Evaluation of Chromium Application in the Steel Industry in China: Implications on Environmental Quality

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Abstract. This study provides vital analysis of environmental consequences of the steel industry in China on outdoor air quality, surface, and groundwater quality as well as global production of Chromite ore, its associated cost on health locally and internationally. The steel industry emissions currently amount to 50, 200, and 300 µg/m³ for PM$_{2.5}$, SO$_2$ and NO$_2$ respectively exceeding WHO recommended emissions values. Out of 365 cities in China, 70% of these cities representing 256 cities in 2018 had their annual mean particulate matter emission being 44.1 µg/m³ which is significantly higher than the WHO standard. Imported chromite from 1996 to 2016 amounted to 106,090,000 Mt by China. The production of crude steel increased from 870.9 to 928.3 Mt in 2017 and 2018 respectively. The proportion of good groundwater quality reduced from 26.9 to 25.4% in three years. Nearly 68% of total chromium emissions come from the metallurgical industry with an annual increment of 15.6% with an annual average PM$_{2.5}$ value of 53 ug/m³ which is significantly very high.

1. Introduction

China is endowed with deposits of many mineral resources in minable quantities such as fossil fuels such as coal, natural gas, and oil. It is also known for being a top producer of aluminium, tungsten, zinc, copper, magnesium, lead, gold, mercury, iron, steel [1]. In 2016, China was the topmost country in the world with 24% percentage world mining whilst other countries such as the United States of America, Russia, and Australia recorded 11.5, 9.1, and 7.3% respectively. At the continental total mining outputs levels, Asia came top with 58.2% followed by North America 14.1%, Europe 8.5%, Oceania and Latin America followed with 6.9% each, and Africa coming behind with 5.4% [2]. Records showed that China is the number one producer of twenty-eight different raw mineral materials such as mineral fuels, industrial minerals, precious metal, non-ferrous metals, and iron and ferroalloy metals. This gives China a competitive edge and a very strategic position in terms of socio-economic growth at the same time serious challenges with environmental pollution. Apart from the 28 raw mineral deposits, China does not have sufficient chromium deposits despite that it’s the top consumer of chromium and producer of steel in the world. Chromite resources in China are very limited and between 2011 to 2016 production had been on the decline. Globally, chromite resources that are economically viable in terms of quantities are estimated to be more than 12 billion metric tonnes. Interestingly, about 95% of the world’s chromite deposits are geographically located in two countries namely South Africa and Kazakhstan [3]. Chrome ore is a mineral made up of chromium and iron oxide (FeCr$_2$O$_4$) but known commercially as chromite. Chromite is an essential material in the production of stainless steel given the fact that it serves as an alloying agent. Chromite is a very important and suitable material in the production of stainless steel given its anti-corrosion resistance properties [4]. The aims of this study were to i) provide empirical
chromite import and production analysis ii) examine the impact of the growing steel industry in China on environmental health and iii) analyze the contribution of the steel industry to national emissions and identify any associated health risks involved. Given the increasing patronage and wide usage of stainless-steel products globally, and because China is the largest producer of stainless-steel and related products in the world, it is significant to do a critical assessment of its impact on the environment. The objectives were achieved through critical analysis of data obtained. It is anticipated that the results would help in understanding the intricacies involved in the chromite industry. To ensure exhaustive investigation, this study analyzed chromite production and imports data from 1996 to 2016. In addition, recent emissions and effluents discharge reports have been examined to ascertain the current trends. The implications of rapid growth of the steel industry in China on health and environmental sustainability. Effluents discharge and emissions of toxic gases have been analyzed critically.

