Use of Incinerator Bottom Ash for Frit Production

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loop closing
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waste valorization

Summary

This article presents the results of an experimental activity aimed at investigating the technical feasibility and the environmental performance of using municipal solid waste incineration bottom ash to produce glass frit for ceramic glaze (glaze frit). The process includes an industrial pretreatment of bottom ash that renders the material suitable for use in glaze frit production and allows recovery of aluminum and iron. The environmental performance of this treatment option is assessed with the life cycle assessment (LCA) methodology. The goal of the LCA study is to assess and compare the environmental impacts of two scenarios of end of life of bottom ash from municipal solid waste incineration (MSWI): landfill disposal (conventional scenario) and bottom ash recovery for glaze frit production (innovative scenario). The main results of the laboratory tests, industrial simulations, and LCA study are presented and discussed, and the environmental advantages of recycling versus landfill disposal are highlighted.
Introduction

In July 2008, the European Commission presented the Communication on the Sustainable Consumption and Production (SCP) and Sustainable Industrial Policy Action Plan (EC 2008). The plan encourages improvement of products' environmental performance and energy efficiency and promotes the demand for more sustainable goods and production technologies. It calls on industry to transform environmental challenges into economic opportunities and on consumers to make informed choices with the help of more coherent and simplified labeling. The plan builds on a number of policies already implemented in Europe, even as it highlights the need to put greater efforts toward reducing dependency on raw materials and encouraging optimal resource use and recycling. Over the past few years, the revision of the European waste policy has addressed the reduction of the overall negative environmental impact of resource use. The “thematic strategy on the prevention and recycling of waste” (EC 2005) promotes several actions to improve waste policy, including the introduction of life cycle thinking and a further development of the European Union’s (EU’s) recycling policy.

Life cycle assessment (LCA), a standardized methodology (ISO 2006a, 2006b) that allows the assessment of the environmental impacts associated with the whole life cycle of a product or service from cradle to grave, can be usefully applied to assessing the environmental sustainability of waste management (White et al. 1995; Clift et al. 2000; Ekvall & Finnveden 2000; Bjarnadottir et al. 2002; Eriksson et al. 2005). It has been widely used as a decision-supporting tool to compare integrated waste management systems, to highlight environmental hot spots, and for the environmental assessment of waste treatment technologies. Comparative studies have been carried out, for instance, on integrated waste management (Masoni et al. 2000; Buttol et al. 2007), landfill technologies (Menard et al. 2004; Kirkeby et al. 2007), thermal treatments (Assefa et al. 2005; Fehrenbach et al. 2007), energy recovery (Finnveden et al. 2005; Sánchez et al. 2007), and materials recycling (Craighill & Powell 1996; Björklund & Finnveden 2005) and on different end-of-life solutions for specific waste flows, such as landfill versus incinerator (Rabl et al. 2008) or landfill versus recycling (Finnveden & Ekvall 1998). As studies differ in assumptions, waste characteristics, type of technology, spatial and temporal factors, and the related information, it is difficult to generalize the results obtained.

Moreover, several studies have been published that address the methodological aspects of the application of LCA in waste management (Finnveden 1996, 1999; Finnveden and Ekvall 1998; Sundqvist 1999; Ekvall et al. 2007). Important methodological issues include system boundary definition, multi-input allocation, time frame, and assumptions.

The definition of the system boundary concerns two aspects: upstream and downstream boundaries, and multifunctional systems. Researchers often address the first aspect by excluding the production of waste and the fate of materials and energy recovered in waste management systems (Finnveden 1999; Coleman et al. 2003). The second aspect often occurs in waste management applications, where to the main function (i.e., the treatment of solid waste) other functions may be added, such as the production of heat, electricity, or materials. In this case, two solutions are available: allocation between products, and system boundary expansion, the latter of which is the most widely used approach (Finnveden 1999; Giegrich 2003), even though criticism and concerns have been raised against it (Heijungs & Guinée 2007).

Multi-input allocation occurs when the waste under investigation is a fraction of the waste stream and the aim of the study is to analyze the environmental impact caused by this fraction. Knowledge of the causal relationships based on natural science is important for a correct allocation, but, in absence of a complete understanding, allocation based on mass, energy, or content of an element in the waste can be used. As emissions can be product related or process related and emission factors often have a nonlinear relationship with the input, the allocation factors are difficult to estimate, and different choices may sometimes lead to different conclusions.

