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# Review of lead flows in the anthropogenic environment

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MFA (material flow analysis) is a common approach for assessing stocks and fluxes of material and substances in the environment. MFA has demonstrated over the last many years that it improves understanding of the sources and sinks of the metal-containing goods. This article shows the in-depth analysis of the literature related to flow of lead in the environment. The review describes the significant inflows, outflows, and stocks of lead, based upon eighteen MFA studies done at various geographical levels throughout the world. The information compiled on major fluxes and stocks at various geographical scales may be used to improve future studies aimed at quantifying flows of lead. The insights presented in here may also guide the policy and management choices for lead for a city or region. [copyright information to be updated in production process].

**Keywords:** Material flow analysis; lead; flow; stock

## INTRODUCTION

Lead is a naturally occurring substance and the world's lead deposits have been estimated to be 90 million tons by lead content [1]. Australia controls 40% of the world's reserves, followed by China (20%), Russia and Peru (7% each), Mexico and the United States (6% each), and so on [2]. According to [1], worldwide production of lead in terms of metal composition was around 4.8 million tons in 2018, which is roughly identical to the amount produced in 2017. The country with the greatest production capacity is China, having an estimated yearly production of 2.28 million tons (48 % of world production). They are followed by Australia (9%), Peru (6%), the United States and Mexico (5% each), Russia and India (4% each) [1].

India is home to large lead reservoirs with its annual production of 265,651 tons of lead concentrates in the year 2019. Rajasthan is the only state responsible for whole lead production in India (IBM, 2020). Till 2018, India was the net importer of lead [1]. In 2019, India has started exporting lead because of the increase in mining activities in the country [3]. Lead is totally recyclable and retains its qualities after recycling. Lead recycling is a growing sector in the country. However, because informal lead recycling poses a health concern, the lead recyclers are required to obtain permit from Central Pollution Control Board to assure compliance with environmental standards.

Lead is a heavy metal that has been linked to cancer in humans. Anemia, weakness, renal and brain damage are just a few of the adverse consequences that occur in individuals exposed to extremely high levels of lead. Lead exposure at exceptionally higher levels can be lethal. As lead may cross the placental barrier, pregnant women exposed to it risk harming their unborn child as well. Lead is hazardous to an infant's developing nervous system [4, 5].

So, lead is widely used in a number of products and has the potential of affecting the human health and the environment. As a result, it becomes important to understand the flow of Pb. However, there has not been any systematic review elaborating on lead flows in the anthropogenic environment. This study attempts to fill this gap in literature.

The objective of the study is to critically review the flows of lead in the environment. The study aims to identify the key sectors, key inflows and outflows and key stocks important for the studies of Pb flow.

### *Materials and methods*

This study is based on the review of the literature published till May 2021. For the literature, the search was made on the websites of the following publishers: Elsevier, Wiley, and SAGE Publications. The searches were also made on Google Scholar platform. Eighteen studies related to Pb flow were finally chosen for this assessment based on the following criteria: (i) studies using MFA as a method; (ii) studies being conducted at any spatial scale; (iii) studies estimating lead flows over one or more than one year of time-period. There were mainly three geographical scales found among these studies: (i) smaller system (e.g. a waste treatment plant), (ii) city level and, (iii) region level.

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## RESULTS AND DISCUSSION

### *Critical sectors of Pb flow*

Any Pb flow analysis will produce a result based on how the system is described in terms of the spatial scale and the main sectors responsible for Pb flow. The critical sectors for Pb flow vary at different geographical scales (Table 1). The different geographical levels may be smaller system, city level, region level.

Based on the assessment of the literature, a smaller system may consist of a university campus, treatment units (e.g., wastewater treatment plants and solid waste treatment facilities), and waste utilization units (composting units, smelting plants). In smaller systems, primary sectors may vary depending upon type of the treatment facilities. At the city scale, the primary sectors of Pb flow are private residences, waste treatment units (wastewater treatment plants or solid waste treatment facilities), landfills, and various categories of soil (e.g. agriculture soil, urban soil).

