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Life Cycle Assessment of Alternative Processes to Treat Fly Ash from Waste Incineration

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Unsustainable consumption and production patterns, together with industrialization and population growth, have increased the generation of municipal solid waste (MSW), causing several environmental problems. The European Waste Framework Directive (WFD) sets waste prevention, preparation for reuse and recycling as priority strategies. Nevertheless, still a great amount of MSW ends up in landfills and waste-to-energy (WtE) plants. WtE plants reduce~~s~~ waste volume and allow~~s~~ efficient recovery of energy, however, incineration results in various types of solid wastes, bottom, boiler and fly ashes (FA). Due to the concentration of dangerous substances, FA are treated by means of stabilisation/solidification (S/S), thermal treatments or combined treatments, to reduce their toxicity and to avoid negative impacts on the environment and human health. Among S/S alternatives, stabilisation with cement and carbonation are one of the most popular. To determine the environmental performance of these processes this paper conducted a life cycle assessment (LCA). The study evaluated FA stabilisation with cement and water and FA carbonation for 55 % and 100 % excess of CO_2 in the flue gas at the outlet of the reactor, and pressures of 1, 5, 10, 15 and 20 bar. The results showed that the range of pressure between 3 and 4 bar, and 55 % excess of CO_2 in the flue gas have an efficient performance. The comparison of FA carbonation and stabilization displayed that the latter has higher impacts than the alternative carbonation due mainly to the cement production and the reduction of lixiviation and CO_2 capture in the ash.

1. Introduction

Unsustainable consumption and production patterns, together with industrialization and population growth, have increased the generation of municipal solid waste (MSW), causing several environmental problems. Our economic system is based on a linear model, assuming that resources are abundant, available, easy to source and cheap to dispose of. This unsustainable consumption and production pattern, together with industrialization and population growth have increased the generation of municipal solid waste (MSW), causing several environmental problems (Margallo et al., 2018). Current global MSW generation levels are approximately 1.3×10^9 t/y, and are expected to increase to approximately 2.2×10^9 t/y by 2025 (Hoornweg and Bhada-Tata, 2012). In this sense, waste management is one of the most complex environmental challenges faced by modern societies. The European Waste Framework Directive (WFD) (EC, 2008) is promoting a more sustainable performance, reducing waste generation and connecting resource use and waste residuals (Tsai, 2016). WFD sets waste prevention, preparation for reuse and waste recycling as priority strategies. Nevertheless, recycling and reuse are not always suitable for all waste streams; and thus, a great amount of MSW ends up in landfills and waste-to-energy (WtE) plants, considered by European policies as last-resort options. WtE plants are one of the most robust waste treatments, which not only reduce~~s~~ waste volume, but also allows efficient recovery of energy (Margallo et al., 2014). However, incineration results in various types of solid wastes, primarily including bottom, boiler and fly ashes (Tsai, 2016). Fly ashes (FAs) represent only a few percent of the input waste. They are fine and are normally characterised by a high content of chlorides and significant amounts of dangerous substances, such as heavy metals or organic compounds. Due to its composition, FA must be treated in order to reduce its toxicity and to avoid negative impacts on the environment and human health. The application of a

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certain treatment may have two approaches: ensure landfilling of FA in non-hazardous landfills or improve the possibilities of its valorisation (Margallo et al., 2015). Regarding the former, FA are often treated by means of separation processes, stabilisation/solidification (S/S), thermal treatments or combined treatments. Among S/S alternatives, stabilisation with cement and carbonation are one of the most popular. Stabilisation with cement involves the immobilisation of the hazardous components in a solid matrix. The energy consumption linked to cement production is a drawback of this technique. For that reason, carbonation could be an alternative treatment that enables the adsorption of the heavy metals present in the FA to the carbonates produced in the reaction of calcium. However, a deep analysis is required to determine the hotspots of the process and to compare its environmental performance. Several environmental tools are available, being life cycle assessment (LCA) widespread. LCA quantifies all the inputs and outputs of the material flows and assessing how these inputs and outputs impact the environment (Mah et al., 2017). Therefore, this tool allows to assess the potential environmental impacts and resources used throughout a product´s life-cycle (Margallo et al., 2013) and reveals cross-media issues (Laso et al., 2016). In this sense this work evaluated and compared the environmental performance of two FA treatments in order to propose improvement measures to the waste management sector.