2. Global chromite production

Chromite ore production in 2016 was 30.4 million metric tonnes (Mt) compared with a revised production quantity of 31.2 Mt in 2015, an indication of a 3% decline over the previous year. South African maintained its lead in chromite production in 2016 with 48% of worldwide production. On the contrary, global ferrochrome production went up to 10.9 Mt compared to 10.3 Mt in 2015. South Africa was the leading producer of ferrochrome accounting for 33% of world total production [5]. In 2017, the four largest chromium producers globally were South Africa (15 Mt), Kazakhstan (5.4 Mt), India (3.2 Mt), and Turkey (2.8 Mt) [6]. The International Stainless Steel Forum (ISSF) 2015 disclosed that South Africa has an approximated 72% of world chromite ore reserves followed by Zimbabwe with an estimated 12% of world chromite ore deposits [7]. Based on critical analysis of data, the total quantity of chromite produced by each of the world's top four countries such as Turkey, India, Kazakhstan, and South Africa in the last 21 years stood at 32,603,051; 56,490,042; 66,224,478, and 190,778,601 Mt respectively. The total quantity of chromite ore produced by the top four global producers in the past two decades amounted to 346,096,172 Mt [8-11]. This represented a significant quantum of global chromite ore produced in the past 2 decades. Fig. 1a and 1b showed the proportion of chromite ore produced by each of the top four global producers percentage-wise.

2.1 Dynamics of chromium production and trade

Chromium has wide applications in different industries globally ranging from metallic ceramics, paints and dyes, chrome plating, tannery and leatherwork, electric furnace, anti-corrosion resistance. Given the diverse applications of chromium by industries worldwide, Grand View Research Inc. (GVR), market research and consultancy firm in the US has predicted that global trade in chromium is expected to hit a 2.7% compound annual growth rate (CAGR) representing the market size of US$ 16.55 billion by the year 2025 from US$13.07 billion in 2016 [11]. The global chromium market growth is driven by rising demands by industries that manufacture aircraft and stainless steel as end-use. Additionally, the robust growth of the automobile and the electronic industry in the Asia Pacific region where China and India are located contribute significantly to the rising demand for chromium. China and South Africa play a very critical role in the production of ferrochrome for global market supply. In 2014, the total global production of ferrochrome by the two countries of 11,236 tonnes (t), this exceeded the global demand by +219 t. In 2015 and 2016, the total ferrochrome produced was 10,699 and 10,806 t respectively. This means that market demands for ferrochrome globally outweighed total production by China and South Africa by -141 and -851 t in 2015 and 2016 respectively. China imported a total of 106,090,000 (Mt) of chromite between 1996 to 2016 valued at US$23,821,101 based on analysis of import data. During this period, the lowest and highest chromite imports by China were 12,090,000 (Mt) in 2013 and 760,000 (Mt) in 1996 as vividly shown in Fig. 1c. Again, Fig. 1e showed ferrochrome production by China and South Africa from 2014 to 2016, total demand, supply, and projections regarding production between 2017 to 2021. Fig. If showed aggregated chromite ore production (%) by the top 4 countries from 2006 to 2016.
Authors’ analysis (Data sources: US Geological Survey & Macquarie Group Ltd)

Figure 1. Global top 4 chromite ore producers (a) 1996 to 2005, (b) 2006 to 2016, (c) trends of China’s chromium imports and costs from 1996 to 2016 (d) chromite ore production trends by top 4 countries from 1996 to 2016, (e) ferrochrome production by China and S. Africa, total global demand and supply and (f) aggregated chromite ore production (%) by the top 4 countries from 2006 to 2016.