The region scale is much larger than the city level and often encompasses Pb mining and import sectors. At regional level, the key sectors include housing, agriculture, and industry along with Pb mining and import sectors. On a region level, the production of Pb *via* mining ores is a critical sector, and the primary distinction between city and region scales is the presence of this field. However, sometimes production sector is included at the city-level as the production units are in the city.

**Table 1.** Multiple diverse sectors across various geographical scales

| Geographical Scale (Ref.) | Location, Country | Type of system | Year of flow | Key Sectors |
|---|---|---|---|---|
| Smaller System [4] | MNIT Jaipur, India | Anthropogenic System | 2019 | Public Household, WWTP |
| Smaller System [6] | Smelting Plant, China | Anthropogenic System | 2013 | Palletisation, Blast furnace, Primary Smelting |
| Smaller System [7] | Avedore WWTP, Denmark | Wastewater system | 2011 | Pre-treatment, Primary treatment, anaerobic digester |
| City [9] | Hitachi, Japan | WEEE management | 2010 | Agriculture soil, Forest soil, Urban soil, Households, Landfill, Industry |
| City [10] | Norrkoping, Sweden | Recovered Waste wood Management | 2002 | Biofuel boiler, Waste Incinerators |
| Region [8] | Swiss region, Switzerland | Anthropogenic System | 1987 | Household, Industry, Agriculture soil |
| Region [11] | Malaysia | Wastewater system | 2019 | Klang River, Treatment Plant |
| Region [12] | China | Lead Acid Batteries | 2018 | Lead Rod/Mixer factory, Battery factory, Customer, All collection |
| Region [13] | China | Anthropogenic System | 2015 | Primary lead, Batteries, Old scrap |
| Region [14] | China | Anthropogenic System | 2014 | Lead Acid Batteries (LAB) production, LAB use, recycling |
| Region [2] | Korea | Anthropogenic System | 2014 | Lead ore |
| Region [15] | China | Anthropogenic System | 2010 | Production, Use |
| Region [16] | China | Anthropogenic System | 2010 | Production, Use |
| Region [17] | Japan | Anthropogenic System | 2007 | Raw material, Material production, recycling |
| Region [18] | Austria | Anthropogenic System | 2005 | Industry business service, PHH, Waste management |
| Region [19] | China | Anthropogenic System | 1999 | Lead concentration, Refined lead, Manufacturing of LAB |
| Region [20] | Denmark | Anthropogenic System | 1994 | Batteries, building materials, cable sheets |
| Region [21] | Switzerland | Waste Management System | 1988 | Agriculture soil, Forest soil, Urban soil, Households, Landfill, Industry |

### *Key inflows*

It is crucial to know the major inflows at various geographical scales to establish the priorities for control of Pb. Table 2 summarizes this information in terms of geographical and temporal dimensions, system type, total inflow, important inflows, and sectors receiving the inflows.

The largest Pb influx to the city scale happens because of imported commodities. In a city-scale study that examined the Pb flow through the WEEE system in Hitachi (Japan) for 2010 [9], it was found that nearly 90% of the total Pb inflow is from used cars and scrap metals. For Pb contaminant fluxes in cities, the private residences and industries are the two important contributors to the influx of Pb. This highlights the importance of understanding all the Pb consumption scenarios, including any household-level emissions. At the household level, the input flow is generally computed from the mass balance using the emissions through wastewater and solid waste. In this approach, the stocks of Pb in the public household are neglected in almost all the studies.

While global trade for consumer products and used automobiles is a significant contributor to the Pb inputs to the environment, other key Pb input pathways occur at a regional scale. As an example, in a research conducted on Swiss area (Switzerland) which focused on the industrial sector, as well as the products consumption sector, over 97% of the total inflow was found to occur through used automobiles [8]. According to the results of [2], about 67% of the overall intake in the Pb flow occur through the anthropogenic system originating from mineral ore in the territory of Korea. In China, a countrywide scale study on the lead acid batteries management system [12], lead rod has been found as the primary input, where it accounts for almost 100% of the overall input in 2018. This study did not consider other important sectors, e.g. public household. It can be inferred that in the absence of availability of mineral ore for Pb production, the predominant Pb inflow to the country is either lead rods or used automobiles, whereas the presence of mineral ore in a country makes it the predominant Pb inflow.

