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Estimation of the Turkish Boron Exportation to Europe

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Abstract: Borate is an essential material to numerous industries and even to individual countries' economies, defense, and politics. Almost all industries need borates for production, and almost everybody needs their products. Borate is a compound that contains or supplies boric oxide (B_2O_3). Among the minerals that contain boric oxide, there are only four minerals significant from an economic standpoint, namely borax (tincal), colemanite, ulexite, and kernite. Turkey has almost 70% of all known reserves in the world. Therefore, borates and their products could be one of the main topics for sustainable development in the whole world. The recent development and pursuit of new boron-consuming technologies and alternative products to existing borate-consuming products introduce additional uncertainty to the sustainability of boron minerals. Therefore, the European Union (EU) Commission also declared borate one of the 30 critical raw materials. Turkey is a prosperous country in terms of boron reserves, and it exports almost 96% of borates' production. In order to better understand the relation between borate minerals and borate products, a material flow analysis (MFA) study has been carried out within the content of this work in order to update the data about the current status of boron. For this purpose, a system has been established that shows the flow of boron material. The extraction, enrichment, and refining processes of boron products are drawn. The results indicate that about 41% of extracted colemanite ore is converted into refined borate, about 31% of tincal ore is converted to refined borate, and 4% of tincal ore is converted to end-usage products, such as detergent. The correctness of the data and the sensitivity of the processes are all estimated values. The results can help in the development of boron sustainability and boron production strategies. The MFA study on tincal and colemanite ore may be an example of boron studies in different countries.

Keywords: borate; material flow analysis; boron process; criticality assessment

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1. Introduction

1.1. What Is Boron?

In the last decades, the demand for metals, minerals, and natural materials rose significantly due to continuing global industrial and technological development. Those raw materials that are the most important economically and have a high supply risk are called critical raw materials. In 2020, the EU Commission listed critical raw materials for the EU. The list contains 30 materials, and borate is on the list [1].

Borate is defined as any compound that contains or supplies boric oxide (B_2O_3). Borates were first used over 4000 years ago in precious metalworking and are now essential components of modern industry. Although borates can be obtained from many minerals containing boric oxide, there are only four minerals: borax, colemanite, ulexite, and kernite, used worldwide as the primary commercial sources of borate. The most important continental borate deposits are found in Turkey, the USA, Argentina, Chile, Peru, and China.

Boron mineral is a rare element and belongs to the group of nonmetals [2]. Boron mineral was determined to be among the "critical" 26 minerals, according to Diemer [3]. Boron mineral was designated as "important," as it was categorized as a mineral needed for the economy, according to a review of criticality studies conducted by Jin et al. [4]. According to the study of Henckens et al. [5], boron can be referred to as a geologically scarce resource.

Although boron is a rare and disorderly located mineral on earth, it is economically measurable. It is one of the least found elements in nature. There are more than 250 types of boron minerals in the world. However, only the four borate minerals—colemanite, kernite, tincal, and ulexite—account for 90% of the borate minerals used by industry [2,6]. Although the term "boron" is commonly referenced, it does not occur in nature in an elemental state. Boron combines with oxygen and other elements to form boric acid, or inorganic salts called borates. Boron compounds, chiefly borates, are commercially important; therefore, boron products are priced and sold based on their boric oxide (B_2O_3) content, varying by ore and compound and by the absence or presence of calcium and sodium.

The majority of boron reserves are found in Turkey, the USA, and Russia. Besides these regions, it is known that there are other reserves in Peru, Argentine, China, and Bolivia. Turkey has the highest portion of the world's boron reserves. However, reserve estimates reported for the boron mineral by respective institutions have a wide range. There is also a significant difference between previously reported and updated values [7]. World totals cannot be calculated because production and reserves are not reported consistently by all countries [8].

The global supply of borates is dominated by just two producers. The first one is the state-owned ETI Maden, a monopoly on the world's largest deposits in Turkey. ETI Maden supplies almost half of the global market. The second one is the U.S. Borax of America, which operates a boron open-cut mine in the U.S.A. Borax in the U.S. (~30%) and ETI Maden of Turkey (>50%) account for approximately 80% of the total global market share.