3. Impact of the steel industry on environmental sustainability

Ferrochrome and steel industries require huge amounts of energy as well as the minerals for production to meet the ever-increasing demands for stainless steel and ferrochrome products. This also means that significant quantities of wastes are generated in the production processes. These wastes end up in the environment via disposal routes. These wastes contain substantial quantities of toxic pollutants, wastewater, residues, and other by-products that are generated in the course of the production. It has been reported that ferrochrome and steel industries emit dust with significant amounts of certain organic compounds and heavy metals. This is attributed to the use of electric arc furnaces in the steel manufacturing plants. Carbon dioxide (CO$_2$) is one of the constituents emitted into the environment in the production process. The International Iron and Steel Institute (IISI) has indicated that electric arc furnace plants emit nearly 0.7 tonnes of CO$_2$ per each tonne of steel produced. Similarly, integrated plants emit between 1.6 to 2.4 tonnes of CO$_2$ per tonne of steel produced [12]. The steel industry in
China discharged 1.73 Mt of sulfur dioxide (SO\textsubscript{2}) in 2007 which represents 7\% of the total national sulfur dioxide discharge. The same industry discharged 1.07 Mt of dust in the same year which represented 15\% of total national dust emitted. The steel industry also discharged 228.5 Mt of solid wastes in 2007 which represented 13\% of total national solid wastes discharged in that year. The quantity of wastewater discharged by the steel industry represented 8\% of total national wastewater discharge [12]. China has been the world’s number producer of stainless steel for over a decade now. In 2017, China has ranked 1\textsuperscript{st} in world crude steel production with 870.9 Mt. Japan was 2\textsuperscript{nd} with a production record of 104.7 Mt. India was 3\textsuperscript{rd} with 101.5 Mt while the US ranked 4\textsuperscript{th} with 81.6 Mt. The rest were Russia 5\textsuperscript{th} position with crude steel production of 71.5 Mt, South Korea 6\textsuperscript{th} position with 71.0 Mt, Germany 7\textsuperscript{th} with a production record of 43.3 Mt. The last three countries were Turkey 8\textsuperscript{th}, Brazil 9\textsuperscript{th} and Italy 10\textsuperscript{th} position with 37.5 Mt, 34.5 Mt and 24.1 Mt respectively. In 2018, China still maintained its dominant lead in the production of crude steel as the world’s number one with 928.3 Mt, an increase in production by 57.4 Mt compared to 2017. India however displaced Japan to occupy the 2\textsuperscript{nd} position in 2018 after it produced 106.5 Mt of crude steel. Japan dropped to 3\textsuperscript{rd} position with a production record of 104.3 Mt. The US maintained its 4\textsuperscript{th} position after its production in 2018 increased slightly to 86.6 Mt from 81.6 Mt in 2017. South Korea displaced Russia to occupy the 5\textsuperscript{th} position with total crude steel production of 72.5 Mt. Russia came 6\textsuperscript{th} in crude steel production of 71.7 Mt, but Germany also maintained its previous rank of 7\textsuperscript{th} with 42.4 Mt despite a little decline in production. The remaining three countries all maintained their 2017 positions such as Turkey 8\textsuperscript{th} with 37.3 Mt, Brazil 9\textsuperscript{th} with 34.9 Mt, and Italy 10\textsuperscript{th} with 24.5 Mt of crude steel [13].

3.1 Cost of pollution on economies
According to the Organization for Economic and Co-operation and Development (OECD) 2016 report, an estimated 3 million premature deaths in 2010 globally due to exposure to polluted outdoor air quality. It is further predicted that, if stringent measures are not put in place by countries worldwide, the number of premature deaths will increase to 6-9 million by 2060 annually. The cost of healthcare due to air pollution-related illness is predicted to increase from US$21 billion in 2015 keeping the 2010 US$ exchange rate constant to US$176 billion in 2060. Within the same period, loss of productivity as a result of the annual loss of working days is estimated to cost US$3.7 billion globally [14]. In 2018, the estimated cost of global air pollution due to exposure to PM\textsubscript{2.5}, NO\textsubscript{2} and O\textsubscript{3} about fossil fuel were US$2.7 trillion (3.1\% of GDP), US$750 billion (0.9\% of GDP), and US$524 billion (0.60\% of GDP) respectively. It is predicted that 1.8 million people in Mainland China die prematurely as a result of exposure to outdoor air pollution yearly [15]. A total amount of 9.95 billion yuan equivalent to US$1.42 billion was spent as cost of air pollution control facilities operations such as desulfurization by the steel industry e.g smelting, metal products processing, and manufacture in China in 2016. In the same year, a total of 4.40 billion yuan an equivalent of US$629 million was expended by the steel industry in China as an operational cost for wastewater treatment facilities regarding smelting and ferrous metals processing. Nearly 423 Mt of raw steel was produced by the steel industry in China in 2006. Of this total production, the cost of operating air pollution control equipment stood at 23.5 yuan equivalent to US$3.36 per tonne of steel produced while the cost of operating wastewater treatment facilities amounted to 10.4 yuan equivalent to US$1.49 per tonne of steel produced in 2006. This excluded maintenance and other related operational costs [16].

