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Tuçe TÜRKBAY, Bertrand LARATTE, Ayenur ÇOLAK, Semra ÇORUH, Birol ELEVLI - Life Cycle Assessment of Boron Industry from Mining to Refined Products - Sustainability - Vol. 14, n°3, p.1787 - 2022

sustainability

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Life Cycle Assessment of Boron Industry from Mining to Refined Products

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Abstract: Although there are a lot of studies in literature related to the life cycle assessment (LCA) of mining, there are only a few studies done on the boron mining industry. This paper presents an LCA of the boron mining industry including the extraction, beneficiation, and refinement processes. The main purpose is to identify and compare the environmental impacts associated with the production of 1 ton of refined products (boric acid, borax pentahydrate, borax decahydrate, and sodium perborate) starting from an open pit mine located in Turkey. The life cycle inventory (LCI) was obtained from the data collected from the related literature sources and the company's reports. This cradle-to-gate analysis has been carried out using the commercial software called SimaPro employing the International Reference Life Cycle Data System (ILCD) 2011 Midpoint+ Life Cycle Impact Assessment (LCIA) method. The results showed that the environmental impact of the refinement process is critical compared to the mining and beneficiations processes. Sulphuric acid, steam, hydrogen peroxide, and sodium perborate which are used in refined boron production cause most of the impact and emission into the environment. Among the refined boron products investigated, the impact of sodium perborate is quite high.

Keywords: life cycle assessment; environmental impact; boron mining; colemanite; ulexite; tincal

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Citation: Türkbay, T.; Laratte, B.; Çolak, A.; Çoruh, S.; Elevli, B. Life Cycle Assessment of Boron Industry from Mining to Refined Products. *Sustainability* **2022**, *14*, 1787. https://doi.org/10.3390/su14031787

Academic Editors: Dmitriy Makarov and Vladimir Masloboev

Received: 8 December 2021
Accepted: 31 January 2022
Published: 4 February 2022

1. Introduction

The boron element has been used in a wide range of industries such as glass, ceramic, detergent, etc., and also in the agricultural field [1]. Boron is widely used in the glass industry to reduce thermal expansion, increase durability and chemical resistance, and provide resistance to vibration, high temperature, and thermal shock. In the ceramic industry, it is used to increase chemical, thermal, and wear resistance. Boron has been used as a laundry additive since the 1900s in the detergent and soap industry; it softens hard water by binding to the calcium ions in hard water. It is also used in the agricultural field as a micronutrient in fertilizers as it contributes to fruit and seed production [2]. A detailed table of boron uses is given in Table A1 [2–8].

The interest and demand for boron increased over time as a result of development in industrial activities and technologies [9]. It is then necessary to consider the impact of boron minerals on the environment in order to perform a life cycle assessment (LCA) of industrial products containing boron elements from cradle to gate. There are many LCA studies on mineral mining in the literature such as iron, lithium, manganese, uranium, gold, cobalt, etc. [10–15]. Nevertheless, there is a great lack of literature on the LCA of boron mining.The study by Azapagic and Clift (1999) [16] presented the results of the application of LCA on boron mining. They studied the LCA of five different borates: disodium tetraborate decahydrate or 10 Mol borate ($Na_2B_4O_7.10H_2O$), disodium tetraborate pentahydrate or 5 Mol borate ($Na_2B_4O_7.4.67H_2O$), orthoboric acid (H_3BO_3), disodium tetraborate or anhydrous borax ($Na_2B_4O_7$), and boric oxide or anhydrous boric acid (B_2O_3), with the functional unit of operation of the system for one year. In their system boundaries, all activities from extraction to the packing and shipping of the boron products were included.

Another study related to the LCA method of cradle-to-gate of borax and boric acid derivation from ludwigit and szaibelyite in China has been done by An and Xue (2014) [17] by using GaBi 4.4 software and their results were classified according to the CML2001 method. The functional unit was considered as 10,000 tons of borax and 10,000 tons of boric acid production. In their system boundaries, mining, dressing, and borax and boric acid production were included.

The most recent LCA study on boron was published by Wu et al. (2021) [18]. They investigated the potential environmental impact of boric acid production using the solvent extraction technique from salt-lake brine with the functional unit of 1 ton of boric acid production. In their boundary systems, acidification, extraction, reverse extraction, and drying were included.

This study performed LCA to evaluate the potential environmental impact of boron mining in Turkey. This paper focuses on three mining processes: open-pit mining, beneficiation, and refinement; bridges the research gaps in the existing literature; and aims at providing the baseline data for future research directions in the field of LCA and Sustainable Energy applied to boron mining. Studies conducted within the scope of this paper are grouped under five following sections:

- Section 1 describes the boron reserves, borate extraction techniques, beneficiation techniques, and chemical process for derivation of boric acid (BA), borax pentahydrate (BP), borax decahydrate (BD), and sodium perborate (SP).
- Section 2 describes the methodology within the scope of four main stages of LCA.
- Section 3 discusses the analysis results in the context of comparative impact categories.
- Section 4 discusses the results compared with the literature.
- Section 5 concludes with the summary of analysis results and recommendations to reduce the environmental effects of all the stages of the boron industry, from mining to refined products.

1.1. Boron Mining in Turkey

The important borate deposits in the world are located in Turkey 73.4%, Russia 7.8%, and the U.S.A. 6.2%. The majority of borate minerals in the world are located in Turkey. Therefore, the focus has been given to the mining, processing, and refining of the borate minerals (tincal and colemanite) in Turkey in this study. Boron mines are operated by the company Eti Maden under the control of the state in Turkey [19,20]. There are five operation directorates belonging the Eti Maden company: Emet, Bigadiç, Kırka, Kestelek, and Bandırma [1], see Figure 1. The borate minerals extracted in Turkey are tincal, colemanite, and ulexite [9,20]. Sodium-based borate minerals are called tincal (borax), calcium-based ones are called colemanite, and sodium-calcium-based ones are called ulexite [20,21]. Colemanite deposits are mainly located in Emet and Bigadiç, and tincal deposits are located in Kırka where the largest tincal deposit is worldwide. Furthermore, it is known that there is a small amount of ulexite in Bigadiç [22].

The facilities, the amount of the ore reserves, and refined products of the borate minerals are given in Table 1 [20,21,23–25]. In this study, the focus has been given to four refined products: BA, BP, BD, and SP.

