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Characterisation and Environmental Analysis of Sewage Sludge as Secondary Fuel for Cement Manufacturing

Alfonso Aranda-Usón, Germán Ferreira*, Ana M. López-Sabirón,
Eva L. Sastresa, Aitana S. de Guinoa

CIRCE - Centre of Research for Energy Resources and Consumption - University of Zaragoza. Mariano Esquillor
15, 50018, Zaragoza, Spain
germanf@unizar.es

An evaluation of the environmental performance of clinker production using sewage sludge as alternative fuel has been conducted. To this end, the life cycle assessment (LCA) methodology has been applied to estimate the main environmental impacts in four different scenarios considering conventional combustion with petroleum coke, the replacement of fossil fuel by sewage sludge and the variation of the moisture in the alternative fuel.

The Recipe method, as midpoint and endpoint approach, has been used to calculate life cycle impact category indicators. Results have been classified into the main impact categories in each case, e.g. global warming, acidification or eutrophication. To obtain more real conclusions avoiding problems associated with subsequent scale factors, this research analyses the environmental performance of sludges as alternative fuel from the industrial point of view. The results show significant technical and environmental improvements in cement manufacturing when sludge is introduced although chemical composition of the studied sewage sludge as well as the moisture level affect notably to the final impacts.

1. Introduction

Sludge originates from the process of treatment of waste water and they are characterised by a rich composition in nutrients (nitrogen, phosphorous and valuable organic matter) that are useful when soils are depleted or subject to erosion. Because of its chemical composition, spreading in agriculture issues is one of the main priorities according to the Waste Framework Directive 2008/98/EC. However, the sludge amount production and its heavy metals concentration, as well as other poorly biodegradable compounds and potentially pathogenic organisms, have increased in the last years motivated by a growth of the population, household product use such as detergents or medicines and industrial discharges. Considering this current approach, the spreading of sewage sludge on agricultural land can contribute to the damage of the soil quality and it is necessary to find other environmentally friendly alternative use to landfilling. In fact, this is a current practice in Europe representing a 15 % of the disposal available methods in 2005 (Kelessidis and Stasinakis, 2012). However, it leads to negative outputs which mainly consist of emissions to the air, soil and water and also other impacts in terms of noise and dust from the delivery vehicles, as well as odours, land use, disturbance of vegetation and the landscape (European Commission, 2001).

There is a great potential for the use of solid wastes as alternative fuels and raw materials in the cement manufacturing industry. The replacement of fossil fuels is not only an environmentally friendly method of waste management but also a cost saving and suitable way to conserve fossil fuels and

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natural resources since it is considered that between 60 and 130 kg of non-renewable fuels are fired per tonne of cement manufactured (Cembureau, 2011).

Additionally, the cement industry is an energy-intensive and high pollutant emitting industry since it accounts for approximately 12-15 % of the total industrial energy use worldwide and contributes approximately 6 % of the total global carbon dioxide emissions (Madlool et al., 2011). Consequently, the cement industry presents the opportunity to recover the energy from several waste materials under optimal technical and environmental conditions (temperature, residence time or pH environment in the kiln), avoiding losses of energy to processes associated with the waste management chain, such as incineration or landfilling (Choate, 2003). In contrast to incineration, in this approach the heavy metals contained in the combustion ashes are added to the final product and, consequently, the management of final residues with high levels of metals are significantly minimised. In fact, it was demonstrated that the content of some heavy metals such as Cr, Zn, and Ni have no influence on the formation of the clinker phases and, subsequently, in the quality and mechanical properties when their concentrations are low in the raw mixture (Chen et al., 2010).

Although some studies about co-combustion of sewage sludge with coal have been found (Zabaniotou and Theofilou, 2008), no studies regarding a life cycle assessment (LCA) of petroleum coke (pet coke) and sewage sludge co-combustion in cement production have been achieved. In addition, there is a significant lack of knowledge regarding the environmental impacts characterisation using the RECIPE method. Therefore, this research develops an environmental analysis based on the LCA methodology, using RECIPE method for quantifying the life cycle impact category indicators, to determine if the use of sludge sewage as secondary fuel in cement production is a sustainable option in a Spanish cement plant based on pet coke as fuel. Inputs and outputs have been defined and the inventory emissions calculated using Simapro v7.3.2 (PRé, 2007) and the Ecoinvent v2.2 database (Ecoinvent Centre, 2007), which have been classified into different impact categories. Four scenarios with variations of the replacement ratio and humidity are studied to explore a wide range of conditions. Additionally, the sludge considered has a significant composition in heavy metals.

