework*. ISO.
44. Nurzhan, A., Ruan, X., & Chen, D. (2025). *A review of life cycle assessment application in municipal waste management: Recent advances, limitations, and solutions.* Sustainability, 17*(1)*, Article 302. https://doi.org/10.3390/su17010302
45. Shabani, T., Jerie, S., & Shabani, T. (2023). *Applicability of the life cycle assessment model in solid waste management in Zimbabwe.* Circular Economy and Sustainability, 3(4), 2233–2253. https://doi.org/10.1007/s43615-023-00268-z
46. Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M. D. M., ... & van Zelm, R. (2017). *ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level.* The International Journal of Life Cycle Assessment, 22(2), 138–147. https://doi.org/10.1007/s11367-016-1246-y
47. Rosenbaum, R. K., Bachmann, T. M., Gold, L. S., Huijbregts, M. A. J., Jolliet, O., Juraske, R., et al. (2008). *USEtox—the UNEP-SETAC toxicity model: Recommended characterization factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment*. International Journal of Life Cycle Assessment, 13(7), 532–546. https://doi.org/10.1007/s11367-008-0038-4
48. Stabile, P., Bello, M., Petrelli, M., Paris, E., & Carroll, M. R. (2019). *Vitrification treatment of municipal solid waste bottom ash*. Waste Management, 95, 250–258. https://doi.org/10.1016/j.wasman.2019.06.021
49. Eom, J. Y., Yang, S. J., Lee, M. J., Yang, Y. R., Wie, Y. M., Lee, K. G., & Lee, K. H. (2024). *Recycling fly ash into lightweight aggregate: Life cycle assessment and economic evaluation of waste disposal*. Sustainability, 16(21), Article 9271. https://doi.org/10.3390/su16219271
50. Allegrini, E., Vadenbo, C., Boldrin, A., & Astrup, T. F. (2015). *Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash*. Journal of Environmental Management, 151, 132–143. https://doi.org/10.1016/j.jenvman.2014.11.032
51. Richard, E. N., Hilonga, A., Machunda, R. L., & Njau, K. N. (2021). *Life cycle analysis of potential municipal solid wastes management scenarios in Tanzania: The case of Arusha City.* Sustainable Environment Research, 31(1), Article 1. https://doi.org/10.1186/s42834-020-00075-3
52. Manders, J. (2008, June 12). *Life cycle assessment of the treatment of MSW in "the average" European waste-to-energy plant* [Conference presentation]. CEWEP Congress on Waste-to-Energy, Bordeaux, France. CEWEP. Retrieved June 25, 2025, from https://www.cewep.eu/wp-content/uploads/2017/11/372_LCA_Jan_Manders.pdf