The role of potential emissions from waste leaching over time should not be neglected in LCA studies. Even if all authors agree that
emissions from landfills will continue for a long time and that long time horizons should be included in life cycle inventories (Hellweg 2001; Björklund 2003; Doka & Hischier 2005; Hellweg et al. 2005), different approaches can be found in literature (Finnveden 1999), from the “surveyable time period” to the “infinite time period.” The former is defined as the time period to reach a pseudo-steady state in the landfill and corresponds to about 100 years. During this period, emissions from the landfill can be predicted on the basis of the current knowledge and acceptable extrapolations (Nielsen & Hauschild 1998). The latter is defined by total emission of landfill materials and leads to an assessment of the maximum impact.

In this study, the LCA methodology is used to compare the environmental performance of an industrial process of waste recovery with the landfill disposal option. Experiences of waste recycling in industrial processes can be found in several production sectors. The ceramic industry, for instance, makes an important contribution to the recycling of several waste types: urban solid wastewater sludge and sawdust (Cusidó et al. 1996), integrated gasification gas combined cycles (IGCC) slag (Acosta et al. 2002), and windshield glasses (Mortel & Fuchs 1997) can be used in brick manufacture; fly ash from municipal solid waste incineration (MSWI) and granite sawing residues can enter as components into porcelainized stoneware (Hernández-Crespo & Rinçon 2001). Additionally, bottom ash has properties that make it suitable for use as material in industrial productions, as shown in the review by Reijnders (2005). In particular, the use of MSWI bottom ash has been investigated for road construction (Izquierdo et al. 2001; Forteza et al. 2004; Birgisdóttir et al. 2006; Olsson et al. 2006), embankment and structural fills (Rivard-Lentz et al. 1997; Muhunthan et al. 2004), cement production (Pan et al. 2008), soil improvement in agriculture (Zhang et al. 2002; Mukhtar et al. 2003), flue gas cleaning systems (Lee et al. 2005), and sintering promotion in the production of porcelainized stoneware (Barbieri et al. 2002). It can also be an alternative aggregate for the production of building concrete (Pera et al. 1997; Bertolini et al. 2004; Cai et al. 2004), although it is better if pretreated to avoid swelling and cracking of the product due to the reaction between cement and metallic aluminum.

In this study the technical feasibility of using MSWI bottom ash to produce a glass frit for ceramic glaze (glaze frit) is investigated by means of laboratory tests and industrial simulations. The frit production in Europe is estimated at 1 to 1.25 million tonnes per year (EC 2001). The most important producers of frit are Spain (about 90% of all EU production) and Italy (about 10%). The total amount of municipal solid waste incinerated in Italy is about 4.5 million tonnes (APAT 2007), with an annual production of MSWI bottom ash of about 800 kilotons (kt;1 Federambiente and ENEA 2009). Bottom ash is characterized by heavy metal content (lead [Pb], copper [Cu], cadmium [Cd], zinc [Zn], etc.) and is classified as not hazardous special waste. About 50% of the MSWI bottom ash produced in Italy is landfilled (Federambiente and ENEA 2009).

According to these data, in the LCA study we aimed to compare the environmental performance of two treatments of MSWI bottom ash: landfill disposal, and waste recycling to produce glaze frit. The activity was carried out in the framework of LITCAR (www.litcar.it), a project funded by the Emilia-Romagna (Italy) regional government and aimed at promoting industrial research on waste prevention, waste treatment optimization, and waste control.

Description of Bottom Ash Treatment Options

The first treatment option investigated in this study is the recovery of bottom ash for glaze frit production. Bottom ash from the municipal solid waste incinerator of Reggio Emilia is transported to the Officina dell’Ambiente industrial plant, at a distance of about 140 kilometers (km). It is then pretreated, which results in a semifinished product called Matrix. The treatment mainly consists of three steps: 3 months aging of bottom ash as received, during which several processes occur, such as uptake of carbon dioxide (CO₂) from the air due to moisture, draining of excess water, and oxidation (EC 2006); grinding in the mill, which produces two fractions of 0 to 2 millimeters (mm)³ and 2 to 8 mm each; and separation of iron and aluminum by means

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of magnetic and eddy current systems. The separated metals are about 8% (7% iron, 1% aluminum) of the total bottom ash and are sent to recycling. About 80% by weight of the bottom ash is recovered as Matrix, a silicon-based chemical matrix with chemical—physical characteristics suitable for cement and concrete production as a substitute for gravel and sand. The rest is water evaporated during the aging treatment (about 10%) and unburned waste. The Matrix is sent to the Colorveggia plant (about 200 km from the Matrix's producer) for production of a colored glaze frit that uses 100% Matrix. The production process includes melting in a furnace at temperatures of 1,400°C to 1,500°C and rapid quenching in water. After quenching, the glaze frit is transported by conveyor belt and packaged into big bags. The process water is treated in a settling tank and is recirculated at the plant. The frit can be used for the production of colored ceramic glazes.