1.2. Boron Processing Method in Turkey

The borate ore (tincal, colemanite, ulexite) is extracted with the open-pit mining method in Turkey [26,27]. Afterward, the run-of-ore is transported to the concentrator facility and enriched by increasing the grade of B_2O_3 in the mineral. Ultimately, refined products are obtained from enriched ore. The schematic diagram in Figure 2 depicts the conceptual workflow including multiple processes, inputs, outputs, mining equipment, and after-mining processes, such as the production of BA, BP, BD, and SP. The colors: white, orange, yellow, green, and violet represent the inputs, machines, products, processes, and outputs, respectively. The diagram consists of three main stages: (i) open-pit mining, (ii) enrichment, and (iii) refinement.

Figure 1. Turkey's boron mine deposits.

Table 1. Borate minerals in Turkey.

Facility	Ore Reserve (ton)	Extracted Run-of-Ore	Concentrated Products	Refined Products
Emet	1,806,998.09	Colemanite	Colemanite	BA
Bigadiç	620,689.75	Colemanite and Ulexite	Colemanite and Ulexite	Grained Colemanite
Kırka	17,924,014	Tincal	Tincal	BD, BP
				Anhydrous Borax
Kestelek	5,254,923	Colemanite	Colemanite	-
Bandırma	-	-	-	BA, BD, BP, SP, Boron Oxide

(i) The mining activity can be described by operations of exploration, drilling, blasting, excavation of run-of-mine borate, loading, and transporting. The overburden layer covering the run-of-mine ore is removed by drilling-blasting methods. The drilling-blasting is followed by ore extraction. Hydraulic crawler excavators, loaders, and trucks are used for loading and transportation. The ore extracted from the mine is stockpiled in open stockpiles to be fed to the concentrator facilities when necessary or fed to the concentrator facility, directly [27,28]. In this stage, heavy-duty vehicles, graders, loaders, ripper dozers, and drillers are used [29].

(ii) Overall, there are five stages in the enrichment process, beginning with crushing and culminating in sieving. Although the machines and the size of the final products after crushing and milling are different, the boron concentrator plants in Turkey generally have these five steps: crushing, milling, screening, washing, and sieving. During the enrichment process, the clays precipitate together with the boron from the waste [30]. The machines used can be generalized as an apron feeder, classifier screw, jaw crusher, roll crusher, belt conveyors, and washer [31].

(iii) Although there are many refined boron products, the focus is given on BA, BD, BP, and SP. The refinement process of BD and BP are similar. The parameters which determine the final products during the refinement process are the temperature of the water and/or the temperature of the crystallizer. Therefore, only one flow chart is used for BD and BP in the diagram in Figure 2 [32].

The inputs for the summarized diagram are taken from [32,33]. The outputs have been estimated by using the LCA of general mining publications [10,12].

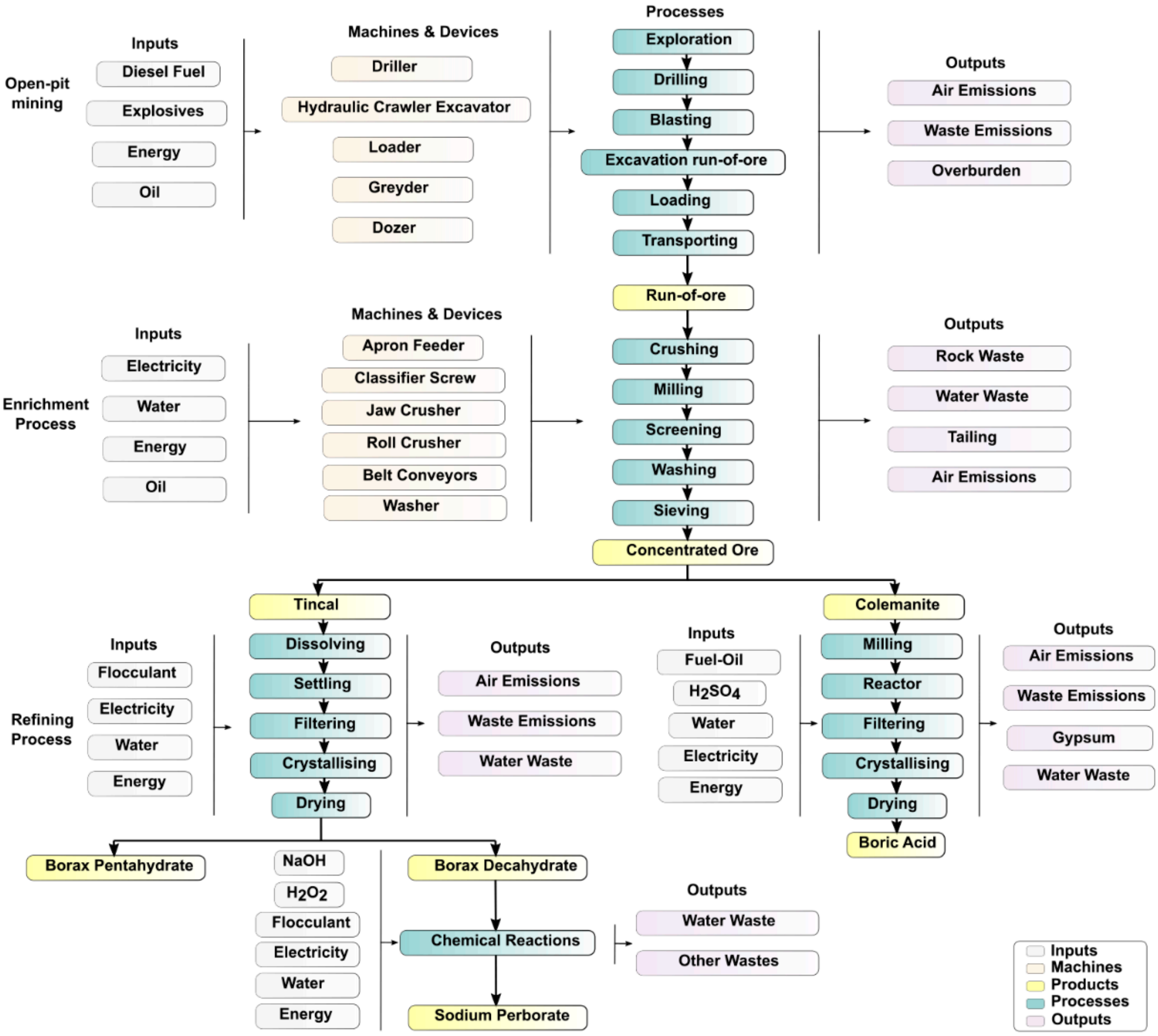

Figure 2. Boron mining process and derivation of refined products.