### *Key outflows*

Table 3 depicts an analysis of the major outflows of lead at various geographical scales. Industry-related products accounted for about 82 percent of output in Hitachi (Japan) in 2010 [9]. Outflow of lead emissions to air, water and soil from industrial production is unproductive and may be posing a serious public health concern for the people in the surrounding environment.

**Table 2**. Key inflows across various geographical scales

| Geographical Scale (Ref.) | Measuring units | Total inflow quantity | Key inflows | % of total inflow |
|---|---|---|---|---|
| Smaller System [4] | Kg/year | 53 | Import of Private households and Inflow to sewer system | 100% |
| Smaller System [6] | Tons/ton of product | 1.2472 | Palletization | 87% |
| Smaller System [7] | Ton/day | 0.000926 | Influent to Pre-treatment | 100% |
| City [9] | Tons | 338 | Used cars and scrap metals | 88% |
| City [10] | Kg | 24000 | RWW | 55% |
| Region [8] | Tons/year | 340 | Consumer goods, used cars | 100% |
| Region [11] | Kg/year | 3817547 | Penchala River | 62% |
| Region [12] | Tons/year | 161050 | Lead Rod/Mixer Factory | 100% |
| Region [13] | Kt | 4073 | Ore to concentrate, Import to concentrate | 90% |
| Region [14] | Tons | 308.86 | Lithosphere to mining, import to smelting | 100% |
| Region [2] | Tons | 96845 | Import of lead ore, metal products | 65% |
| Region [15] | Kt | 3880.8 | Lithosphere to production | 100% |
| Region [16] | Kt | 3137 | Lithosphere to production | 59% |
| Region [17] | Kt | 242.4 | Import to Raw Material and Interim product production | 77% |
| Region [18] | Kt/year | 49 | Industry business service | 100% |
| Region [19] | Kt | 553.54 | Lead ore | 100% |
| Region [20] | Tons/year | 15500 | Raw material | 60% |
| Region [21] | Tons/year | 338 | Used cars and scrap metals | 88% |

So, from these results, it can be concluded that the industrial sector is important in terms of Pb discharge at the city. In order to meet better Pb management goals, greater attention should be paid to the recovery and recycling of Pb from environmental emissions. It has been shown that the major outflow of Pb occurs as Pb from industrial production.

Accordingly, municipal solid waste (MSW) from private households has been recognized as the second-largest source of lead discharge in the Swiss area (Switzerland) [8]. At the region level, the type and amount of significant Pb outflows have been documented to differ significantly between countries. According to nine out of the thirteen region scale evaluations, industrial products has been identified as the most significant outflow. For example, emissions and outmoded cables account for around 34% and 46% of the total yearly outflow in China in 2014 [14] and 1999, respectively [19]. On the opposite side of the scale, 16% of the overall outflow is the export-oriented transport equipment and battery items in Korea [2]. The findings are from a region scale study [2], which examined domestic Pb flow for the year 2014 in South Korea. In 2011, ash from incinerators being disposed of in landfills constituted a major flow of Pb in Denmark[7]. Pb emissions to air, water and soil were found to be quite significant in Sweden in 2002 [10], and in China in 2014 [14]. A comparative assessment of main Pb outflows at different geographical scales demonstrated that large quantities of Pb leave the system as industrial products and other commodities.

### *Key stocks*

As can be seen from Table 4, the stock quantities of Pb in the system at all three levels (smaller system, city and region) account for a large percentage of the overall amount of P that entered the system. In all city-scale assessments, it was discovered that the system stores more than 50% of the entire influx of Pb. At this scale, landfills and soil have been recognized as the primary processes for Pb stocks. About 65% of the total intake of Pb has been shown to be retained within the system in six of the thirteen region scale investigations. As discussed before, it demonstrates that the end-user consumption is the primary driver of Pb stocks at the region scale.