The second option investigated is the landfill disposal of bottom ash in compliance with the Italian regulation (government decree law no. 36, 2003). Bottom ash is transported from the municipal solid waste incinerator of Reggio Emilia to the Rio Riazzone landfill, at a distance of about 30 km. The landfill site, which was originally a clay pit, occupies an area of 147,000 square meters (m²). The bottom liner system of the site consists of a highly compacted clay layer, a geomembrane, and a geotextile fabric. The leachate collection system consists of high density polyethylene (HDPE) pipes located within a drainage layer, which is installed on top of the liner system. Landfill gas is collected through a system of HDPE pipes and is burned to produce electricity. The landfill had an active life of 16 years, during which it received 2 million cubic meters of municipal solid waste and bottom ash from MSWI, and it was closed in 2007. To guarantee the environmental restoration of the area, the public utility operating the landfill installed clay, geotextile liner, and vegetative soil layers on the top and planted grass. During the active phase and the 30-year postclosure care phase, the collected leachate is pumped to a storage tank and then transported to a wastewater treatment plant (WWTP), in accordance with Italian regulations. The WWTP effluent is discharged, and the final sludge is spread on agricultural land (40%) or incinerated (60%).

### Experimental Tests and Product Characterization

We collected samples of bottom ash from the Reggio Emilia incinerator plant in winter, in summer, and at three different times of the day to evaluate the compositional changes. The average chemical composition of bottom ash and Matrix (range of values for the two fractions obtained at Officina dell’Ambiente) was determined by X-fluorescence and is given as metal oxides in table 1. High content of silicon (Si), calcium (Ca), and aluminum (Al) oxides, which are typically of a glassy matrix, were observed. The loss on ignition (LOI) value of table 1 includes carbonates, chlorine, and organic substances. Carbonate content in Matrix (average value = 7%) is

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Bottom ash %</th>
<th>Matrix %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>48</td>
<td>30–47</td>
</tr>
<tr>
<td>CaO</td>
<td>18</td>
<td>17–21</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>12</td>
<td>10–13</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>7</td>
<td>4–11</td>
</tr>
<tr>
<td>Na₂O</td>
<td>5</td>
<td>2–5</td>
</tr>
<tr>
<td>MgO</td>
<td>3</td>
<td>2.8–3</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>1.5</td>
<td>1–2</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.0</td>
<td>0.9–1.0</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.0</td>
<td>0.7–1.0</td>
</tr>
<tr>
<td>CuO</td>
<td>0.7</td>
<td>0.5–0.7</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.3</td>
<td>0.3–0.8</td>
</tr>
<tr>
<td>SnO₂</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>BaO</td>
<td>0.2</td>
<td>0.08–0.10</td>
</tr>
<tr>
<td>MnO</td>
<td>0.1</td>
<td>0.1–0.2</td>
</tr>
<tr>
<td>PbO</td>
<td>0.1</td>
<td>0.2–0.3</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.09</td>
<td>0.03–0.05</td>
</tr>
<tr>
<td>NiO</td>
<td>0.03</td>
<td>0.02–0.03</td>
</tr>
<tr>
<td>CoO</td>
<td>0.003</td>
<td>–</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>–</td>
<td>0.3–0.6</td>
</tr>
<tr>
<td>SO₃</td>
<td>–</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>As₂O₃</td>
<td>–</td>
<td>0.001–0.005</td>
</tr>
<tr>
<td>CdO</td>
<td>–</td>
<td>0.001</td>
</tr>
<tr>
<td>Sb₂O₃</td>
<td>–</td>
<td>0.01–0.015</td>
</tr>
<tr>
<td>V₂O₅</td>
<td>–</td>
<td>0.005</td>
</tr>
<tr>
<td>LOI</td>
<td>1.7</td>
<td>5.6–11.7</td>
</tr>
</tbody>
</table>

Note: LOI = loss on ignition.
was determined by Dietrich Fruhling calcimeter measurements; chlorine content (0.48%) was determined by photometry. The differences of LOI values between bottom ash and Matrix may be due in part to the carbonization reaction that occurs during aging of Matrix.

We performed laboratory tests on Matrix from Officina dell’Ambiente. The finer fraction was selected for testing because it is more similar to the granulometry of the raw materials for conventional production. We vitrified samples of Matrix, with particle sizes ranging from 0 mm to 2 mm, in an electric furnace (Lenton) with a thermal cycle of about 5 hr at \(T_{\text{max}} = 1,450^\circ C\) to increase the homogeneity of the chemical composition and decrease the leaching of metals.