2. Materials and Methods

In this study, an effective environmental impact assessment tool, LCA, is used to determine the impact of the boron industrial processes on several categories such as human health, ecosystems, and natural resources. The LCA approach is used to investigate the environmental impacts of boron mining, enrichment, and refinement processes by defining the input data within SimaPro (Version 8.0.5.13.) software. The LCA method has four steps which are (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation [11], shown in Figure 3.

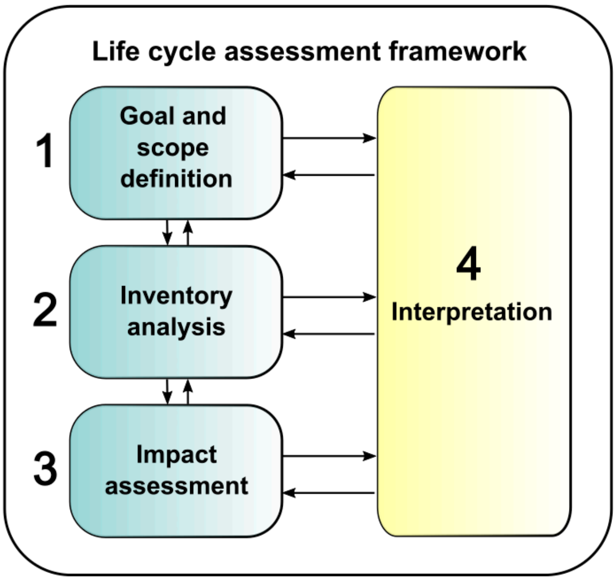

Figure 3. Life cycle assessment framework.

2.1. Goal and Scope Definition of the Study

Turkey is the major boron supplier to Europe. Boron compounds are used in various industrial areas as raw materials, side products, or main products. When LCA is performed on industrial products containing boron, it is necessary to consider the impact of boron on the environment, including the mining processes and derivation of refined boron products.

The goal and scope of the study are given below.

- Determining all the environmental impacts that occurred by all the steps in the boron mining industry in Turkey, such as climate change, ozone depletion, human toxicity, air emissions, etc. such that these results will help to other cradle-to-gate LCA studies where boron included.
- Comparison of the results between different processes,
- Understanding the impacts of each flow (types of boron).

The system boundaries and functional unit (FU) are determined at this stage. It is difficult to determine the functional unit in the mining area as such a domain belongs to hard-to-scale systems [34]. In fact, when comparing BA, BD, BP, and SP one must consider that their yearly production amount differs considerably. Hence, the functional unit should consider rather a normalized amount of boron products (e.g., 1 ton) to facilitate corresponding comparative studies. Moreover, both quantitative and qualitative functions are supposed to be considered for a comprehensive evaluation of the FU [35]. As the scope of this study is to carry out a quantitative LCA within the framework of a "cradle-to-gate" approach, the FU has been simplified as much as possible, keeping it quantitative.

- The system boundaries can be evaluated as the main system and subsystems. The main system consists of mining, beneficiation, and refinement. The subsystem of the mining is the drilling, blasting, extraction, loading, hauling, and transportation; the subsystem of the beneficiation is the apron feeder, classifier screw, jaw crusher, dust collecting system, roll crusher, belt conveyors, and washing; the subsystem of the refinement is the dissolving tank, sieving, pressure filtration, crystallizer, and dryer. Since the cradle-to-gate approach was selected, the transportation for final delivery, the packaging of refined products, the use of the products, recycling, recovery, or final disposal are excluded.
- FU: Comparison of 1 ton of refined boron products: BA, BD, BP, and SP.

2.2. Life Cycle Inventory (LCI) Analysis

LCI involves data collection and calculation to quantify the inputs and outputs of materials and energy associated with a product system. During the LCI analysis stage, data related to mining, concentrating, and refinement facilities are considered. The collected data are shown in the LCI table for BA in Table S1 and BD, BP, and SP in Table S2 (refer to Supplementary Materials). The data required to create the LCI of boron mining have been mainly obtained from the Türkiye Devlet Planlama Teşkilatı ("State Planning Organization of Turkey"), Eti Maden İşletmeleri Genel Müdürlüğü ("Eti Mining Operations General Directorate"), and some theses. The reference for the input data of mining and enrichment refers to 2001, for refinement, they are reported from 1987 [32,33]. These are the most up-to-date data on the enterprise in the literature. The averages of Emet, Hisarcık, and Bigadiç were taken for data related to colemanite ore. Afterward, the data used for the analysis are matched with the data in the Ecoinvent database to conduct the life cycle inventories. The details and assumptions regarding inventories are given in Supplementary Materials detail.

2.3. Life Cycle Impact Assessment (LCIA)

The LCIA stage was performed using the ILCD (International Reference Life Cycle Data System) 2011 Midpoint+ indicator developed by the European Commission. This method was used for the LCA of many mining industries such as aluminum, copper, silver, steel, uranium, and zinc [36]. The characterization method was used as recommended by ILCD. The ILCD 2011 Midpoint+ LCIA method includes 16 midpoint impact categories which are climate change (kg CO2 eq), ozone depletion (kg CFC-11 eq), human toxicity cancerous and non-cancerous effects (CTUh), particulate matter (kg PM 2.5 eq), ionizing radiation HH (kBq U235 eq), ionizing radiation E (CTUe), photochemical ozone formation (kg NMVOC eq), acidification (molc H+ eq), terrestrial eutrophication (molc N eq), freshwater eutrophication (kg P eq), marine eutrophication (kg N eq), freshwater ecotoxicity (CTUe), land use (kg C deficit), water resource depletion (m^3 water eq), and mineral, fossil, and renewable resource depletion (kg SB eq) [37].

2.4. Interpretation

The fourth step is the interpretation step in which the results of the study are put into context and organized to identify the processes that contribute the most impact according to the goal and scope of the study. The interpretation is carried out among the other three stages of the life cycle. If the results from the inventory analysis and impact assessment do not meet those specified in the target and scope definition, the system boundaries should be reviewed again, improved through further data collection, and followed by an enhanced impact assessment. This iterative process should be repeated until the requirements specified in the target and scope phase are met. The uncertainty analysis has been conducted in order to understand the robustness of the indicators. We need still to explore the quality of the data to reduce the large uncertainty of some indicators.

