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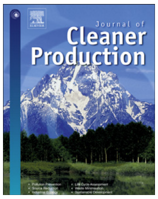

Life cycle environmental impact assessment of borax and boric acid production in China

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ABSTRACT

Borax and boric acid are important primary products in China's boron industry. Their characteristic production technology has been adapted to the low ore grade. To analyze the environmental impacts of different borax and boric acid production processes and to promote cleaner production of boron industry, the life cycle assessment method of cradle-to-gate was applied in this study. GaBi4.4 software was used in the assessment and the environmental impacts were classified according to the CML2001 method. To show the degree of consumption of mineral resources and energy respectively, the abiotic depletion potential was divided into the mineral resources depletion potential and fossil energy depletion potential. A comparison between the mineral processing and entire system studied shows that energy consumption is important in life cycle environmental impacts. Boron production industries should refrain from using coal as their main heat source and try to use clean energy. A comparison between the borax production processes shows that the boron-rich slag is the cleanest material and that blast furnace gas can be used to reduce environmental impacts further in slow cooling link. A comparison between the boric acid production processes shows that flotation (I) is the cleanest process with the material of szaibelyite. Ludwigite should be processed after dressing to reduce the environmental impacts. Boron concentrate can be used to produce borax or boric acid as an alternative to szaibelyite but feasible production processes are still the focus of future research.

1. Introduction

China is rich in boron resources with boron reserves ranking fourth next to Turkey, the USA, and Russia (Liu et al., 2006). Compared with that of the other three countries, the grade of China's boron ore is low and the ore is difficult to process. For example, the main boron-containing minerals in Turkey are colemanite, ulexite, and tincal, with a grade of at least 40% (Kuslu et al., 2010; Kunkul et al., 2012). In China, the main boron-containing minerals are szaibelyite, ludwigite, and brine. Szaibelyite in Liaoning Province is the traditional material used in the boron industry and has a grade of only 12%. The remaining reserves of szaibelyite are limited as it has been used as the major mineral source in China's boron industry for many years. Ludwigite reserves are relatively rich and account for 58.4% of the total Chinese boron reserves, but the content of B_2O_3 is in the range of only 6–9%. The mineral structure of ludwigite is complex because boron, iron, and magnesium are intergrown (Zheng, 2007). Therefore, there has been no large-scale exploitation of this mineral.

The boron industry was established in China in the 1950s. Over the past 60 years, China has developed a fairly sophisticated boron industrial system including mining, dressing, processing, refining, and other related businesses. Approximately 50 boron-containing products can be manufactured, but the output of most fine chemicals is still relatively small (Liu et al., 2006). Borax and boric acid are important primary products produced in large output and with high output value. Therefore, the production of borax and boric acid plays an important role in China's boron industry.

An environmental impact assessment was conducted because borax and boric acid are important primary products in the boron industry and their production processes contribute significantly to environmental impacts. Limited work has been conducted on the life cycle environment impact assessment of boron-containing

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products as researchers have been more concerned with the environmental risk of boron in boron-containing products and environmental media (Jensen, 2009; Graan et al., 1997; Batayneh, 2012; Edwards et al., 2012) and its toxicity to exposed workers (Basaran et al., 2012; Duydu et al., 2012). Our research group has evaluated the life cycle environment impacts of borax and boric acid using the AT&T matrix method (Qian et al., 2009; Xue et al., 2009). However, results from this work only show relative rather than absolute scores of the environmental impacts at different borax and boric acid production stages. The aim of this study is to analyze the environmental performance of different borax and boric acid production processes to provide a theoretical basis for improving the processes, and to promote cleaner production in China's boron industry.

2. Materials and methods

2.1. System definition

In China, borax is produced mainly by the CO_2-soda process where boron ore is decomposed by soda and CO_2 (from calcined limestone). Boric acid is produced by the one-step and two-step process. In the one-step process, the mineral is converted directly to boric acid. Boron ore is reacted with sulfuric acid at a certain temperature and the B_2O_3 in the ore is transferred to the liquid phase in the form of H_3BO_3. Flotation or salting-out is then used for the separation of boric acid and magnesium sulfate liquor. In the two-step process, the mineral is converted to borax by the CO_2-soda process and boric acid is then produced from borax and sulfuric acid. The above two steps can be completed in one or in two different plants. These production processes have been adapted to China's characteristic low-grade boron ore and China holds intellectual property rights to the CO_2-soda process.