2. Methodology

The most up-to-date structure of the LCA is proposed by the standard ISO 14040 (International Organization for Standardization, 2006). This methodology is synthesised in four interrelated phases between them: goal and scope definition, inventory analysis, impact evaluation and interpretation.

2.1 Scope of the analysis and functional unit

The functional unit is defined as the measure of the performance of the functional outputs of the production system. Its main goal is to provide a reference to which the process inputs and outputs are correlated. In this research, 1 kg of clinker production has been chosen as functional unit and all inputs and outputs have been managed consistently.

2.2 System description and boundaries

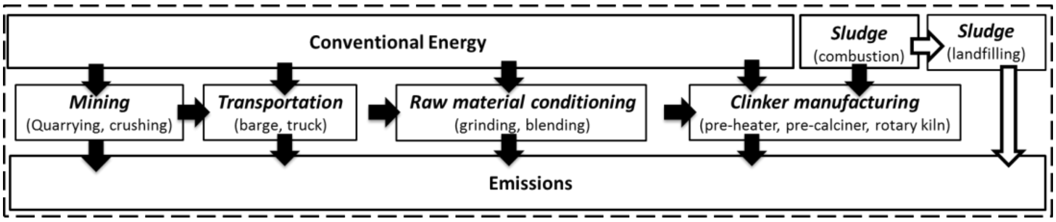

Figure 1: System boundary

As is represented in Figure 1, the system boundaries include the whole manufacturing process to produce clinker: raw material mining and conditioning, conventional energy production, distribution and consumption, transportation of raw materials to the plant and clinker manufacturing including rotary kiln and pre-processes, and the emissions associated. Related to the sewage sludge two main aspects are considered. First, the combustion process in the cement plant, excluding the environmental impacts associated with the sludge production since sludge is a waste material (Strazza et al., 2011). However, the research includes the environmental impacts avoided in case of the sludge were disposed in a landfilling as non-desirable end of life stage instead of not recovered.

2.3 Selected case studies

Consistent with the goal of the assessment, this study focuses mainly on the use of sewage sludge as secondary fuel in the cement production and the influence of its humidity in the kiln process. In this sense, four different case studies were analysed:

(i) Set 1: Combustion without sludge
(ii) Set 2: Dry sludge with a replacement ratio of 5 % of the clinker production
(iii) Set 3: Wet sludge with a replacement ratio of 5 % (dry basis) and a moisture content of 10 %
(iv) Set 4: Wet sludge with a replacement ratio of 5 % (dry basis) and a moisture content of 40 %

These scenarios have been chosen taking into account the clinker production necessities. According to several authors (Werther and Ogada, 1999; Zabaniotou and Theofilou, 2008) a maximum sludge feed rate of 5 % of the clinker production capacity is permissible to maintain the clinker quality.

Additionally, considering that the use of sludge in cement kilns is an alternative option to recover the energy and materials, these scenarios include the avoided environmental impacts associated with landfill sludge as a disposal method.

2.4 Life cycle inventory

Life cycle inventory (LCI) contains the energy and material quantities involved in the analysed scenarios. These data have been obtained by the combination of different sources and considering the functional unit previously established. Mainly, Spanish data has been used, in other cases, European data supported by Ecoinvent database have been chosen. In particular, this study is based on the clinker process production data of a Spanish cement plant where pet coke is fed as primary fuel (Valderrama et al., 2012).

Additionally, environmental pollutant emissions factors for CO_2, CO, NMVOC, NOx, SO_2, CH_4 associated with the pet coke and sludge combustion have been obtained from the EMEP/CORINAIR Air pollutant emission inventory guidebook (EEA, 2007). These emission factors are provided as a function of the fuels energy content fuels and different technology approaches.

Table 1: Energy content and heavy metal composition of the fuels considered and their transfer-coefficients between the air and the clinker retention for co-incineration in cement manufacturing

Dry basis	Pet coke (Dako Coal GmbH, 2011)	Sewage sludge (ECN laboratories, 2009)	Air transfer coefficient (%)
LHV (MJ/kg)	34.850	15.282	N/A
As (ppm)	0.1	6.8	0.020
Cd (ppm)	0.1	1.0	0.050
Cr (ppm)	1.0	39.0	0.012
Cu (ppm)	4.0	345.0	0.0093
Hg (ppm)	0.1	---	50.000
Ni (ppm)	120.0	22.0	0.030
Pb (ppm)	2.0	---	0.050
Zn (ppm)	11.0	830.0	0.027

On the other hand, the air emissions of heavy metals have been calculated as a function of the chemical composition of both fuels considering the substance transfer-coefficients between the air and the clinker retention for co-incineration in cement manufacturing (Lederer and Rechberger, 2010). These data and the main fuels composition considered in this study can be seen in Table 1.