3. Results

Data collection in boron mining is one of the targets of this study and it is necessary to create an inventory that will be used for a corresponding life cycle assessment. Gathering the data about boron mining, concentrating, and refinement has been one of the major challenges of this work as only a few original datasets are reported in the literature. In fact, there are many LCA studies on a number of mineral mining, but only a few involving boron. In the review paper of Türkbay et al. (2021) [38], 63 literature sources about boron mining were investigated in detail. The present work is a continuation of that review paper. All the literature sources were investigated in detail to create an inventory. Despite a very comprehensive study, the number of original data in the literature is still quite limited; in fact, several of those 63 boron mining papers reviewed by Türkbay et al. (2021) [38] rely on the same few datasets.

The inventory for the 1 ton of refined products (BA, BD, BP, and SP) from Tables S1 and S2 was analyzed with SimaPro using ILCD 2011 Midpoint+ LCIA method, and the impact assessment network was calculated. According to the comparative analysis results from the ILCD 2011 Midpoint+ LCIA method, 16 impact categories are shown in Figure 4. The detailed characterized results are given in Table S3 in Supplementary Materials. The impact assessment shows that SP has the largest impact on all the categories except water resource depletion and mineral, fossil, and renewable resource depletion.

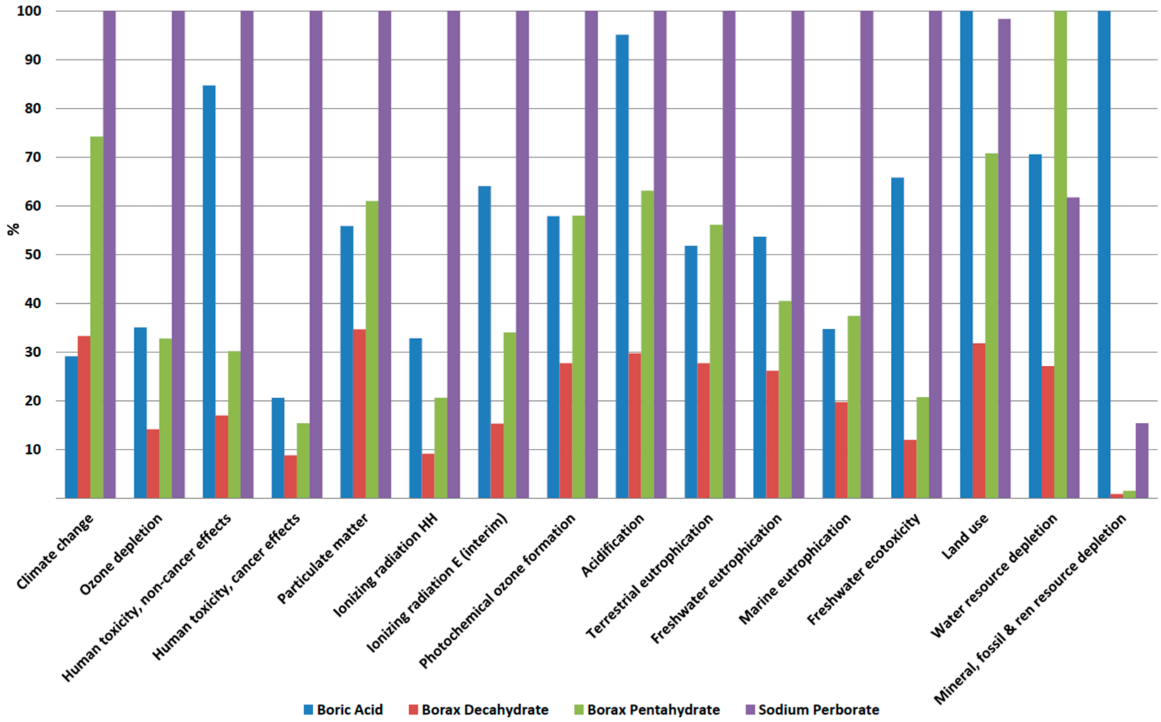

Figure 4. Characterized results for comparative analysis results of refined products.

The results of four different boron refined products are given in Figures 5–8. The colors on the bar charts are given in order with the name of materials/energy sources on the right.

BD and BP are both produced from concentrated tincal, and their refinement processes are similar. Therefore, their LCIA outcome on the 16 categories shows similar results, see Figures 6 and 7. BP ($Na_2B_4O_7.5H_2O$) includes 5 moles of water and BD ($Na_2B_4O_7.10H_2O$) includes 10 moles of water. Therefore, extra processes are necessary to reduce the water in BP's content and its impact on the environment is higher than BD, see Figure 4. Since SP is produced from another refined boron product (BD) instead of a concentrated mineral, it is expected that SP has the largest impact in comparison to other products, see Figure 4.

Global warming in consideration of BA results in a total impact of 495.31 kg CO_2 eq. The largest impact during all the steps is the steam during the refinement process which corresponds to 227.36 kg CO_2 eq. Sulfuric acid is the second largest contributor to this impact (143.01 kg CO_2 eq), followed by electricity (88.05 kg CO_2 eq). For BD, the total impact is 566.03 kg CO_2 eq. Steam is the largest contributor to global warming and is responsible for 454.73 kg CO_2 eq. Similar results are shown with BP as well. The total impact is 1262.96 kg CO_2 eq and the largest contributor's impact is 1136.82 kg CO_2 eq. For SP, the total impact found in terms of global warming is 1701.52 kg CO_2 eq. Steam contributes to 727.56 kg CO_2 eq, 381.14 kg CO_2 eq is from H_2O_2 (hydrogen peroxide), and 401.32 kg CO_2 eq is from NaOH (sodium hydroxide). The ***ozone depletion*** impact category is caused primarily by sulfuric acid. It is followed by the heavy fuel oil used during the refinement process. For BA, the analysis of inventory results from the total value of 12.126 × 10^{-5} kg CFC 11-eq confirms that sulfuric acid and heavy fuel oil are responsible for 9.3 × 10^{-5} kg CFC 11-eq. For BD and BP, the largest contributor to this impact is steam. For SP, the total impact on ozone depletion is 0.000347 kg CFC-11 eq and 0.000234 kg CFC-11 eq of the total is by the H_2O_2, followed by steam.

