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A multilevel sustainability analysis of zinc recovery from wastes

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ABSTRACT

As waste generation increases with increasing population, regulations become stricter to control and mitigate environmental emissions of substances, e.g. heavy metals such as zinc and copper. Recovering these resources from wastes is the key interest of industries. The objective of this paper is the sustainability and feasibility evaluations of zinc recovery from waste streams. Sustainability and feasibility of a resource recovery strategy from wastes in a circular economy are governed by avoided environmental impacts and cost-effective transformation of an environmental contaminant into a valuable resource, e.g. as a coproduct by making use of an existing infrastructure as much as possible. This study, for the first time, gives a comprehensive overview of secondary sources and processes of recovering zinc, its stock analysis by country, regional and global divisions by a Sankey diagram, policies to regulate zinc emissions and avoided environmental impacts by zinc recovery. Two representative cases are further investigated for economic feasibility analysis of zinc recovery from (1) steelmaking dust and (2) municipal solid waste (MSW). The amount and value of zinc that can be generated from dust emitted from various steelmaking technologies are estimated. Additional revenues for the steelmaking industrial sector (with electric arc furnace), at the plant, national (UK), regional (EU) and global levels are 11, 12, 169 and 1670 million tonne/y, or 19–143, 20–157, 287–2203 and 2834–21740 million €/y, respectively. The second case study entails an integrated mechanical biological treatment (MBT) system of MSW consisting of metal recovery technologies, anaerobic digestion, refuse derived fuel (RDF) incineration and combined heat and power (CHP) generation. An effective economic value analysis methodology has been adopted to analyse the techno-economic feasibility of the integrated MBT system. The value analysis shows that an additional economic margin of 500 € can be generated from the recovery of 1 t of zinc in the integrated MBT system enhancing its overall economic margin by 9%.

1. Introduction

Demand for zinc and its production are increasing at the rates of 4.7% and 2.7% per year, respectively, since 2012. At the current rate of usage, its demand will reach 2.7 times of today's demand by 2050. Zinc production has been predominantly relying on primary mining, which is resource intensive. 1 kg of zinc production by primary mining from copper-lead-zinc-silver-gold ore containing 62% zinc uses 23 MJ of fossil resources and causes global warming potential (100 years) by 0.8 kg CO_2 equivalent. This is equivalent to 10.64 million tonne CO_2 emissions per year or 0.03% of global CO_2 emissions. To cut down CO_2 emissions by 80% by 2050 from its current level (i.e. to lower the emission below 2.13 million tonne CO_2 equivalent), a maximum of only 7% contribution may be allowed from primary mining to fulfil its increased demand by 2050 and the balance of the demand must be met by secondary recovery of zinc from wastes – a challenging prospect.

Recovery of zinc from secondary sources – waste is important in the present context of circular economy. The production and consumption of zinc at global level have been increasing and primary resources of zinc from ore is depleting rapidly. Hence, effective extraction of zinc from secondary sources can bring several advantages such as saving in virgin resources and in fossil resources used to supply energy in primary mining processes, increased resource

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efficiency, reduced landfilling and loss of zinc or any metal recovered to the landfill, waste remediation, mitigation of environmental and health effects and enhancement of economic performance of an existing infrastructure. Zinc is considered as a base metal, similar to copper, iron, nickel and lead. Zinc is malleable at the temperatures of 100–150 °C (World Health Organization (WHO), 2001). This is an important property of zinc that makes its easy transformation into different shapes. Zinc is originated from natural resources primarily from sphalerite (ZnS), which also contains traces of cadmium, iron, indium, gallium and germanium. The copper-lead-zinc-silver-gold ore upon smelting gives 36.8, 1.4, 61.7, 0.095 and 0.002 percentages, respectively (GaBi, 2016). Other primary sources of zinc include zinc oxide, zinc carbonate and zinc sulphate (Minerals, 2004). Zinc is also present in various geological sources: lithosphere (52 mg/kg); soil (60 mg/kg); stream water (20 μg/L); sea water (1–4.9 μg/L) and biota (46 mg/kg) (United Nations Environment Programme (UNEP), 2013).

Zinc is an essential element needed in human body, particularly in building cells and enzymes and helping in wound healing. Deficiency of zinc in human body leads to several adverse effects, including anorexia nervosa (loss of appetite and eating disorder), taste abnormality (losing sense of taste), growth retardation, lethargy (tiredness and lack of energy), delayed healing of wounds and so on (Prasad, 2013). Other symptoms such as diarrhoea, night blindness and delayed sexual maturation may occur in the case of severe zinc deficiency. It has been estimated that there are approximately 17.3% of the world population suffering from zinc deficiency (Wessells and Brown, 2012). Therefore, adequate consumption of zinc in daily diet is fairly important to prevent diseases and illnesses, typically 5.5–9.5 mg/day of zinc intake is recommended for men and 4.0-7.0 mg/day is recommended for women (National Health Service (NHS), 2016). Zinc can be found in major food sources such as meat (4.65–64.9 mg/kg) and fish (3.12–19.5 mg/kg) (Bilandžić et al., 2014). Although zinc is important to human health, it should not be neglected that zinc is a carcinogen and excess zinc consumption (100–500 mg/day) can lead to toxicity in human body (Senthilkumar et al., 2006). The advisable limit of zinc intake from drinking water is less than 0.2 mg/day (World Health Organization (WHO), 2001).