**Table 3.** Key outflows across various geographical scales

| Geographical Scale (Ref.) | Measuring units | Total Outflow | Key Outflows | % of total outflow |
|---|---|---|---|---|
| Smaller System [4] | Kg/year | 28 | MSW from households, outflow from storm water drain | 53% |
| Smaller System [6] | Tons/ton of product | 1 | Lead Ingot from casting | 81% |
| Smaler System [7] | Ton/day | 0.000034 | Ash from incinerator | 4% |
| City [9] | Tons | 277 | Products from industry | 82% |
| City [10] | Kg | 400 | Emission to air and water | 2% |
| Region [8] | Tons/year | 280 | Products from industry | 83% |
| Region [11] | Kg/year | 3817546 | Other purposes | 100% |
| Region [12] | Tons/year | 156645 | Lead acid battery and unknown products | 98% |
| Region [13] | Kt | 898 | Export, Products | 23% |
| Region [14] | Tons | 103.39 | Products and emissions | 34% |
| Region [2] | Tons | 15101 | Transportation equipment, battery and metal products | 16% |
| Region [15] | Kt | 3207.1 | Production to export, Fabrication and manufacturing to export | 83% |
| Region [16] | Kt | 2153 | Production to export, Fabrication and manufacturing to export | 69% |
| Region [17] | Kt | 152.8 | Export from final product production | 64% |
| Region [18] | Kt/year | 46 | Industry business service to PHH | 94% |
| Region [19] | Kt | 253 | Obsolete cable and construction materials | 46% |
| Region [20] | Tons/year | 2610 | Semi manufactures and manufactured products, scrap and other waste products | 17% |
| Region [21] | Tons/year | 280 | Steel and filter products | 83% |

**Table 4.** Key outflows across various geographical scales

| Geographical Scale (Ref.) | Measuring units | Total stocks | % of total inflow | Key stocks |
|---|---|---|---|---|
| Smaller System [4] | Kg/year | 25 | 47% | Soil |
| Smaller System [6] | Tons/ton of product | 0.1228 | 10% | N/A |
| Smaller System [7] | Ton/day | N/A | N/A | N/A |
| City [9] | Tons | N/A | N/A | Landfill and soil |
| City [10] | Kg | N/A | N/A | N/A |
| Region [8] | Ton/year | 60 | 18% | Agriculture soil, Forest soil, Landfill |
| Region [11] | Kg/year | N/A | N/A | N/A |
| Region [12] | Tons/year | N/A | N/A | N/A |
| Region [13] | Kt | N/A | N/A | N/A |
| Region [14] | Ton | 91.84 | 30% | Lead in use stock |
| Region [2] | Ton | N/A | N/A | N/A |
| Region [15] | Kt | 1758 | 45% | Production and In use |
| Region [16] | Kt | 1996 | 64% | Production and In use |
| Region [17] | Kt | N/A | N/A | N/A |
| Region [18] | Kt/year | 2.7 | 6% | PHH, Waste Management |
| Region [19] | Kt | 483.62 | 87% | Chemical products, LABs, Construction material and cables |
| Country [20] | NA | NA | NA | N/A |
| Region [21] | Tons/year | N/A | N/A | Landfill and soil |

In China, about 64% of the entire annual influx of Pb remained inside the industrial production sector, while the other 36% of the total annual inflow of Pb ended up being exported in China in 2010 [15, 16]. Large amounts of lead are buried in landfills and land soils in Switzerland [8]. In Austria, a mass bulk of the Pb was held in private households [18]. It is obvious that on a regional and city scale, landfill and soil make up a major percent of the overall stock every year. The buildup of Pb in this manner over the course of many years might result in the soil having an excessive amount of Pb. A further complication to this problem is that runoff water can leach Pb into groundwater. Thus, rather than allowing any lead to be deposited in soil or landfill, it is preferable to recycle the substance [22]. An additional benefit of using soil Pb stockpiles for production is that it will minimize the demand for mineral lead input, which eventually helps to alleviate the problem of mineral lead shortages. As a result, future choices on Pb management at the regional and region levels should place greater emphasis on determining the Pb stock in the soil.

## CONCLUSION

This study has effectively identified major Pb inflows, outflows and stocks. Our study shows that at city scale, the largest Pb influx happens as a result of imported commodities and at the region level, major inflow of lead occurs through the lead ore. At city scale as well as region scale, landfill and soil have been identified as the major stocks of Pb.

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