2. Life cycle assessment methodology

LCA methodology was applied according to the ISO 14040 (ISO, 2006) to evaluate the treatment of FA. This methodology is based on a four-phase process: i) definition of goal and scope; ii) life cycle inventory (LCI); iii) life cycle impact assessment (LCIA) and iv) interpretation (Margallo et al., 2014).

2.1 Goal and scope

Goal and scope definition is one of the most important phases of the LCA methodology, because the choices made at this stage influence the entire study (De Marco et al., 2017). The goal of this study is to evaluate the treatment of FA from a WtE plant located in Cantabria Region (North of Spain). The plant produced in 2014 4,655 Mt of FA (GOBCANT, 2016). The amount of FA was selected as functional unit in order to compare the efficiency of the solidification and carbonation treatments. Figures 1a and 1b depict the flow diagram of FA carbonation (scenario a) and FA stabilisation (scenario b).

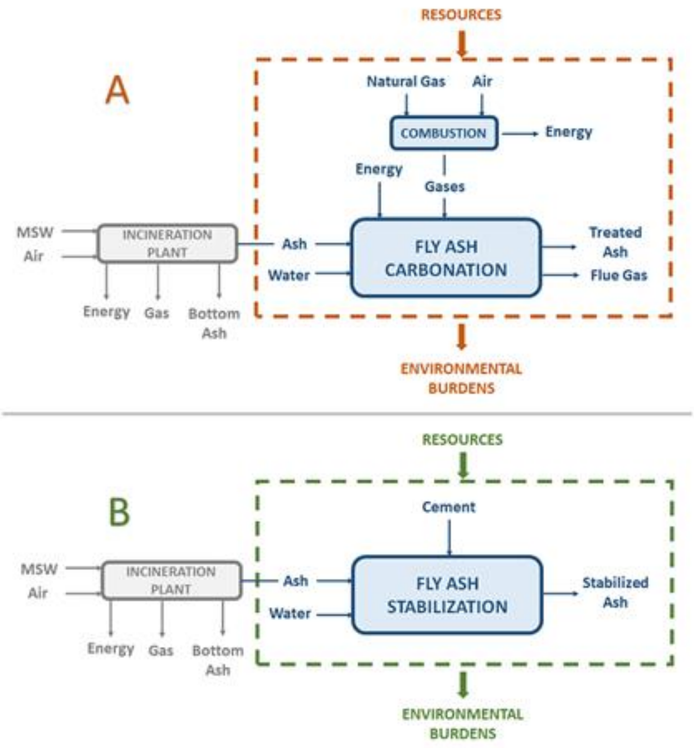

Figure 1: Flowsheet of A) FA carbonation (scenario a) and B) FA stabilisation (scenario b)

The analysis was structured in two blocks: i) the comparison of FA carbonation at different pressures and excess of CO_2 in flue gas and ii) the comparison of the FA carbonation and stabilisation processes. Regarding carbonation, to determine the reactor dimensions, the following scenarios were studied: 55 % and 100 % excess of CO_2 in the flue gas at the outlet of the reactor, and pressures of 1, 5, 10, 15 and 20 bar. The comparison of FA carbonation and stabilization has to be done based on the same function. The combustion process of natural gas is considered a part of the life cycle of the FA carbonation and thus, the environmental impacts related to the generated electricity are considered as a secondary function of the system.