3.2 Consequences of pollution on health
In 2019, South China Morning Post revealed that the Chinese government disclosed that curbing pollution was one of the “three critical battles” China continues to fight against apart from the eradication of poverty and financial risk control. Coal-powered plants and the steel industry are the biggest conduits of pollutant emissions in China. The steel industry in 2017 emitted 2.81 Mt of particulate matter (PM) which accounted for 20\% of China’s total PM emissions [17]. Additionally, China’s steel industry generated 1.72 Mt of nitrogen dioxide (NO\textsubscript{2}) and 1.06 Mt of sulfur dioxide. This means that current emission levels by the steel industry stand at 50 micrograms per cubic meter (µg/m\textsuperscript{3}) for PM\textsubscript{2.5}, 200 µg/m\textsuperscript{3} for SO\textsubscript{2} and 300 µg/m\textsuperscript{3} for NO\textsubscript{2} per annum instead of WHO standard permissible emission limits of 10 µg/m\textsuperscript{3}, 20 µg/m\textsuperscript{3} and 40 µg/m\textsuperscript{3} for PM\textsubscript{2.5}, SO\textsubscript{2} and NO\textsubscript{2} respectively [18]. It is
anticipated that this year 2020, 60% of the steel manufacturing plants in areas in China will meet these standard benchmark values with the hope that by the year 2025, 80% of the steel manufacturing companies in China will meet the required standards. Between now and the next 5 years, China will continue to battle with toxic emissions into the atmosphere from the steel industry. Chinese government as part of its measures to encourage the steel industry in the country to meet these standards, companies that finish the upgrade by the stipulated time would be supported financially, given tax incentives, and protected by environmental policies.

China’s rapid industrial and economic growth in the last 40 years came with associated consequences in terms of environmental pollution and human health. According to the World Bank, many cities in China are polluted due to emissions from industries. China is the largest contributor to Greenhouse Gases (GHG) globally. In 2016, China was the third country to launch a satellite to monitor CO₂ emission after the US and Japan [19]. In 2014, the annual average PM₂.₅ concentration was 93 micrograms per cubic meter (µg/m³), which was more than twice China’s national standard limit for PM₂.₅ of 35 µg/m³ and the World Health Organization (WHO) permissible limit of 10 µg/m³ for PM₂.₅ and PM₁₀ of 20 µg/m³. Despite the efforts of China’s government to curb air pollution, the World Bank’s latest annual average PM₂.₅ value is 53 µg/m³ in 2017 which is still higher than both the national standard and WHO annual mean of 10 µg/m³ [20]. The economic and social cost of China’s air pollution cannot be underestimated considering the number of fatalities recorded yearly due to poor outdoor air quality. In a recent study on morbidity, mortality, and risk factors in China in 2019, it was revealed that the second and third highest cause of deaths in China in 2017 was ischaemic heart disease and lung cancer respectively with stroke coming first [21]. Zhou et. al, (2016) revealed that poor outdoor air quality was the 5th leading cause of premature deaths in China in 2013, thus contributing to 916,000 premature deaths in China in the same year.

In 2018, Green Peace in its air pollution control report card for 2017 revealed that 365 cities in China had a mean PM₂.₅ concentration of 44.1 µg/m³ as compared to 46.2 µg/m³ in the previous year. Even though in comparison, 2017 mean PM₂.₅ concentration represented a 4.5% drop but the average value of 44.1 µg/m³ was still higher than the national standard permissible limit of 35 µg/m³ and more than three times of WHO permissible mean PM₂.₅ concentration of 10 µg/m³. Similarly, 74 crucial cities across China had their mean PM₂.₅ concentration dropping to 48 µg/m³ in 2017 from 2013 mean value of 72 µg/m³ which represented a decline of 33.3% in four years since China launched its pollution control campaign. Again, even though this looks progressive, the mean PM₂.₅ concentration for those 74 key cities is almost five times higher than WHO permissible annual mean PM₂.₅ concentration and also still higher than China’s national standard limit. This is an indication that, despite the progress made, more work still needs to be done to achieve at least the national standard for PM₂.₅. It is important to note that, based on the 2017 air pollution control scorecard assessment on 365 cities across China by Green Peace Initiative (GPI), 256 which represents over 70% of the total cities have PM₂.₅ concentration higher than the national secondary standard of 35 µg/m³. In terms of Ozone (O₃) concentration in the 365 cities surveyed across China, the mean concentration was 144.5 µg/m³ representing a 6.3% increment whilst NO₂ mean concentration was 30.5 µg/m³ representing 3.3%. Similarly, the 74 crucial cities had their mean O₃ concentration of 155 µg/m³ representing an 11.5% increment over that of 2013 [15].