Finally, Simapro v7.3.2 libraries, especially Ecoinvent v2.2 database, have been used to estimate the rest of the environmental pollutant emission and other inventory data related to the provision and conditioning of raw materials, fossil fuels, transport and electricity consumption.

Table 2 illustrates a summary of selected parameters of the LCI data for 1 kg of clinker production.

Table 2: LCI selected data for 1kg of clinker

Inputs/emissions	Units	Set 1	Set 2	Set 3	Set 4
Pet coke	kg	$1.06\cdot10^{-1}$	$8.41\cdot10^{-2}$	$8.44\cdot10^{-2}$	$8.62\cdot10^{-2}$
Sewage sludge	kg	0.00	$5.00\cdot10^{-2}$	$5.56\cdot10^{-2}$	$8.33\cdot10^{-2}$
Electricity	kg	$7.57\cdot10^{-2}$	$7.57\cdot10^{-2}$	$7.57\cdot10^{-2}$	$7.57\cdot10^{-2}$
Hard coal	kg	$5.61\cdot10^{-9}$	$5.61\cdot10^{-9}$	$5.61\cdot10^{-9}$	$5.61\cdot10^{-9}$
Heavy fuel oil	kg	$1.61\cdot10^{-9}$	$1.61\cdot10^{-9}$	$1.61\cdot10^{-9}$	$1.61\cdot10^{-9}$
Limestone	kg	1.18	1.18	1.18	1.18
Clay	kg	0.35	0.35	0.35	0.35
Sand	kg	0.07	0.07	0.07	0.07
Iron ore	kg	0.01	0.01	0.01	0.01
Transport barge	t km	1.01	1.01	1.01	1.01
Transport truck	t km	$1.76\cdot10^{-2}$	$1.76\cdot10^{-2}$	$1.76\cdot10^{-2}$	$1.76\cdot10^{-2}$
SO_2	kg	$1.600\cdot10^{-3}$	$1.409\cdot10^{-3}$	$1.414\cdot10^{-3}$	$1.441\cdot10^{-3}$
NO_x	kg	$1.603\cdot10^{-3}$	$1.397\cdot10^{-3}$	$1.402\cdot10^{-3}$	$1.429\cdot10^{-3}$
NMVOC	kg	$5.541\cdot10^{-6}$	$1.051\cdot10^{-5}$	$1.053\cdot10^{-5}$	$1.062\cdot10^{-5}$
CH_4	kg	$5.541\cdot10^{-6}$	$2.390\cdot10^{-5}$	$2.391\cdot10^{-5}$	$2.401\cdot10^{-5}$
CO	kg	$1.478\cdot10^{-4}$	$3.464\cdot10^{-4}$	$3.469\cdot10^{-4}$	$3.494\cdot10^{-4}$
CO_2	kg	$3.713\cdot10^{-1}$	$9.210\cdot10^{-1}$	$9.223\cdot10^{-1}$	$9.286\cdot10^{-1}$
As	kg	$5.172\cdot10^{-5}$	$8.687\cdot10^{-5}$	$8.704\cdot10^{-5}$	$8.792\cdot10^{-5}$
Cd	kg	$2.247\cdot10^{-13}$	$6.818\cdot10^{-11}$	$6.818\cdot10^{-11}$	$6.818\cdot10^{-11}$
Cr	kg	$5.618\cdot10^{-13}$	$2.545\cdot10^{-11}$	$2.545\cdot10^{-11}$	$2.546\cdot10^{-11}$
Cu	kg	$1.348\cdot10^{-12}$	$2.351\cdot10^{-10}$	$2.351\cdot10^{-10}$	$2.351\cdot10^{-10}$
Hg	kg	$4.180\cdot10^{-12}$	$1.608\cdot10^{-9}$	$1.608\cdot10^{-9}$	$1.608\cdot10^{-9}$
Ni	kg	$5.618\cdot10^{-10}$	$4.456\cdot10^{-10}$	$4.475\cdot10^{-10}$	$4.570\cdot10^{-10}$
Pb	kg	---	$1.505\cdot10^{-5}$	$1.505\cdot10^{-5}$	$1.505\cdot10^{-5}$
Zn	kg	$1.124\cdot10^{-11}$	$3.009\cdot10^{-9}$	$3.009\cdot10^{-9}$	$3.009\cdot10^{-9}$