2.2 Life cycle inventory

The life cycle inventory is one of the most effort-consuming steps and consists on the collection and interpretation of the data necessary for the environmental assessment of the observed system (Iannone et al., 2014). Input and output data are based on experimental data, calculations and bibliographic sources (Biellen et al., 2014). Secondary data were taken from other databases such as PE International (PE International, 2017) or IPCC (IPCC, 2006). LCI was calculated for different pressures and excess of CO_2 in the flue gas with respect to the CO_2 that reacted in the experimental set-up. Figure 2 shows that for the 55 % and 100 % CO_2 excess, a similar diameter (and height) is obtained, while for the 10 % excess, the dimensions are noticeably higher. The results highlight that the higher pressure, the less reactor volume is necessary and, therefore, the required diameter (and height) is smaller. This gradient is particularly high for pressures below 5 bar. Thus, the LCA was performed for a pressure range between 1 and 5 bar, and a CO_2 excess of 55 and 100 %, in order to understand the trade-off between these variables. Table 1 and 2 summarised the life cycle inventory of FA carbonation and stabilization, respectively.

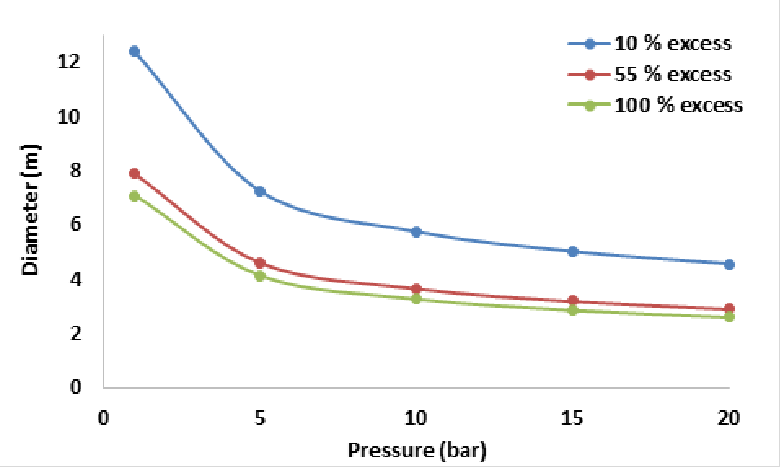

Figure 2. Variation of diameter of the reactor with pressure and composition of flue gas

Table 1: Life cycle inventory of carbonation (5 bar / 55 % excess of CO_2 in the flue gas)

	Flows		Amount	Units	Data source
Inputs	Fly ashes		1.00	t FA	GOBCANT (2016)
	Energy				
		Compression	2.40E-02	kWh/t FA	Own calculations
		Stirring	281	Kwh/ FA	Own calculations
	Natural gas		241	t/ t FA	Own calculations
	Water		6,000	l/ t FA	Own calculations
Outputs	Treated ashes		7.00	t/ t FA	Own calculations
	Flue gas		4.39		Own calculations

Table 2: Life cycle inventory of FA stabilisation

	Flows	Amount	Units	Data source
Inputs	Fly ashes	1.00	t FA	GOBCANT (2016)
	Cement	0.30	t/ t FA	Biellen et al. (2014)
	Water	389	l/ t FA	Biellen et al. (2014)
Outputs	Stabilised ashes	1.69	T/ t FA	Biellen et al. (2014)

2.3 Life cycle impact assessment

The life cycle impact assessment stage was conducted with the LCA software GaBi 6 (PE International, 2017). The environmental impact categories used for this study are described in Table 3. These impact categories have been chosen because i) climate change is a pressing issue nowadays, ii) abiotic depletion potential and total freshwater consumption allow putting into perspective the scarcity of raw materials and water in order to minimise resource consumption, and iii) ecotoxicity takes into account the detrimental consequences of the processes on the ecosystem, which are the reason FA cannot be directly landfilled.

Table 3: Impact categories of the LCA study

Impact category	LCIA method	Units	Data source
Global Warming Potential (GWP)	IPCC	kg CO2 – Equiv.	IPCC (2013)
Abiotic Depletion potential (ADP)	CML 2001	kg Sb – Equiv.	Guinèe et al. (2001)
Total Freshwater Consumption (TFC)	Swiss Ecoscarcity	kg water	Frischknetcht et al. (2006)
Ecotoxicity (Ecotox.)	USEtox	Comparative Toxic Units for ecotoxicity effects (CTUe)	Rosenbaum et al. (2008)

3. Results

Figure 3 shows the environmental performance of the FA carbonation for different pressures and the two studied scenarios: 55 % and 100 % excess of flue gas for each selected impact category.