Zinc is an important nutrient to plants. The typical concentration of zinc in agricultural soil is 10–300 mg/kg (Broadley et al., 2007). Deficiency of zinc in plant can cause chlorosis (discolouration of leaf) and root apex necrosis (dieback) and further lead to reduction in crop yield (Broadley et al., 2007). Toxicity of zinc in soil can occur as a consequence of using contaminated water by mining and smelting industries. The symptom is obvious when the concentration of zinc is more than 300 mg/kg in leaf, which can result in significant reduction in crop yield (Broadley et al., 2007).

Zinc has prominent corrosion resistant properties, thus making it an important element in steel coating (galvanising) to prevent rusting. It can also combine with other metals to form alloy. Zinc, with combination of aluminium can be used to produce alloy which is used in die casting. Die casting is the process of forcing molten metal into the mold cavity by applying a high pressure. Brass (copper and zinc) and bronze (copper, zinc and tin) have a wide range of applications including coin-making, decoration such as sculptures, musical instruments, machinery parts, plumbing and electrical applications. Zinc has the main usages in galvanisation, alloys, brass and bronze, semi-manufactures, chemicals and miscellaneous totalling to 13.5 million tonne in year 2014 (International Lead and Zinc Study Group (ILZSG), 2015). Significant amount of zinc is used in galvanising, contributes to 50% towards the total usage. 17% of zinc is used for alloying such as die casting and a similar proportion is used to produce brass and bronze. Other applications of zinc include roofing, gutters and downpipes for housing and construction purposes (6%), chemicals such as zinc oxide and zinc sulphate (6%) and miscellaneous (4%).

The world consumption of zinc has increased by 7% over the last five years (2010–2014), despite a fall in 2012 (International Lead and Zinc Study Group (ILZSG) and null, 2015). The production of zinc has also increased and followed the trend of consumption. It can be seen that when primary mining of zinc falls short of its total production and the balance needs to be supplied by secondary recovery from wastes, its market price increases. This can be observed in years 2010–2011 and 2012–2014 (The World Bank, 2015). An increase by 4% in zinc production from mine between 2011 and 2012 has resulted in 11% drop in the price of zinc from 2193.9 US$/tonne in 2011–1950.4 US$/tonne in 2012.

It has been estimated that, globally, 13.9 million tonnes of zinc has been extracted from mine in 2014 (World Bureau of Metal Statistics, 2015). China (39%), Australia (11%) and Peru (10%) are the top three largest producers of zinc, predominantly by primary mining. Europe has produced approximately 1 million tonne of zinc in 2014, which is 8% of the total output of zinc worldwide. The Republic of Ireland (27%), Sweden (21%) and Turkey (20%) are the largest producers of zinc within the Europe (World Bureau of Metal Statistics, 2015). An input-output model consisting of production, consumption, import and export of zinc of major regions is illustrated in Fig. 1 in the form of a Sankey diagram. The data can be obtained from (World Bureau of Metal Statistics, 2015). The width of the arrows represents the mass flowrate of zinc in thousand tonnes (kt). This diagram pinpoints three major countries/regions involving the zinc business: China (largest producer and consumer of zinc with low degree of international trading of zinc, i.e. high level of local satisfaction of resources with low dependence on import and export); Europe (equal reliance on local zinc production as well as import and export); and Australia (second largest mine producer of zinc, no zinc is imported to the country and the country exports majority of the zinc slab produced due to low consumption within the country itself). The recycle flowrates have been estimated from imbalance between production + import and consumption + export. Although the data does not directly indicate whether zinc slabs are produced from primary or secondary sources, there is sufficient evidence showing that the global consumption of zinc is heavily relying on primary sources of zinc, i.e. mining. The first piece of evidence is the close proximity between the total global mine production of zinc and global zinc slab production, i.e. 13.9 and 13.5 million tonnes, respectively. Higher mine production compared to zinc slab production shows extraneous primary extraction of resources. This occurs in year 2012–2014. The second piece of evidence is the low recycle of zinc (Fig. 1). This shows that zinc consumption primarily relying on its production is still prominent in most countries in the world, in particular, Australia and China. As a consequence of these activities, excessive amount of zinc is produced each year and if the resource management is not properly controlled (i.e. supply > demand), it can induce a drop in the market price of zinc as has been the case in year 2012. The environmental impact due to zinc is significant and discussed in Section 4.1. The utilisation of secondary sources of zinc should be considered as this will lessen the impact on the environment in spite of increases in energy requirement in recycling due to dilution effect due to mixing with scrap (example in the case of aluminium (Cullen and Allwood, 2013)).

Zinc has been identified as one of the fifty-four materials that is important to the EU's economy (European Commission, 2014). Huge demand of zinc has given rise to rapid depletion of primary sources. Therefore, the recovery of zinc from secondary sources such as wastes is of paramount importance to sustain the activities related to zinc. There are many literatures that have provided comprehensive reviews on recovery of heavy metals, including zinc. However, no study brings together various aspects of sus-