The compliance leaching test (UNI 2004; derived from the European norm EN 12457, “Characterisation of waste-Leaching-Compliance test for leaching of granular waste materials and sludges”) was performed on both MSWI bottom ash and vitrified material. Samples smaller than 4 mm were put in contact with distilled water in capped bottles. Liquid-to-solid ratio was 10:1, and the suspension was agitated for 24 hr at room temperature (20\(^\circ\)C ± 5\(^\circ\)C). Solid residue was separated by filtration; on each eluate, pH and conductivity were determined. After acidification at \(pH = 2\) with nitric acid (HNO\(_3\)), we analyzed Al, arsenic (As), Cd, cobalt (Co), chromium (Cr), Cu, iron (Fe), potassium (K), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb), and Zn with inductively coupled plasma atomic emission spectroscopy (ICP/AES). The reduction of the glass leachate conductivity value of about two orders of magnitude is an index of the vitrification effectiveness (see table 2). The process reduces drastically the solubility of the material because the chemically stable amorphous structure fixes metals by chemical bonds. In particular, the low content of Al, which behaves as a glass network former, demonstrates that the glass lattice is not solubilized. The content of soluble metals, such as Na and K, is low because they are embedded in the matrix.

As the thermal behavior is the most significant parameter during the firing of a tile, the prepared frit was characterized from a thermal point of view and compared with commercial colored frits that contain Fe and Fe + Cr + Mn. Hot-stage microscopy tests were carried out at the Colorveggia industrial plant. The thermal analysis showed that the frit based on Matrix and the commercial frit that contains the three chromophore ions have the same thermal behavior (see table 3), especially up to the softening point.

To complete the tests on the technical feasibility of frit from Matrix, we tailored a ceramic glaze formulation in collaboration with Colorveggia, taking into account the content of chromophore metals, in particular iron. Glaze is a layer or coating of a vitreous substance that is fired to fuse with a ceramic object to color, decorate, strengthen, or waterproof it. The frit represents the nonplastic component of the glaze; other components are plastic materials (clays, generally kaolin and bentonite) and additives (dispersing and deflocculating agents, binders, and

| Table 2 | Leaching test comparison between municipal solid waste incineration bottom ash and vitrified material |
|-----------------|-----------------|-----------------|
| Leaching parameters | Bottom ash | Glass |
| Conductivity \([\mu S/cm]\) | 1,490 | 11.4 |
| pH | 11.16 | 6.32 |
| Cr \((\mu g/L)\) | <1 | <1 |
| Cd \((\mu g/L)\) | 8 | <1 |
| Ni \((\mu g/L)\) | <3 | <3 |
| Cu \((\mu g/L)\) | 480 | 32 |
| Pb \((\mu g/L)\) | 530 | 15 |
| Al \((mg/L)\) | 90.4 | 0.10 |
| As \((mg/L)\) | 0.033 | 0.003 |
| Co \((mg/L)\) | <0.003 | <0.003 |
| Fe \((mg/L)\) | <0.01 | 0.17 |
| Mn \((mg/L)\) | <0.003 | 0.007 |
| Na \((mg/L)\) | 0.019 | 0.073 |
| Zn \((mg/L)\) | 151 | 0.31 |
| K \((mg/L)\) | 52.8 | 0.26 |

Note: \(\mu S/cm = \text{microsiemens/cm}; \mu g/L = \text{micrograms per liter}; \text{mg/L} = \text{milligrams per liter.}

| Table 3 | Characteristic temperatures of Matrix frit and commercial frit |
|-----------------|-----------------|-----------------|
| Characteristic temperature \((^\circ C)\) | Fe frit | Fe, Mn frit | Cr frit |
| T\(_{\text{sintering}}\) | 780 | 610 | 780 |
| T\(_{\text{softening}}\) | 830 | 650 | 830 |
| T\(_{\text{melting}}\) | 1,310 | 890 | 1,150 |
| Matrix frit | 1,190 |
defoaming agents). The frit based on Matrix is especially suitable for the production of a particular glaze called “flash effect glaze.” This is a colored glaze that is sprayed onto the tile and creates highlighting effects. It can be covered with a traditional transparent glaze or can be the top layer of the tile surface. The glaze was prepared with 97% frit from Matrix and 3% kaolin. The ceramic glazed tiles were produced according to the following steps, which were carried out at Colorveggia:

- spraying of an engobe on the ceramic support,
- spraying of flash effect glaze on the surface, and
- brushing of the surface to partially remove the glaze and confer an aesthetic effect.