3. Results and discussion

3.1 Midpoint approach

Table 3 and Figure 1 compare the midpoint approach in the four different scenarios considered. The results demonstrate that exit two different behaviours depending on the impact category considered. Mainly, all categories excluding human toxicity, terrestrial ecotoxicity and marine ecotoxicity, have a similar behaviour where the major impacts are observed on the base line scenario (without sludge), decreasing significantly when the fossil fuel is substitute partially by the dry sludge. This can be explained by the fact that sludge is considered a biogenic source in combustion. On the other hand, a special mention is required in human toxicity, terrestrial ecotoxicity and marine ecotoxicity. In this case the introduction of sludge in the clinker production process provokes an important increment in the impacts. The main reason for this situation is found when the metal composition in the sludge and pet coke are compared. As can be seen in Table 1, sludge accounts a higher quantity of metals. Although the basic environment in the kiln contributes to condense the heavy metals on dust molecules and return back to the clinker, there is a partial transference to the air emission. In this case the high level of metals in the sludge causes a greater effect on the emissions than the heavy metal sequestration during the clinker production process.

However, the moisture in the biogenic fuel provokes a similar effect over the most of the impact categories. The moisture content has a negative effect on the combustion process associated with the heat loss due to water evaporation (2,257 kJ/kg_{water}), which reduces the net amount of energy released during sludge combustion. This negative impact contributes to an inefficient auto-thermal combustion, and supplementary fuel must be supplied to overcome the heat losses and maintain the required combustion conditions. In fact, lower moisture values than 20 % are desirable (Madlool et al., 2011). This situation is supported with the results obtained in this study as can be seen in Table 3. Unlike the set 4 (sludge with a moisture content of 40 %), the results of set 3 (moisture content of 10 %) are very similar to those of set 2 (dry sludge) in all impact categories.

Table 3: Results obtained in the midpoint analysis

Impact category	Units	Set 1	Set 2	Set 3	Set 4
Climate change	kg CO_2 eq	1.243	1.123	1.125	1.132
Ozone depletion	kg CFC-11eq	$6.531\cdot10^{-8}$	$5.371\cdot10^{-8}$	$5.389\cdot10^{-8}$	$5.483\cdot10^{-8}$
Human toxicity	kg 1.4-DB eq	$3.314\cdot10^{-2}$	$3.139\cdot10^{-1}$	$3.140\cdot10^{-1}$	$3.141\cdot10^{-1}$
Photochemical oxidant formation	kg NMVOC	$3.808\cdot10^{-3}$	$3.490\cdot10^{-3}$	$3.497\cdot10^{-3}$	$3.534\cdot10^{-3}$
Particulate matter formation	kg PM10 eq	$1.343\cdot10^{-3}$	$1.223\cdot10^{-3}$	$1.226\cdot10^{-3}$	$1.240\cdot10^{-3}$
Ionising radiation	kg U235 eq	$2.873\cdot10^{-2}$	$2.807\cdot10^{-2}$	$2.807\cdot10^{-2}$	$2.812\cdot10^{-2}$
Terrestrial acidification	kg SO_2 eq	$4.159\cdot10^{-3}$	$3.722\cdot10^{-3}$	$3.733\cdot10^{-3}$	$3.785\cdot10^{-3}$
Freshwater eutrophication	kg P eq	$3.889\cdot10^{-6}$	$3.292\cdot10^{-6}$	$3.297\cdot10^{-6}$	$3.321\cdot10^{-6}$
Marine eutrophication	kg N eq	$1.294\cdot10^{-3}$	$1.156\cdot10^{-3}$	$1.158\cdot10^{-3}$	$1.170\cdot10^{-3}$
Terrestrial ecotoxicity	kg 1.4-DB eq	$4.783\cdot10^{-5}$	$8.432\cdot10^{-5}$	$8.443\cdot10^{-5}$	$8.499\cdot10^{-5}$
Freshwater ecotoxicity	kg 1.4-DB eq	$2.281\cdot10^{-4}$	$1.672\cdot10^{-4}$	$1.678\cdot10^{-4}$	$1.711\cdot10^{-4}$
Marine ecotoxicity	kg 1.4-DB eq	$3.607\cdot10^{-4}$	$4.406\cdot10^{-4}$	$4.414\cdot10^{-4}$	$4.456\cdot10^{-4}$
Agricultural land occupation	m^2a	$8.116\cdot10^{-4}$	$7.574\cdot10^{-4}$	$7.580\cdot10^{-4}$	$7.611\cdot10^{-4}$
Urban land occupation	m^2a	$3.466\cdot10^{-3}$	$3.160\cdot10^{-3}$	$3.162\cdot10^{-3}$	$3.172\cdot10^{-3}$
Natural land transformation	m^2	$2.741\cdot10^{-4}$	$2.308\cdot10^{-4}$	$2.316\cdot10^{-4}$	$2.353\cdot10^{-4}$
Water depletion	m^3	$2.245\cdot10^{-3}$	$2.123\cdot10^{-3}$	$2.125\cdot10^{-3}$	$2.135\cdot10^{-3}$
Metal depletion	kg Fe eq	$6.734\cdot10^{-3}$	$6.404\cdot10^{-3}$	$6.409\cdot10^{-3}$	$6.432\cdot10^{-3}$
Fossil depletion	kg oil eq	$1.795\cdot10^{-1}$	$1.475\cdot10^{-1}$	$1.481\cdot10^{-1}$	$1.507\cdot10^{-1}$

