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Towards sustainable TiO_2 production: An investigation of environmental impacts of ilmenite and rutile processing routes in Australia

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ABSTRACT

This paper presents life-cycle environmental impacts and health hazards of the ilmenite and rutile processing routes which are very little explored despite a significant quantity of production worldwide. The study is carried out through a life-cycle environmental-impact assessment of the ilmenite and rutile mining production processes in Australia, using the International Reference Life Cycle Data System (ILCD) method under 14 significant impact categories and the Cumulative Energy Demand (CED) method for 10 significant impact categories. The dataset is collected from EcoInvent and the Australian Life cycle assessment database considering Australia as the geographic region. The major impact categories are climate change, human health (cancer), human health (non-cancer), ecotoxicity, and eutrophication. The analysis results show that the highest impact is caused in climate change, at 0.295 kg CO_2 eq, which is due to the large amount of electricity consumption in the ilmenite extraction process. Then, human toxicity-non cancer effects (4.42E-09 CTUh) and particulate matter (0.000155 kg PM 2.5 eq) are also noteworthy. Water resources depletion is affected due to the chemical emissions from ilmenite ore, which are found to be 0.00163 m^3 water eq. Rutile production impacts greatly on climate change at 1.535 kg CO_2 eq owing to large-scale electricity consumption. Electricity consumption for rutile also affects human toxicity-non cancer (2.3E-8 CTUh), particulate matter (0.00081 kg PM2.5 eq), and terrestrial eutrophication (0.024 molc N eq). Water-resources depletion from rutile is due to the ore, which are found to be 0.0085 m^3 water eq. The comparative assessment between ilmenite and rutile implies that rutile has more impact on the environment than ilmenite due to the electricity consumption and fossil fuel consumption. This result is validated through further analysis using the Cumulative Energy Demand method. A sensitivity analysis is also carried out to elucidate that the electricity grid mix from country-to-country contributes to sustainability by reducing the environmental impacts significantly.

1. Introduction

Ilmenite and rutile are the most commonly found and abundant form of titanium oxide. Ilmenite is weakly magnetic mineral sand, grey-black in color, solid in form, and exists in a triangle crystal structure. On the other hand, rutile is reddish-brown in color and exists in a tetragonal crystal structure. These heavy mineral sands are excavated and dredged, mostly to commercially produce ilmenite, rutile or other titanium-oxide ores. Originally, ilmenite and rutile are titanium oxides which may contain a variable amount of magnesium or manganese which is often dispersed from its original content (Abzalov, 2016). Ilmenite and rutile, being titanium-oxide minerals are used to produce high-performance metal parts such as artificial human-body parts, aircraft engine parts, sporting equipment, synthetic rutile, pigments etc. These pigments are used for whiten, in papers, paints, toothpaste, adhesive, plastic and foods and in nanotechnologies. From ilmenite ores, through the Becher process, synthetic rutile is produced, which is slightly yellowish and almost transparent in color (Pellegrino and Lodhia, 2012; Ranängen and Lindman, 2017; Raugei and Ulgiati, 2009).

Australia has one of the largest resources of ilmenite and rutile forms of titanium oxide and it is quite expected that Australia is facing the environmental impacts and health effects caused by the

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titanium-ore extraction process (Haque et al., 2014; Jones, 2009; Reichl et al., 2016). The effect of this processing route on human health and ecosystems needs to be identified and minimized to ensure a sustainable, environment-friendly extraction process in the long run.

The major environmental issues of concern from titanium oxide mining are pollution of ground-water resources, mineral transport with heavy vehicles, dredging operations in fragile coastal areas and deforestation. Many motives are associated with this question as to why the environmental impacts caused by mineral sand industries require urgent attention. The first issue is the proper rehabilitation of the abandoned mineral-sand deposits after the decommissioning or depletion of the mineral ore bodies because there is a possibility of leaching to ground-water resources from the abandoned mineral deposits. Moreover, elevated radiation hazards are associated with the mineral-sand loading and storage facilities which require advanced control systems. Secondly, there have been significant changes over the past 40 years in the mode of mining-industry operations, which further leads to the massive scale of the mining activities increasing the chance of abandoning the mineral sand deposits (Haque et al., 2014; Northey et al., 2016; Onn and Woodley, 2014). Thirdly, the reagents added during the secondary processing of mineral-sand deposits which may include chlorides for titanium-oxide processing and increases the radionuclide emission from the abandoned mineral sites to local ground-water systems, as mineral-sand extraction involves the extraction of soil up to 30 m depth or more, where the topsoil is removed prior to mining and then filled by the tailings from mining (Jones, 2009; Moran et al., 2014; Norgate and Haque, 2010; Sonter et al., 2014). As a result, mineral-sand mining leads to loss of trees and plants. All these issues had influenced some previous researchers to investigate the environmental impact assessment caused by the mineral industries with some suggestions for improvement (Durucan et al., 2006; Durucan and Korre, 2003, 1998; Farjana et al., 2018a, b; Frischknecht et al., 2000; Swensen, 1996).