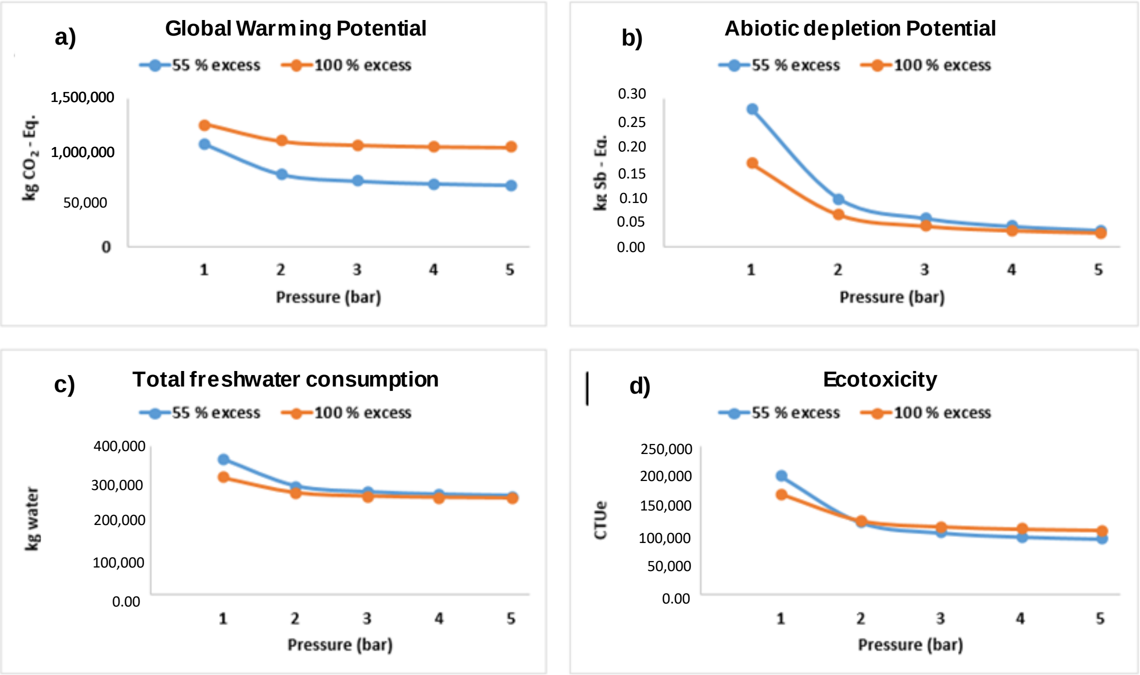

Figure 3. Variation of diameter of the reactor with pressure and composition of flue gas for the impacts categories a) global warming potential, b) abiotic depletion potential, c) total fresh water consumption and d) ecotoxicity

In Figure 3, each represented point reflects a different reactor volume. In general terms, when the pressure increases, a higher equilibrium concentration is obtained and, therefore, the required reactor dimensions are smaller. Since the power of stirring depends on the agitator diameter, and this, in turn, is conditioned by the reactor diameter, which is raised to the fifth, as the flue gas pressure increases, less energy is required for agitation. The total energy of the process is equal to the sum of the energy required for compression and stirring, being the latter significantly higher than the former. As a consequence, the total energy consumption decreases as the pressure of the flue gas increases. Thus, the environmental impacts of the carbonation process decrease as the pressure increases. Regarding the contribution of each process, most of the activities associated with energy generation contribute substantially to all the impact categories. Nevertheless, the consumption of water (process water: almost 70 %) is the main contributor to the environmental impact in the total freshwater consumption category. Figure 4 compares the results of FA carbonation (scenario a) and stabilization (scenario b) for each selected impact category. It can be clearly seen that the main way to treat FA (stabilisation) has higher impacts than the alternative technique (carbonation), due mainly to the reduction of lixiviation and CO_2 capture in the ash. Moreover, energy demand for cement production is the main contributor of FA stabilization. In fact, cement manufacturing is responsible for nearly 80 % of the overall abiotic depletion indicator.