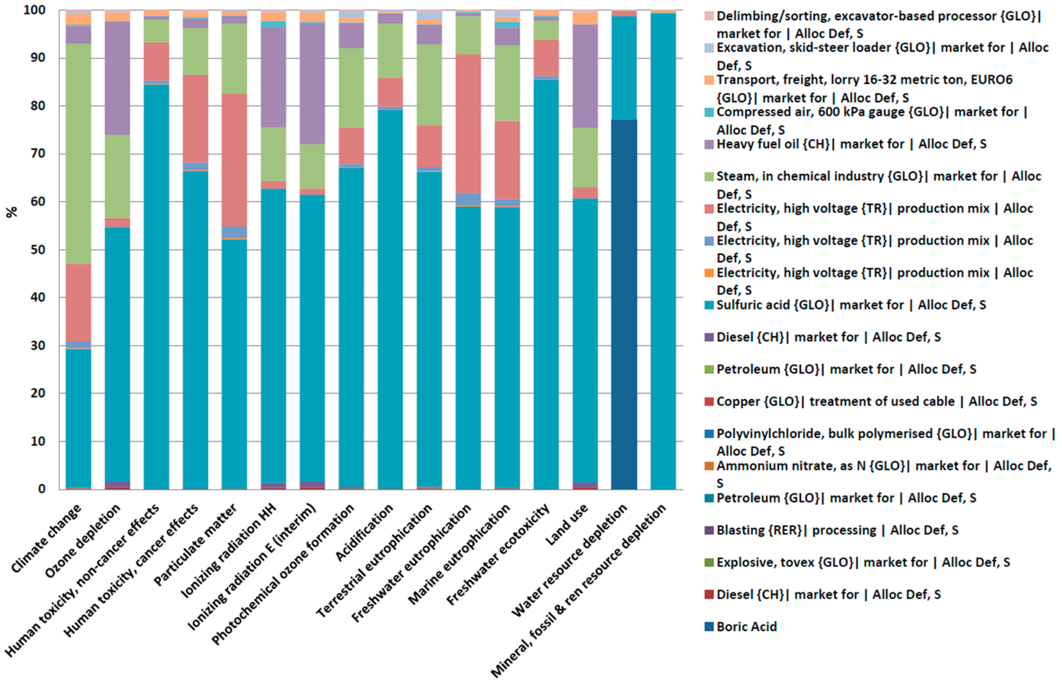

Figure 5. Characterized LCIA results for 1 ton of BA production.

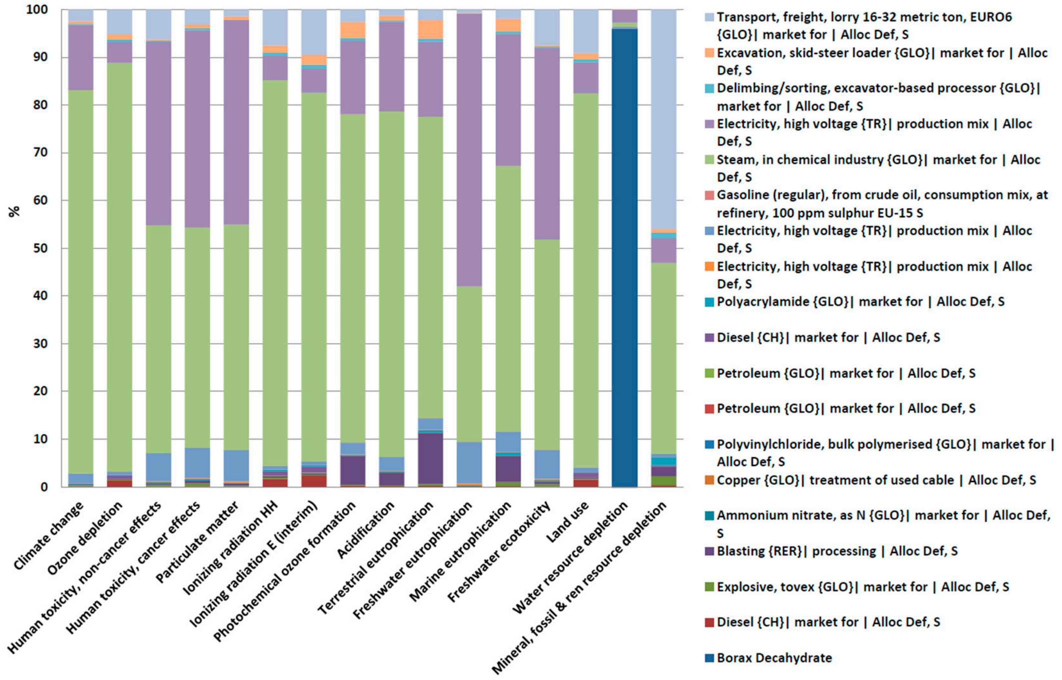

Figure 6. Characterized LCIA results for 1 ton of BD production.

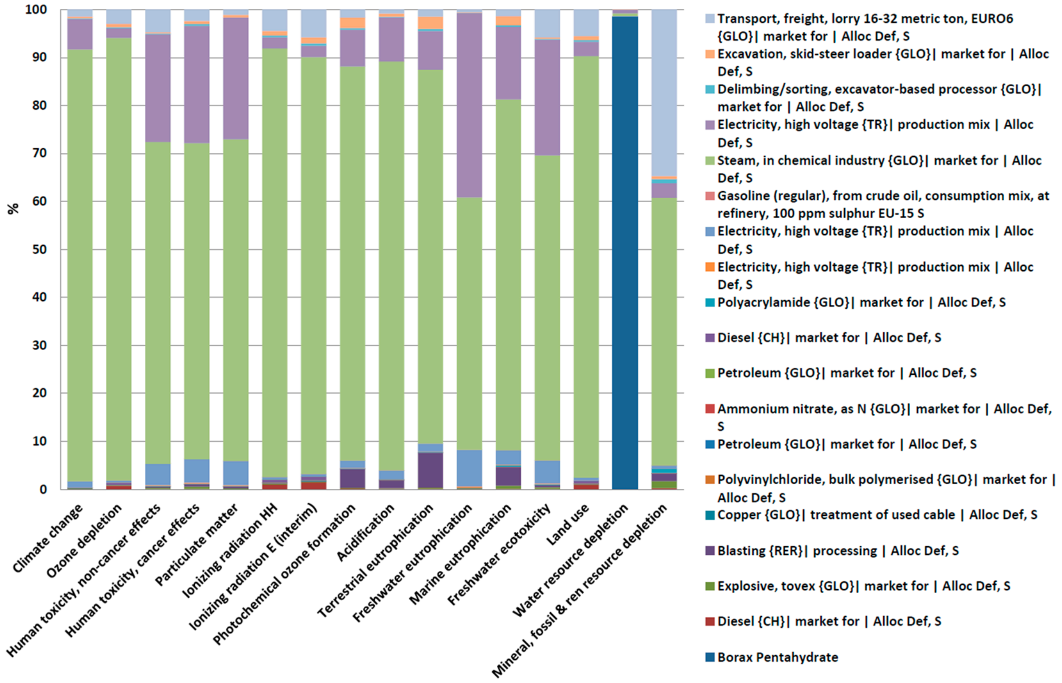

Figure 7. Characterized LCIA results for 1 ton of BP production.