In some samples, a traditional glaze was also applied between two layers of flash effect glaze.

Under these conditions, no technical defects were detected on the tiles’ surface. Aesthetic performance was compared to standard glaze formulations containing Fe, Fe + Mn, and Fe + Mn + Cr. The comparison highlighted the fact that manufacturers need to improve aesthetic properties to promote a better development of the color. The lack of aesthetic performance is probably due to the presence of many other elements in the bottom ash, different from the chromophore cations, which may hinder the color development. Further investigations are in progress for a better understanding of the problem.

**Life Cycle Assessment Study**

The LCA study was carried out according to ISO 14040 standards (ISO 2006a, 2006b). The goal of the study was to assess and compare the environmental impacts of two scenarios of end of life of bottom ash from MSWI: bottom ash recovery for colored glaze frit production (innovative scenario), and landfill disposal (conventional scenario).

The primary function of the systems investigated is bottom ash treatment in compliance with Italian law. Additional functions in the innovative scenario are the production of colored glaze frit and the recovery of secondary materials (aluminum and iron). In the system boundaries definition, systems associated with the delivery of these additional functions (i.e., glaze frit, aluminum, and iron production) were included in the conventional scenario, as a comparison between systems should be made on the basis of the same functions (see figure 1).

The system boundaries of the innovative scenario include the transport of bottom ash from the incinerator to the treatment plant, the production of Matrix, the recycling of aluminum and iron, the production of the innovative glaze frit, the recycling of the frit production scraps to produce glass, and the transport between plants. The system boundaries of the conventional scenario include the transport of bottom ash from the incinerator to the landfill site; the landfill construction and operations; the leachate transport to the WWTP; the WWTP construction and operations allocated to the volume of the conveyed leachate; the production and transport of raw materials (boric acid, alumina, calcium carbonate, dolomite, borax, quartz, and iron oxide) for glaze frit production; and the production of glaze frit, aluminum, and iron.

The plant’s construction is included in both scenarios. The MSWI, which produces the bottom ash, is not included because it is the same for both scenarios and can be neglected in a comparative analysis. The use and end of life of all the produced products are not included, as we assumed that they are the same for the two scenarios. Actually, a difference could exist in the use phase of innovative and conventional frit due to a different leaching behavior. For this reason, we carried out a sensitivity test to evaluate how much the metals leaching from innovative frit affect the LCA results. The functional unit (FU) adopted is the treatment, in compliance with the law, of 1 kilogram of bottom ash from MSWI with the average composition shown in table 1.

Primary data were collected at the Rio Riazzone landfill (ENIA 2005), at the pretreatment plant (Officina dell’Ambiente), and at the glaze frit production plant (Colorveggia) by means of questionnaires, environmental declarations, technical reports, and laboratory tests. These data are representative of Italian production and refer to the 5-year period from 2002 to 2007.
Secondary data come from the literature and from the Ecoinvent database (2000) and are representative of average European technologies. For the electricity consumption of the landfill, pretreatment process, and frit production, the Italian electricity production mix shown in table 4 was used.

To model the systems and assess the environmental potential impacts, we used the SimaPro7 software and the method CML2000 (Guinée et al. 2002). Primary energy consumption was evaluated with the nonrenewable energy category from the IMPACT 2002+ assessment method (Jolliet et al. 2003; Humbert et al. 2005).

The main assumptions adopted concern the following issues:

1. time horizon of the study,
2. leachate generation (amount and chemical composition) and treatment, and
3. relationship between materials recovery and system expansion to compare the same functions in both scenarios of the study.

**Time Horizon of the Study**

As the landfilled bottom ash from MSWI undergoes weathering reactions, pollutants are released by leaching. Many studies concerning the
characterization of bottom ash in terms of solubility, composition, and leaching behavior at different stages can be found in the literature (Johnson et al. 1996; Kersten et al. 1997; Dijkstra et al. 2002). Indeed, the pollution due to bottom ash leaching should be investigated from a long-term perspective, because pollutants can be released at different times and for hundreds of years. In this study, we include the leachate generation over 100 years, which is a period longer than the legal responsibility of controlling landfill emissions by Italian law but shorter than the pollutants’ total potential emission. Moreover, as standard LCA studies are based on static models, the pollutants emitted over 100 years have been assumed to occur all at the same time. This time frame is in agreement with the LCA study published by Nielsen and Hauschild (1998).