Szaibelyite is the traditional raw material for producing borax and boric acid. Because of its continued exploitation over many years, the available reserves of szaibelyite have become limited. Some effort has been made to produce boron-containing products using ludwigite instead of szaibelyite. However, it is difficult to produce borax or boric acid directly from ludwigite because of its low grade and complex mineral structure. Based on the characteristics of ludwigite, the Northeastern University (Shenyang, China) has invented a separation technology by blast furnace. After dressing, the ludwigite ore is divided into boron concentrate and boron-containing iron concentrate. Then, boron-containing iron concentrate is smelted in the blast furnace to obtain boron-containing pig iron while the slag is enriched with boron (Zhang et al., 1995; Cui et al., 1994). The B_2O_3 content in the boron concentrate and boron-rich slag is over 12%. They can therefore satisfy present industrial use requirements and be the materials to produce borax or boric acid instead of szaibelyite (Liu et al., 1996; Chen et al., 1996).

The life cycle assessment (LCA) is an environmental impact assessment method from 'cradle' to 'grave' (Guinée et al., 1993a, b). Because of different evaluation scope and limitation of data, some life cycle stages can be omitted for evaluation purposes (Neupane et al., 2011; Memary et al., 2012). The complete life cycle for boron products include raw materials production, primary products production, refined chemicals production, terminal products production and application, and waste disposal and recycling. The goal of this study is to analyze the environmental impacts of borax and boric acid using different raw materials and different production processes. Results will provide references for improving processes and taking measures to relieve environmental pressure. The LCA cradle-to-gate method was applied and the corresponding evaluation scope (see Fig. 1) includes the production of mineral materials, the production of borax and boric acid, and the background production of coal and electricity consumed in the production process. 10,000 tons of borax and 10,000 tons of boric acid were considered to be the functional unit with the main flows referring to them.

2.2. Life cycle inventory

2.2.1. Material and energy consumption inventory

Sixty percent of China's boron reserves are distributed in Liaoning and szaibelyite from Liaoning is the major raw material of China's boron industry. Liaoning is also the largest production base for boron-containing products with borax and boric acid outputs of 85% and 40%, respectively. Data from Liaoning's boron industry therefore represent the general situation in China's boron industry. Most of the data on the material and energy consumption for producing borax and boric acid come from the Liaoning Boron Industry Association and data for the roasting of boron concentrate were obtained from Zhang et al. (2009). The consumption inventory for mining, dressing, borax production, and boric acid production is summarized in Table 1. During borax production, the raw ore should be roasted to enhance its activity and promote its rate of utilization. The mineral structure and chemical composition of boron concentrate and szaibelyite are different and so is their energy consumption during roasting. After smelting in the blast furnace, the boron-rich slag requires slow cooling rather than roasting to enhance its activity and this consumes limited energy. During boric acid production, the lower the ore grade and the more complex its structures, the more energy it consumes.

2.2.2. Pollutants discharge inventory for mining and dressing

At present, the szaibelyite grades can meet process requirements without dressing. Because of the low grade of ludwigite and the intergrown iron and boron, dressing is required to separate iron and boron. In this paper, dressing refers only to that of ludwigite. During mining and dressing, the output of waste rocks and tailings is 100 and 538 kg/t respectively. The output of chemical oxygen demand in wastewater is 28.6 g/t. Dust resulting from rock drilling, blasting, ore loading, and comminuting during mining and dressing is difficult to measure accurately and is disregarded.

2.2.3. Pollutants discharge inventory for borax and boric acid production

The mother liquor from borax and boric acid production can be recycled by returning it to the batch feeder. The cooling water can also be recycled. Low concentration wastewater was disregarded because its recycle rate is unavailable and could not be modeled.

During the actual borax and boric acid production, gaseous pollutants resulting from coal combustion and emissions are related to coal quantities consumed, coal characteristics, and combustion technology and equipment. The pollutants considered in this study include carbon dioxide, sulfur dioxide, nitrogen oxides, dust (combustion), carbon monoxide, methane, and non-methane volatile organic compounds (NMVOC). The amount of pollutants can be calculated using the quantity of coal consumed and the emission factors:

$$P_i = W_c \times d_i,\ i = 1, \cdots, n$$

where $P_1, \cdots, P_n$ are the CO_2, SO_2, NO_x, dust (combustion), CO, CH_4 and NMVOC emissions (kg); W_c is the quantity of coal consumed (t or TJ), and $d_1, \cdots d_n$ are the emission factors of CO_2, SO_2, NO_x, dust (combustion), CO, CH_4 and NMVOC (kg/t or kg/TJ).

$$d_{CO_2} = 3.67 \times C_C \times r$$