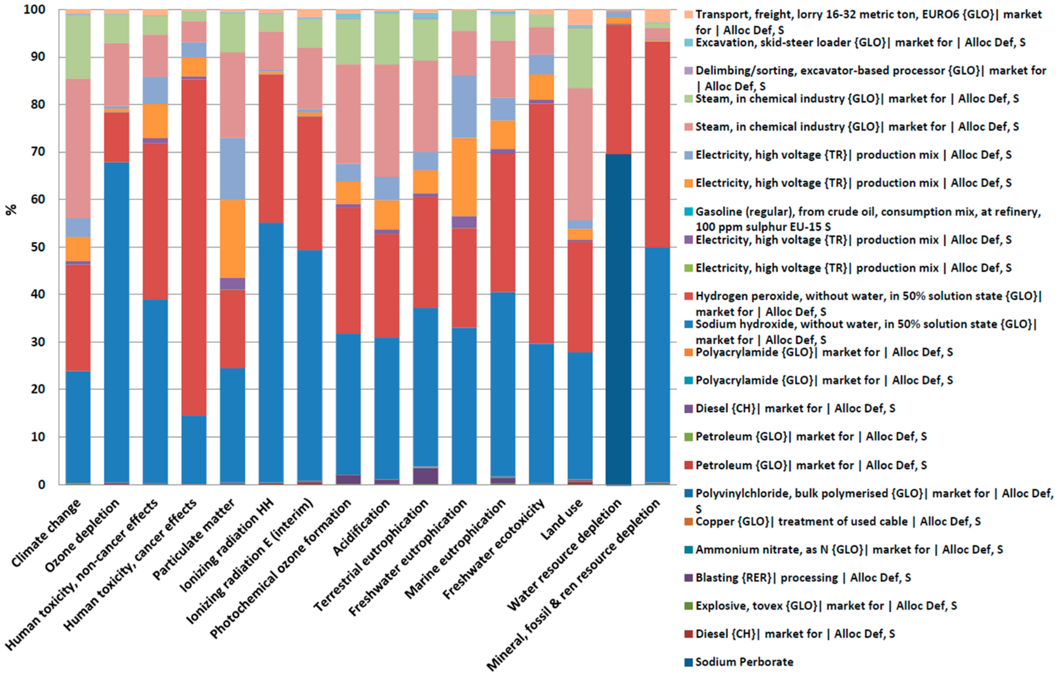

Figure 8. Characterized LCIA results for 1 ton of SP production.

Human toxicity can be classified as cancerous or non-cancerous. According to the results for human toxicity using the ILCD method, it is one of the largest impact categories from the analysis of all refined boron products (non-cancerous effects). For BA, steam, electricity, and sulfuric acid lead to detrimental human health effects. For BD and BP, steam and electricity have the highest impact. Finally, for SP, H_2O_2 and NaOH have the largest impact on the human toxicity impact category.

Terrestrial, freshwater, and marine eutrophication are investigated together in the **eutrophication** category. For BA, sulfuric acid is responsible for causing eutrophication. For BD and BP, steam and electricity are both responsible for eutrophication. For SP, H_2O_2, NaOH, and steam have the highest impact on the eutrophication impact category, followed by electricity.

According to the ILCD method, **ecotoxicity** is classified as freshwater toxicity. As happened in the other categories for BA, the sulfuric acid used for the refinement process of BA is responsible for freshwater aquatic ecotoxicity. For BD and BP, steam and electricity are both responsible for eutrophication, followed by transportation. Similar to the other categories for SP, H_2O_2 and NaOH have the largest impact on ecotoxicity, as well.

Land and water use is the least impactful category. However, a few environmental effects are evident from the analysis of the results. Sulfuric acid has an impact on land use for BA. For BD, BP, and SP, steam has the largest impact.

Sulfuric acid has a major impact on the **fossil fuel category** for BA. For BD and BP, transportation and steam have the largest impact. Similar to the other categories for SP, H_2O_2 and NaOH have the largest impact on this category, as well.

4. Discussion

To ensure the accuracy of the collected datasets from the literature, the uncertainty analysis of LCI datasets for three mining steps was conducted based on the ILCD method, and the Monte Carlo technique was used. The impact assessment was calculated 3000 times. The uncertainty analysis was performed up to 95% of confidence level and shows the mean, median, and standard deviation. The uncertainty analysis results for BA, BD, BP, SP (including the mining, enrichment, and refining process) are given in Figure 9 in order to more clearly compare the results in the impact categories and uncertainty analyses of the four boron refining products. The Pedigree Matrix is given Table S4 in the Supplementary Materials. The marked categories are ionizing, freshwater eutrophication, land use, and mineral, fossil, and renewable resource depletion.