Australia has a great resource for mineral-sand industry, the highest in the entire world, but as compared to the total deposit only a small fraction is currently being extracted. By ensuring an eco-friendly sustainable extraction process, Australia could potentially increase its current production of mineral sands like ilmenite and rutile. To facilitate that process, effective measures should be taken to make the mining extraction processes sustainable (Awuah-Offei and Adekpedjou, 2011; Law and Lane, 1991; Mudd, 2009; Navarro and Zhao, 2014; Norgate et al., 2007). Although the mining processes are impactful to the environment in different categories of global warming, greenhouse-gas-emissions, human health and ecotoxicity, such a critical issue has not been reported anywhere in the open literature that provides a comprehensive analysis of the environmental impacts caused by ilmenite and rutile mining technologies in Australia. This paper provides the knowledge gap with an effort to promote a sustainable extraction process of ilmenite and rutile in Australia. The paper starts with a brief introduction followed by a detailed overview of the ilmenite and rutile extraction processes and their mining technologies in Section 2. Section 3 introduces the global producers of the ilmenite and rutile forms of titanium oxide. Section 4 outlines the life-cycle inventory input and output datasets of both the ilmenite and rutile mining methods and detailed analysis results of the ilmenite-rutile production process. This section also discusses the life-cycle analysis results under the environmental-impact categories outlined. Furthermore, it also explains the environmental and human-health effects, government concerns and public awareness about titanium-oxide mining methods. Section 5 summarizes the whole paper in terms of scope and results, thus recommends the environmental-effect reduction methods for selected titanium-ore extraction processes.

2. Ilmenite-rutile mining and processing

Hard-rock mining methods are used for the recovery of mineral-sand products in some countries. Whereas in Australia, Iluka Resources entail dry mining, which involves the typical extraction of heavy mineral ores from entirely shallow, free-flowing, and hollow deposits. Dry mining requires transportation like trucks, loaders, excavators, or scrapers to recover ore from the mining plant. This transportation unit then delivers the ore to the wet concentration plant. For large ore bodies with low clay content, the wet method of mining is preferred. To reduce the cost in the wet method, dredging with bucket wheels and suction is done. On the other hand, dry methods involve earth-moving equipment to excavate and transport the mineral sand to a separate feed-preparation section. Pumpers or conveyors differentiate among various dry-mining processes. Another exception involves hydraulic mining using high-pressure water. Dredging is done depending on the variability of the ground condition and the amount of available water. After the rehabilitation studies, the land is cleared and preparation starts for mining. Topsoil and subsoil is removed, stripped, and stockpiled. Transportation like scrapers or trucks is utilized to collect and transport the ore from the mining plant. Then the ore is screened to make it free from oversized materials, which may include rocks or debris. These oversized items are then returned to the pit to be transferred to the concentrator plant via conveyor. The wet concentration process produces a higher grade heavy mineral concentrate. Spiral separators are then used to wash the ore through gravity separation. This process consumes a huge amount of water which is then recycled back to the clean-water-dam. The concentration process produces a mixture of valuable and non-valuable heavy-sand minerals. From this mixture, ilmenite, rutile, zircon, and monazite are then separated through dry processing. Ilmenite is a titanium-oxide mineral which is upgraded to 85 to 95 percent titanium oxide which in turn comes as rutile. Synthetic rutile production consists of two stages including pyro-metallurgical processing, while ilmenite is heated in a large rotary kiln. It produces iron oxide impurities within the crystal lattice. In the next stage, irons is removed by oxidation and leaching in hydrometallurgical processing (Indian Bureau of Mines, 2016; Jones, 2009; Mineral Deposits Limited, 2011; Nuss and Eckelman, 2014; U.S. Geological Survey, 2012). Fig. 1 illustrates the flow diagram for ilmenite-rutile extraction technologies.

3. Production and resources of ilmenite and rutile

Ilmenite and rutile are the most abundant sources of titanium-oxide in the world. A United States Geological Survey (USGS) report states that ilmenite accounts for 92% of the world's consumption of titanium oxide. China, with 20 million tonnes, has the world's most abundant source of ilmenite while Australia stands in the first position for rutile with a 29 million tonne reserve (USGS, 2017). Fig. 2 shows data in thousands of metric tonnes of titanium-oxide. It also illustrates the global producers of ilmenite-rutile throughout the world based on their production and reserve. In terms of production, Norway and South Africa dominate over China and Australia. On the other hand, Australia have the largest resource and production system of rutile while South Africa comes in the second position for reserve (Agency et al., 2014; Mudd, 2009).

Table 1 summarizes the current mineral-sand mining operations in Australia. There are 15 operating mines which produce ilmenite-rutile in Australia. In the early years, Australia produced 1 million tonnes of ilmenite of which nearly half were converted into synthetic rutile through the Becher process. Now a days around 50%