**Leachate Generation and Treatment**

The amount of leachate depends on a water balance that includes precipitation, runoff, evapotranspiration, and initial moisture of waste (Demetracopoulos et al. 1986; Baccini et al. 1987; Piotrowski 1995; El-Fadel et al. 1997). The leachate composition changes during the top-down percolation as a function of the solubility rate of specific waste. The major potential environmental impact is pollution of groundwater and surface waters (Kjeldsen et al. 2002). To calculate leachate amount and chemical composition, we have divided the 100-year time frame into three phases:

1. the landfill active phase (16 years), which ends with the landfill closure,
2. the postclosure care phase (30 years after the landfill closure), and
3. the postcare phase.

For the first phase, primary data are available. For the second and third phases, no data are available, but literature data suggest that infiltration of 22% of local precipitation occurs (Doka 2003, part III). We have assumed that the amount of leachate produced in the second and third phases is equal to the water infiltrated and that during the first and the second phases all of the produced leachate is collected and sent to the WWTP. As the landfill site was originally a clay pit, we have assumed that in the third phase leachate does not reach the water table and is dispersed into the soil.

As regards the leachate composition, primary data from the first phase reflect the weathering of the total waste disposed into the landfill. To obtain the pollutants related to the bottom ash disposal, we used an Ecoinvent model that calculates pollutant concentration starting from the bottom ash composition by means of transfer coefficients (Doka 2003, part III). The same model was used to calculate the pollutant concentration for the second and third phases.

Sludge composition and water emissions at the WWTP were calculated according to another Ecoinvent model (Doka 2003, part IV) that estimates emissions starting from leachate composition. As the organic compound content in bottom ash is negligible (Doka 2003, part III), we have assumed that chemical oxygen demand (COD) and biochemical oxygen demand (BOD) in sludge and water at WWTP are equal to zero and that no biogas is produced in the landfill.

**Relationship Between Materials Recovery and System Expansion**

We have assumed that the yield of metals recovery is 100% and that 1 kilogram of recovered metal replaces the same amount of primary metal produced by average European industrial technologies. From a market viewpoint, as about 77% (Schiona 2008) of the aluminum and 60% (CONAI 2007) of the steel produced in Italy come from secondary production with a net import of secondary materials, the Italian market can absorb an increase in internal offering of recycled metals.

**Results**

Table 5 shows the results of the comparative analysis of the two scenarios investigated, innovative and conventional. The results refer to the treatment of 1 kg of MSWI bottom ash. The innovative scenario shows lower potential environmental impacts than the conventional scenario for all impact categories.

Figure 2 shows the results as percentages of the maximum values (set equal to 100) of each
Table 5  Life cycle impact assessment results of innovative and conventional scenarios

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Innovative scenario</th>
<th>Conventional scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abiotic depletion potential (ADP)</td>
<td>kg Sb eq</td>
<td>9.26E-04</td>
<td>3.91E-03</td>
</tr>
<tr>
<td>Global warming potential (GWP100)</td>
<td>kg CO$_2$ eq</td>
<td>1.56E-01</td>
<td>6.22E-01</td>
</tr>
<tr>
<td>Ozone layer depletion potential (ODP)</td>
<td>kg CFC-11 eq</td>
<td>1.51E-08</td>
<td>4.46E-08</td>
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<td>Human toxicity potential (HTP)</td>
<td>kg 1.4-DB eq</td>
<td>3.78E-02</td>
<td>7.22E-01</td>
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<tr>
<td>Fresh aquatic ecotoxicity potential (FAETP)</td>
<td>kg 1.4-DB eq</td>
<td>2.43E-02</td>
<td>1.81E-01</td>
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<tr>
<td>Marine aquatic ecotoxicity potential (MAETP)</td>
<td>kg 1.4-DB eq</td>
<td>2.96E+01</td>
<td>5.55E+02</td>
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<td>Terrestrial ecotoxicity potential (TETP)</td>
<td>kg 1.4-DB eq</td>
<td>5.45E-04</td>
<td>1.66E-03</td>
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<td>Photochemical ozone creation potential (POCP)</td>
<td>kg C$_2$H$_4$</td>
<td>2.51E-05</td>
<td>1.91E-04</td>
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<td>Acidification potential (AP)</td>
<td>kg SO$_2$ eq</td>
<td>5.84E-04</td>
<td>2.70E-03</td>
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<tr>
<td>Eutrophication potential (EP)</td>
<td>kg PO$_4^{3-}$ eq</td>
<td>9.91E-05</td>
<td>2.89E-04</td>
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<td>Nonrenewable energy (NRE)</td>
<td>MJ primary</td>
<td>2.13E+00</td>
<td>8.48E+00</td>
</tr>
</tbody>
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Note: Sb eq = antimony equivalent; CO$_2$ eq = carbon dioxide equivalent; CFC-11 eq = trichlorofluoromethane equivalent; kg 1.4-DB eq = kilograms of 1.4-dichlorobenzene equivalent; SO$_2$ eq = sulfur dioxide equivalent; PO$_4^{3-}$ eq = phosphate equivalent; one megajoule (MJ) = $10^6$ joules (J, SI) $\approx$ 239 kilocalories (kcal) $\approx$ 948 British Thermal Units (BTU).