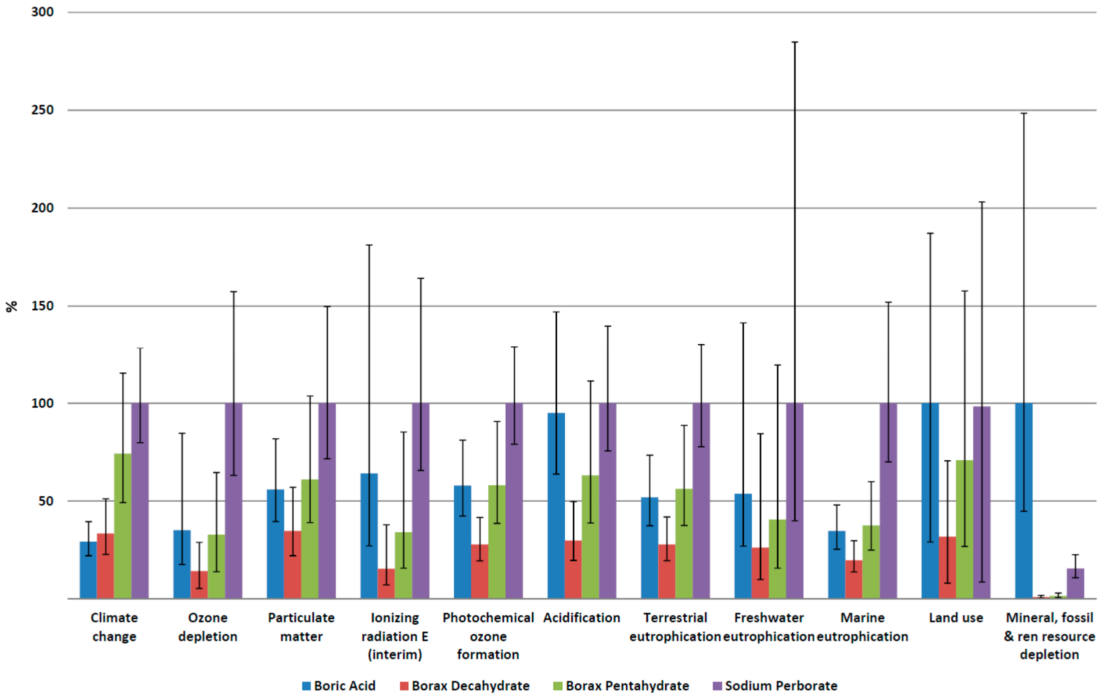

Figure 9. Characterized LCIA results and uncertainty analyses results from the ILCD method.

In the literature, there is a similar study done by Azapagic (1996) [39] concerning the LCA of boron mining for BA, BD, and BP. They employ the mid-point approach of Heijungs et al. (1992) [40], which corresponds to the CML 1992 method [41]. Azapagic's Ph.D. thesis [39] was used for the comparative study with the literature. Azapagic created the inventory using certain data from Borax-Europe Ltd. Company in the UK. However, these datasets were given in Volume II of Azapagic's Ph.D. thesis, which is made available only under special permission from Borax-Europe Ltd. Company. As we were not granted such permission, the inventory of the present study could not be compared with Azapagic's inventory.

In Figure 10, the present study (a) and the study of Azapagic are given to highlight if the final boron products (BD, BP, and BA) are the same; the origin of the source borate minerals to produce the final products are not same. Therefore, we also compare the environmental impacts of the different processes to obtain the same final products.

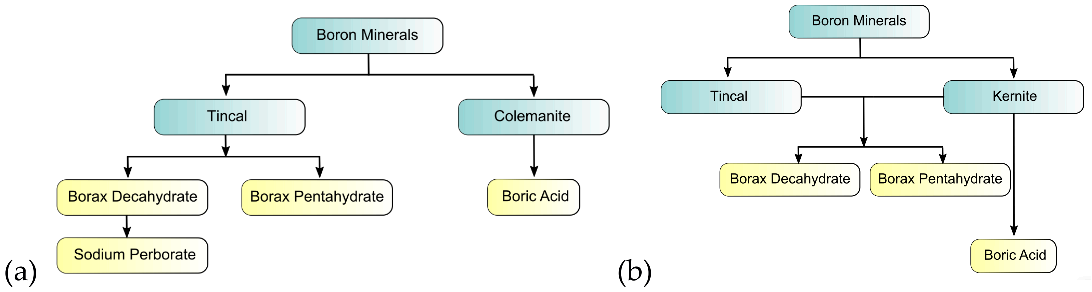

Figure 10. The source borate minerals in the present work (**a**) and Azapagic's work (**b**).

The data sets in the inventory of our study for BA, BD, and BP were reanalyzed using the CML 1992 method instead of the ILCD 2011 Midpoint+ LCIA method. Thus, the same method used by Azapagic was used and the data were compared. Although we employed the same method, the reference quantities of Azapagic's results on some impact categories are different from the ones of this study. For this reason, only a few impact categories (greenhouse, ozone layer, and acidification) were considered and compared, see Figure 11. The results are similar in the category of greenhouse and acidification (except the greenhouse impact of BP). On the other hand, there is a big difference between the data in terms of the ozone layer impact category.

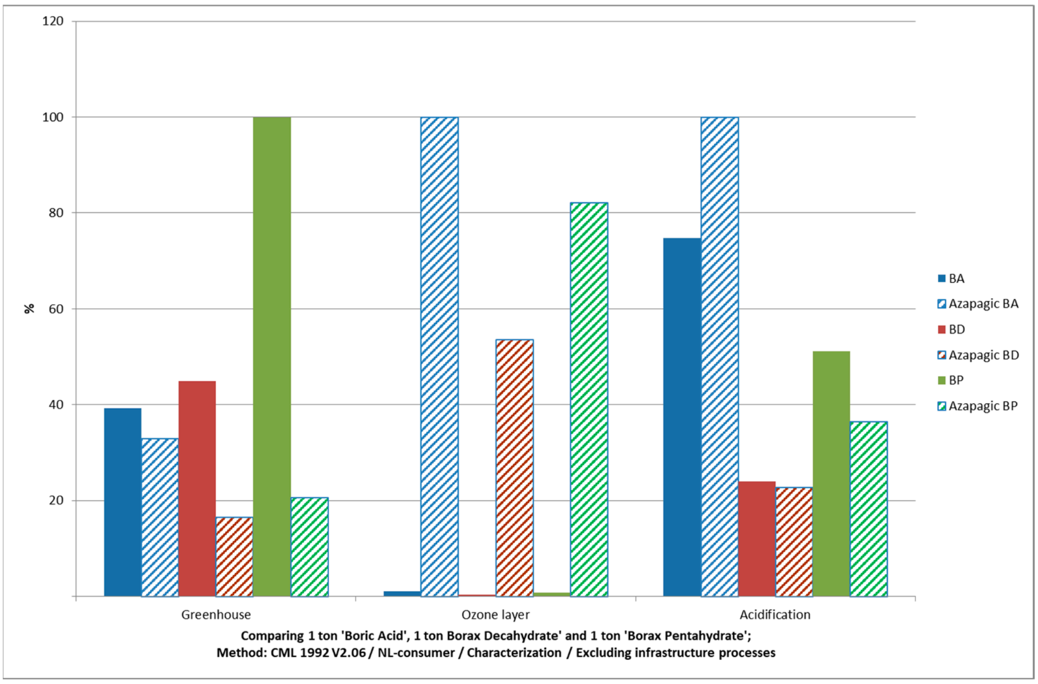

Figure 11. Characterized LCIA results with the CML 1992 results of BA, BD, and BP with the results of Azapagic.