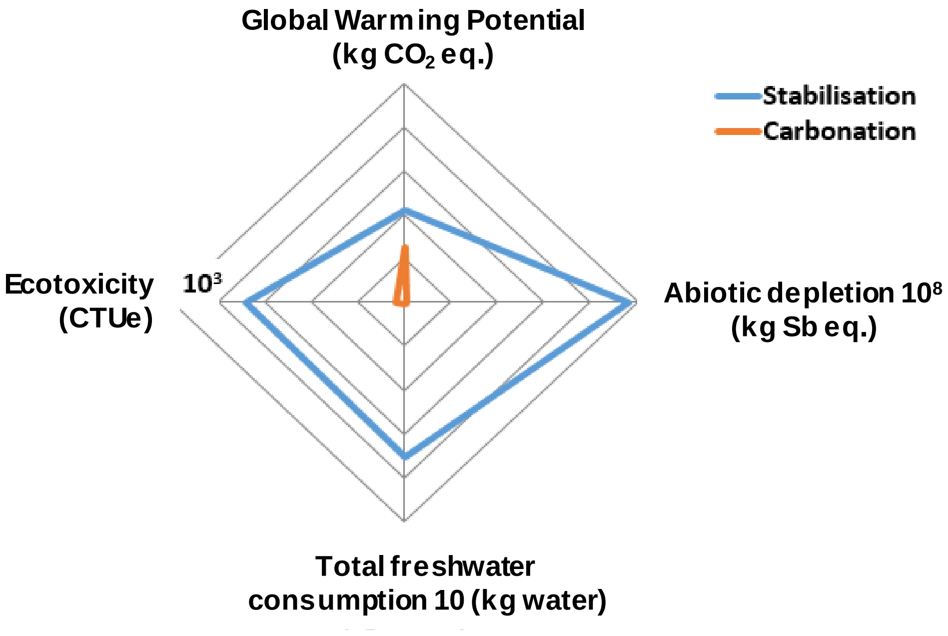

Figure 4. Comparison of environmental impact of FA carbonation (scenario a) (5 bar and 55% excess of CO_2 in the flue gas) and FA stabilisation (scenario b)

4. Conclusions

This work conducted a quantitative environmental assessment of two treatments for the FA from MSW incineration (stabilisation and carbonation) in Cantabria (Spain).

FA stabilization resulted as the least environmental friendly treatment. The emergent technique of carbonation presents improvements in the chemical properties of FA and a new future use in the industry. This process allows reducing the riskiness of the waste and the discharge volume. Additionally, as for the avoided burdens, the FA carbonation process achieves to reduce the environmental impacts due to the fact that the generation of electricity from natural gas combustion can replace the required electricity in the process itself.

Regarding the operational conditions, several pressures and CO_2 excesses were studied to evaluate the influence of them on the reactor dimensions. It can be concluded that on the one hand, the range of pressure between 3 and 4 bar, and on the other hand, 55 % excess of CO_2 in the flue gas provide an efficient result. As the results have revealed, for pressures higher than 3 bar, the environmental impacts decrease minimally, that is, there is not a significant difference among the choice of 3, 4 or 5 bar. So, this minimum pressure allows reducing the energy of compression. Furthermore, the choice of 55 % excess of CO_2 in the flue gas is due to the fact that with this CO_2 excess and this range of pressures, less impacts are obtained in GWP and ecotoxicity while similar values are achieved in abiotic depletion and the total freshwater consumption. To sum up, this choice is not the best option for all the environmental impacts. Nevertheless, it allows achieving a balance between the environmental impacts, the total used energy and a reasonable reactor volume.

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