The maximum values always refer to the conventional scenario. The figure also shows the contribution of the processes for each scenario. The innovative scenario results are the sum of the contribution given by the production of the glaze frit from Matrix and the production of secondary iron and aluminum from MSWI bottom ash. The conventional scenario results are

Figure 2  Comparative analysis of the innovative (first bar) and the conventional (second bar) scenarios. ADP = abiotic depletion potential; GWP100 = global warming potential; ODP = ozone layer depletion potential; HTP = human toxicity potential; FAETP = fresh aquatic ecotoxicity potential; MAETP = marine aquatic ecotoxicity potential; TETP = terrestrial ecotoxicity potential; POCP = photochemical ozone creation potential; AP = acidification potential; EP = eutrophication potential; NRE = nonrenewable energy; WWTP = wastewater treatment plant.
Figure 3 Terrestrial ecotoxicity potential for bottom ash landfill disposal and leachate treatment. kg 1.4-DB eq = kilograms of 1.4-dichlorobenzene equivalent.

The sum of the contribution given by the conventional production of the glaze frit, the landfill disposal of bottom ash (including the leachate treatment in WWTP), and the production of primary iron and aluminum.

The potential environmental impacts of the innovative scenario are reduced by between 95% (marine aquatic ecotoxicity potential [MAETP]) and 66% (eutrophication potential [EP]) of the impacts of the conventional scenario. The contributions of aluminum and iron recycling to the innovative scenario are very low; in particular, the contribution of aluminum cannot be seen in Figure 2 because it is lower than 0.1%.

For all impact categories, the frit, aluminum, and iron production of the conventional scenario presents higher values than the innovative scenario. Primary aluminum production gives the highest contribution to the human toxicity potential (HTP; 78% of the total impact) and to the MAETP (62%). The contribution to HTP is mainly due to the emission of polycyclic aromatic hydrocarbons (PAHs) during aluminum production. The contribution to MAETP is mainly due to air and water emissions from electricity production and distribution.

The conventional scenario includes the contribution of the MSWI bottom ash landfill disposal and of the leachate treatment at the WWTP. In the conventional scenario, bottom ash disposal and leachate treatment give the lowest contributions to all impact categories, except for to the ozone layer depletion potential category. The main contribution to this category is due to bromotrifluoromethane (Halon 1301) air emissions, associated with the production of fuel for the leachate transport. The main contributions of bottom ash disposal and leachate treatment to all impact categories, apart from TETP, are due to the landfill construction and operations and to the leachate transport to WWTP. Figure 3 shows the contributions given to the TETP category. The impacts of leachate emissions into the environment are 68% of the total impact: The contribution given during the active, postclosure care, and postcare phases is 15%, 4%, and 49% of the total value, respectively.

The results concerning glaze frit production for both scenarios deserve a more detailed
discussion. From a technological point of view, the only difference between the two types of production is the use of Matrix instead of raw materials.

Figures 4, 5, and 6 show the results of the comparative analysis of the production of one tonne of glaze frit for the following impact categories: nonrenewable energy, abiotic depletion, and global warming (GWP 100), respectively. In all figures, the results are broken down under the contribution of the following items: plant, which includes the construction of the plant; transport, which refers to the input materials; materials, which includes the production of the input materials for frit production (i.e., Matrix in the innovative production or mixture of raw materials in conventional production); packaging, which includes materials and transport for big-bag

Figure 4 Nonrenewable energy results of innovative and conventional glaze frit production. Mj primary = megajoules of primary energy.

Figure 5 Abiotic depletion potential results of innovative and conventional glaze frit production. kg Sb eq = kilograms antimony equivalent.
production; furnace, which includes the production of methane and oxygen consumed in the melting furnace; electricity (i.e., electricity consumption at the plant); CO₂ emissions, which are the direct CO₂ emissions due to carbonate dissociation in the furnace; and waste and effluent treatment, which includes the recycling of scraps from frit production, the materials for the flue gas treatment, and the treatment of wastewater at the WWTP.