The Chinese government in February 2010 released data on its First National Census on Pollution Sources (FNCPS). The FNCPS identified a total of over 5.93 million sources of pollution in the country. Out of the total sources reported, 1.58 million of them are industrial sources dotted across the country. The total quantity of Chemical Oxygen Demand (COD) discharge was over 30.3 Mt out of which industrial sources COD discharge amounted to 5.6 Mt, the rest came from agricultural, landfills (leachate) and domestic sources [22]. This is an indication of the complex nature of the industrial effluents given the vast number of sources involved. A similar worrying outcome notice in the report was the amount of heavy metals effluents generated by industries. Heavy metals such as chromium, arsenic, lead, mercury, and cadmium wastewater reached 900 tonnes. It was revealed that SO₂ total emissions in the country stood at 23.20 Mt out of which over 21.20 Mt came from industrial sources while NOₓ total emissions amounted to 17.98 Mt and 11.88 Mt out of the total emissions came from industrial sources. Solid and hazardous wastes were not left out in the 2010 FNCPS, because industrial solid and hazardous waste total discharge was 3.85 billion tonnes (Gt). Wang et al., (2016) reported that nearly 90% of total
PM emissions in the steel industry come from sinter plants and blast furnaces in China [23]. These statistics are frightening given the fact that between 2010 and 2020, industrial production especially in the steel industry continues to rise significantly. This makes the fight against environmental pollution from industrial sources more cumbersome and complicated than it can be imagined.

3.3 Impact of pollution on water resources

China has a good number of water resources from fresh to marine water bodies. However, due to increasing demand for water resources as a result of urbanization and increasing population growth, put pressure on the available water resources. More troubling is the fact that water quality deterioration continues to occur due to anthropogenic activities such as pollution. The pressure is brought to bear on groundwater for purposes of industrial and agricultural activities due to the contamination of surface water bodies. In 2007, the World Bank estimated that the overall cost of water scarcity and groundwater depletion which could be attributed to water pollution-related challenges was in the tune of 147 billion yuan [24]. The steel industry contributes significantly to chromium pollution in water bodies. An inventory study on chromium discharge into water bodies and atmospheric emissions in China by Cheng et al. (2014) revealed that approximately 13,400 tonnes of chromium were discharged into water bodies from six categories of industries in 20 years. The metallurgical industry alone accounted for nearly 68% of the total chromium emission with a yearly increment of 15.6% [25].

Table 1. Freshwater quality changes between 2013 to 2016

| Name of River      | Year | Total water sections under National monitoring | Water quality status (%) | Change in water quality (%) |
|-------------------|------|-----------------------------------------------|--------------------------|----------------------------|
| Songhua River Basin | 2013 | 108                                           | 55.7                     | +4.5                       |
|                   | 2016 |                                               | 60.2                     |                            |
| Huaihe River Basin | 2013 | 180                                           | 59.6                     | -6.3                       |
|                   | 2016 |                                               | 53.3                     |                            |
| Haihe River Basin  | 2013 | 161                                           | 39.1                     | -1.8                       |
|                   | 2016 |                                               | 37.3                     |                            |
| Liaohe River Basin | 2013 | 106                                           | 45.5                     | -0.2                       |
|                   | 2016 |                                               | 45.3                     |                            |
| Yangtze River Basin | 2013 | 510                                           | 89.4                     | -7.1                       |
|                   | 2016 |                                               | 82.3                     |                            |
| Yellow River Basin | 2013 | 137                                           | 58.1                     | +1                         |
|                   | 2016 |                                               | 59.1                     |                            |
| Pearl River Basin  | 2013 | 165                                           | 94.4                     | -4.8                       |
|                   | 2016 |                                               | 89.6                     |                            |

Authors’ analyzed results (Data source: Ministry of Environmental Protection, China)