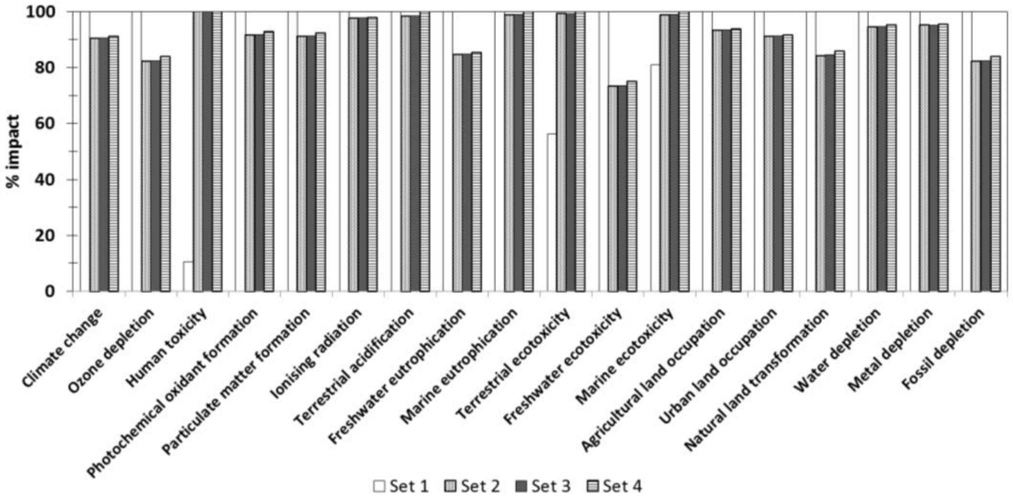

Figure 2: Graphic representation of the midpoint analysis results

3.2 Endpoint approach

An extended analysis was carried out to determine the elements of an environmental mechanism that are in themselves of value to society. In this sense, Table 4 shows the damage endpoint categories for each scenario. The results demonstrate that in all endpoint categories a descent in the level of the damage is observed when the fossil fuel is substituted by sludge as alternative fuel.

Considering the moisture content, an increment in the environmental damage is observed when additional water is confined in the sludge in case of human health and resources. As it was explained previously, this fact is related to additional fuel supplied necessary to evaporate the water and maintain the kiln conditions. However, the effect is opposite to the ecosystem category.

Table 4: Results obtained in the endpoint analysis

Impact category	Units	Set 1	Set 2	Set 3	Set 4
Human Health	DALY	$2.114 \cdot 10^{-6}$	$2.110 \cdot 10^{-6}$	$2.113 \cdot 10^{-6}$	$2.127 \cdot 10^{-6}$
Ecosystems	species.yr	$1.036 \cdot 10^{-8}$	$9.345 \cdot 10^{-9}$	$9.358 \cdot 10^{-9}$	$9.421 \cdot 10^{-9}$
Resources	$	2.884	2.370	2.378	2.420

4. Conclusions

The results show significant environmental improvements in cement manufacturing when pet coke fuel is replaced by sewage sludge in almost all impact categories. Only three midpoint categories indicate an increment in the impacts with the addition of the sludge. The main reason for this fact can be found in the high content of heavy metals of the studied sewage sludge. On the other hand, results asses the extended theory that the lower moisture values of 20 % in the sludge are more desirable to avoid an increment in the fossil fuel use and consequently in the environment impacts. Thus, the LCA analysis, which has been developed using RECIPE method and Spanish data, reveal a significant reduction of the environmental impacts for cement manufacturing for both approach, namely midpoint and endpoint, when sewage sludge is considered as an alternative fuel for pet coke fossil fuel.

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