For all selected categories, the use of Matrix for frit production leads to a drastic reduction of the impacts. The impacts of transport are higher for the conventional frit production because the raw materials come from an average distance of about 300 km, while the distance from the Matrix producer to the frit production plant is about 200 km.

Figure 4 shows the results of innovative and conventional frit production for the nonrenewable energy impact category. For conventional frit, the impact due to the production of raw materials is 72% of the total impact. The main contributions are given by borax (51%) and alumina (11%) production. Similar results can be found for the abiotic depletion category (figure 5), where the contributions given by borax and alumina production are about 55% and 10% of the total impact, respectively. The contents of borax and alumina in conventional frit are about 12% and 4%, respectively. The role played by boron, which is a melting agent, in the conventional frit is played by aluminum in the innovative one.

For the global warming potential results, the production of raw materials also gives the highest contribution (figure 6) to the impact category. In particular, borax production contributes about 38% of the total of the category due to the CO₂ emissions produced by natural gas burning. Moreover, during melting in the furnace for frit production, CO₂ is produced by carbonate dissociation. As the frit from Matrix has lower carbonate content than the conventional frit (about 7% and 27% by weight, respectively), CO₂ emissions during melting decrease by 75%.

The sensitivity test, carried out to evaluate how much the metals leaching from a Matrix-based glaze frit over 100 years (the same time horizon as the landfill model) affect the LCA results, has demonstrated that metals emission estimated on the basis of the data in table 2 contributes less than 0.1% of the impacts of the innovative scenario.

**Conclusion**

The work presented in this article is a success story of research aimed at recovering a waste
stream, the MSWI bottom ash, for innovative products. The research was conducted by an interdisciplinary team with chemical, engineering, and environmental competencies and with the active participation of the stakeholders of the relevant industrial steps: MSWI, bottom ash pretreatment, and final use of the recovered material. Both the technical feasibility and the environmental advantages of the innovative solution have been assessed and confirmed by laboratory tests, industrial simulation, and an LCA.

The laboratory tests demonstrate that vitrification is effective in drastically reducing the solubility of heavy metals contained in the bottom ash and that the thermal behaviors of the innovative and the conventional frit are very similar. The industrial simulation of production of a ceramic glaze shows that the innovative frit is especially suitable for the production of a particular glaze, called flash effect glaze. The LCA study demonstrates that the innovative scenario is environmentally advantageous for all of the selected impact categories. The principal advantages of the proposed system are connected with the metals (aluminum and iron) recovery from bottom ash pretreatment, the use of secondary materials from waste instead of primary raw material in the frit production, and the avoidance of landfill disposal.

If we consider the total amount of colored and colorless frit production in Italy, the yield of Matrix production, and the use of Matrix to produce colored frit (Matrix content equal to 100%) or colorless frit (Matrix content equal to 10% to 30%), about 70 kt of MSWI bottom ash could be used to produce frit in Italy. This amount represents the 17% of the bottom ash that currently goes to landfill disposal. These data show that the reuse of bottom ash to produce frit cannot entirely substitute the landfill option but can be considered as a successful example of industrial ecology. This case study is representative of the Italian situation, given that the ceramic glaze producers are located in a very narrow area district (350 enterprises in 300 km$^2$), but it is possible to transfer this model to other European countries where glaze producers are present (e.g., Spain, which is the largest producer in the world).

A semiquantitative estimation of the economic aspects related to the use of MSWI bottom ash to produce glaze frit shows potential advantages for all of the actors in the chain in comparison with the present landfilling: the incineration plant, because the costs of treatment at Officina dell’Ambiente are slightly lower than the costs of landfill disposal; Officina dell’Ambiente, which can open a new market to Matrix, which is currently used for cement and concrete production; and the frit producer, because the costs of raw materials, which are 50% to 60% of the total cost of frit production, dramatically decrease with the use of the very cheap Matrix.

The technically and environmentally positive results and the potential economic advantages encourage investigators to carry on with the research activity, with the aim of improving the aesthetic characteristics of the obtained product. Further studies are also required to scale up to industrial production and to market the new products.

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Notes

1. One kiloton (kt) = $10^3$ tonnes (t) = $10^3$ megagrams (Mg, SI) ≈ 1.102 × 10$^3$ short tons.
2. One kilometer (km, SI) ≈ 0.621 miles (mi).
3. One millimeter (mm) = $10^{-3}$ meters (m, SI) ≈ 0.039 inches.
4. One square meter (m$^2$, SI) ≈ 10.76 square feet (ft$^2$).
5. One kilogram (kg, SI) ≈ 2.204 pounds (lb).

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