Anthropogenic activities continue to pose severe threats to environmental quality. From Table 1, it can be observed that between 2013 to 2016, apart from Songhua River and Yellow River Basins which witnessed 4.5% and 1% improvement in the Grade I to III water quality over the period, the rest of the
five fresh surface water bodies recorded some level of pollution. The percentage of Grade I to III water quality of the Huaihe River Basin with 180 water sections that are under national monitoring got polluted moderately by 6.3%. Similarly, Grade I to III water quality of the Haihe River Basin with 161 national monitoring sections, Grade I to III water quality of the Liaohe River Basin with 106 national monitoring sections, Grade I to III water quality of the Yangtze River Basin with 510 national monitoring sections and Grade I to III water quality of the Pearl River Basin with 165 national monitoring sections were polluted by 1.8, 0.2, 7.1 and 4.8% respectively compared to the 2013 water quality status of Grade I to III. According to the 2013 State of the Environment Report on China by the Ministry of Environmental Protection, out of a total of 4,778 identified sites (wells) for national groundwater quality monitoring in China, excellent water quality was 10.4% (497 sites), good water quality was 26.9% (1,285 sites), relatively good quality was 31.1% (148 sites), relatively poor quality stood at 43.9% (2,098 sites) and severely poor quality was 15.7% (750 sites) correspondingly [26]. In 2016, the number of groundwater quality monitoring sites (wells) increased to 6,124 as captured in the State of the Environment in China report. Out of the total number of groundwater monitoring sites by the Chinese government, 10.1% (619 sites) had excellent quality, 25.4% (1,555 sites) had good quality, 4.4% (269 sites) had relatively good quality, 45.4% (2,780 sites) had poor quality and 14.7% (900 sites) had very poor groundwater quality [27]. It can be observed that even though the total number of groundwater monitoring sites increased from 4,778 in 2013 to 6,124 in 2016, the percentage of excellent water quality reduced from 10.4% to 10.1% respectively. Within the same period, the percentage of total good groundwater quality also reduced from 26.9% in 2013 to 25.4% in 2016 respectively. The analysis showed that for both excellent and good quality groundwater sites witnessed some level of pollution between 2013 and 2016.

4. China's environmental monitoring and protection strategies
The launch of the CO2 satellite by China to monitor emissions released into the atmosphere was a giant step. Similar monitoring of outdoor air quality takes place in 338 cities in China. These are important measures put in place by the Chinese government to mitigate the increasing air pollution. Chinese government adoption of a “Master Plan for Eco-environmental Protection of Lakes with Fine water Quality 2013-2020”. Under this master plan, the Chinese central government allocated 1.6 billion yuan to help protect 27 lakes in China with fine water quality. Additionally, 1.8 million environmental inspectors were recruited by the Chinese government to monitor regularly 0.81 million enterprises to ensure adherence and compliance with environmental standards and regulations. Nearly 10,000 environmental breaches, non-compliance, hazards, and risks were identified in the process. As part of measures to address the challenges of environmental pollution in the country, the Chinese government through the State Council introduced certain policy interventions aimed at curbing pollution. The 12th Five-Year Plan (2011-2015) is one of such policy interventions recently. The FYPs set out targets such as safe disposal and treatment of solid wastes, controlling the high occurrence of heavy metals pollution, strengthen environmental supervision system, enhance the development of legal regimes, increase investments all aimed at curbing environmental pollution.

The implementation of the 12th Five-Year Plan chalked some successes including a reduction in total COD discharge by 12.5% and a 14.3% reduction in SO2 emissions in comparison to 2005 statistics [28]. However, the 13th Five-Year Plan on the protection of the environment released in 2016 showed that SO2 and COD emissions were still high approximately 20 Mt [29]. Again, 78.4% of cities in China could not meet the standards set for outdoor air quality, 3.2% of the days were classified as extreme pollution. Moving forward, the Chinese government and all other relevant stakeholders ought to join forces together by possibly reviewing some of the existing interventions and tighten the loose ends. This would ensure that drastic measures are taken to fight against the increasing spate of outdoor air pollution.

5. Conclusion
The analysis revealed China’s chromium consumption and importation trends. South Africa showed significantly dominates in chromite ore and ferrochrome production globally. Global ferrochrome production though intermittently recorded some slowdown, there has been increasing trends generally owing to increasing demand and application. The top four chromite-producing countries globally were South Africa, Kazakhstan, India, and Turkey respectively in 2017. China continues to lead the rest of
the world in the production of steel and would likely continue to dominate in this industry for many years to come given its production advantages.

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