5. Conclusions

In this study, the environmental impacts of four different refined boron products from the extraction stage until the refinement process have been assessed using LCA based on data from the Eti Maden mining company. Literature sources and reports from the company were used to estimate the LCI and therefore quantify environmental impacts.

The majority of inventory data collected is from governmental sources. However, some data are based on assumptions such as transportation, water consumption, and waste. They have been estimated based on similar data of different processes.

This LCA study allows the evaluation of potential environmental impacts of boron mining. The proposed approach can be used in further LCAs to reduce environmental impacts. In addition, this study will contribute to the LCA studies of products containing boron.

In conclusion, the LCA analysis based on the ILCD 2011 Midpoint+ LCIA method shows that the refinement process has the greatest environmental impact. The contributions of this study are to show that boron refining is the most energy-intensive process which leads us to conclude that boron refining has a significant environmental impact. Moreover, we carried out a comprehensive LCA applied on the boron mining, beneficiation, and refining processes, which identified the key environmental impact categories affected by boron mining processes. We expect that our LCA for boron mining processes will be of interest to environmental scientists and engineers who invest their effort in reducing the emissions from the boron mining processes. Further plans of our research involve an extension of this study by conducting an uncertainty analysis, as well as a renewable energy integration analysis using different sources of energy, like biomass, solar photovoltaic, and hydropower.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14031787/s1, Table S1: Life cycle inventory for boric acid inputs. Table S2. Life cycle inventory for borax pentahydrate, borax decahydrate, and sodium perborate inputs. Table S3. Impact assessment of 1 ton boric acid, borax decahydrate, borax pentahydrate, and sodium perborate production (characterization), Table S4. The Pedigree Matrix.

Author Contributions: Conceptualization, B.L. and T.T.; methodology, B.L.; software, B.L. and T.T.; validation, B.L. and T.T.; formal analysis, T.T. and B.L.; investigation, A.Ç.; resources, B.E.; data curation, B.E. and S.Ç.; writing—original draft preparation, T.T.; writing—review and editing, T.T.; visualization, B.L.; supervision, B.L.; and funding acquisition, B.L. All authors have read and agreed to the published version of the manuscript.

Funding: This paper has been produced benefiting from the 2232 International Fellowship for Outstanding Researchers Program of TÜBİTAK (Project No: 118C219). However, the entire responsibility of the paper belongs to the owner of the paper. The financial support received from TÜBİTAK does not mean that the content of the publication is approved in a scientific sense by TÜBİTAK.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BA	Boric Acid
BD	Borax Decahydrate
BP	Borax Pentahydrate
kg CO2 eq	Carbon Dioxide Equivalent
kg CFC-11 eq	Ozone Depletion Potential OZDP kg CFC-11 Equivalent
CTUh	Comparative Toxic Unit for Humans
kBq U235 eq	Unit for Ionizing Radiation Described in Kilo Becquerel

	U-235 Equivalent
kg NMVOC eq	Non-methane Volatile Organic Compounds Equivalent
Molc N eq	Mole of Nitrogen Equivalent
kg P eq	Kilograms of Phosphorus Equivalent
kg N eq	Kilogram of Nitrogen Equivalent
CTUe	Comparative Toxic Unit for Ecosystems
kg C deficit	Kilograms of Carbon Deficit
m^3 water eq	Volume of Water Equivalent
kg Sb eq	Kilogram of Antimony Equivalent
MJ	Mega Joule
SP	Sodium Perborate

Appendix A

Table A1. The usage sectors of boron products.

Usage Industry	Usage Area
Military and armored vehicles	Armor plates, ceramic plates, firearm barrels, etc.
Glass	Borosilicate glasses, laboratory glasses, aircraft glasses, boron glass, pyrex, insulated glass fiber, textile glass fiber, optical fibers, glass ceramics, bottles, other float glasses, automotive glasses, etc.
Electronics and Computer	Current plates, heat-wear resistant fiber optic cables, semiconductors, vacuum tubes, dielectric materials, capacitors, delayed fuses, microchips, LCD screens, CD drivers, electrical capacitors, batteries, laser printer toners, cell phones, modems, televisions, etc.
Energy	Storage of solar energy, solar cells, fuel cells, etc.
Photography and Vision Systems	Camera, lenses, cameras, and binoculars.
Pharmaceutical and Cosmetics	Disinfectants, antiseptics, toothpastes, lens solutions, colognes, perfumes, shampoos, etc.
Agricultural	Biological growth and control chemicals, fertilizers, pest-plant killers, weeds, etc.
Chemical	Reduction of some chemicals, electrolytic processes, flotation drugs, bath solutions, catalysts, petroleum paints for waste cleaning purposes, non-flammable and non-melting paints, textile paints, adhesives, cooling chemicals, corrosion inhibitors, ink, paste and varnishes, matches, lime inhibitors, disinfectant liquids, soap, powder detergents, powder whiteners, brighteners, embalming, etc.
Construction	For enhancing strength and insulation of cement
Protector	Wood materials, wood preservatives, dryers of paint and varnish
Nuclear	Reactor components, neutron absorbers, reactor control rods, safety purposes in accidents, and nuclear waste storage
Space and aviation	Friction-abrasion and heat resistant materials, rocket fuel, satellites, planes, helicopters, zeppelins, balloons, etc.
Medicine	In osteoporosis treatment, allergic diseases, psychiatry, bone development, and magnetic resonance imaging devices
Automotive	Airbags, hydraulics, plastic parts, metal parts, oils, antifreezes, etc.
Metallurgy	In the coating industry, stainless and alloy steel, abrasion-resistant materials, abrasives, etc.
Paper	As a whitener
Sports equipment	Ski equipment, tennis rackets, fishing rods, golf clubs, impact protectors, etc.
Textile	Heat resistant fabrics, fire retardant, preventive cellulosic materials, isolation materials, textile dyes, leather colorants, artificial silk polishing materials, etc.

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