U.S. Borax's boron mine produces approximately 1 million tons of refined borate every year, such as borax pentahydrate, borax decahydrate, and boric acid from boron minerals, mainly tincal and kernite. Their fusing plants also produce anhydrous borate products from borax decahydrate. Eti Maden's refined production for the year 2019 was more than 2 million tons, and almost 95% of it was exported. Approximately 70% of Eti Maden ore reserves are colemanite, and 25% of reserves are tincal.

Henckens et al. [9] have studied primary boron substitution, recycling, and efficiency and sustainability in sectors. Boron is a hardly recyclable product. Furthermore, the substitution of boron can be high in cost, which varies in different sectors. The material efficiency and the production process of unsustainable products should be improved. As boron is a nonrenewable resource and defined as critical material, its flow, based on supply, should be investigated.

1.2. Supply Chain and Applications of Boron

For international trade, the World Customs Organization has developed and maintained a commodity identification code known as the Harmonized System Code (HS Code), and 207 countries use these codes to define their products. Every product exported or imported from a country is given an HS Code. The HS is a classification system comprised of 21 sections and 96 chapters. Each chapter is denoted by a 2-digit code, further divided into several 4-digit codes, called headings. These headings (4-digit code) are subdivided into 6-digit codes, which are called sub-headings [10]. HS Code 28 defines inorganic chemicals as organic or inorganic compounds of precious metals, rare-earth metals, radioactive elements, or isotopes. HS Code 25 defines salt–sulfur as earth and stone, and plastering materials, lime, and cement. The international trade of boron products is classified into three sub-classifications as HS2528-Borax, HS2810-Boron, and HS2840-Borates. The flow of refined borate products from boron minerals to their usage area with their HS codes is given in Figure 1.

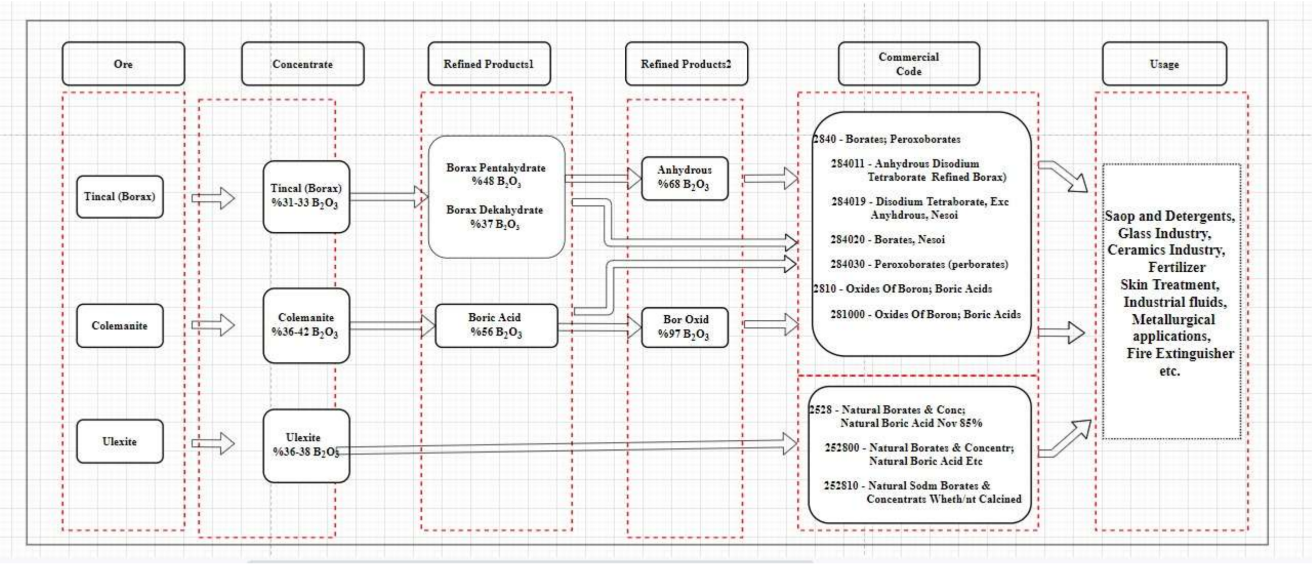
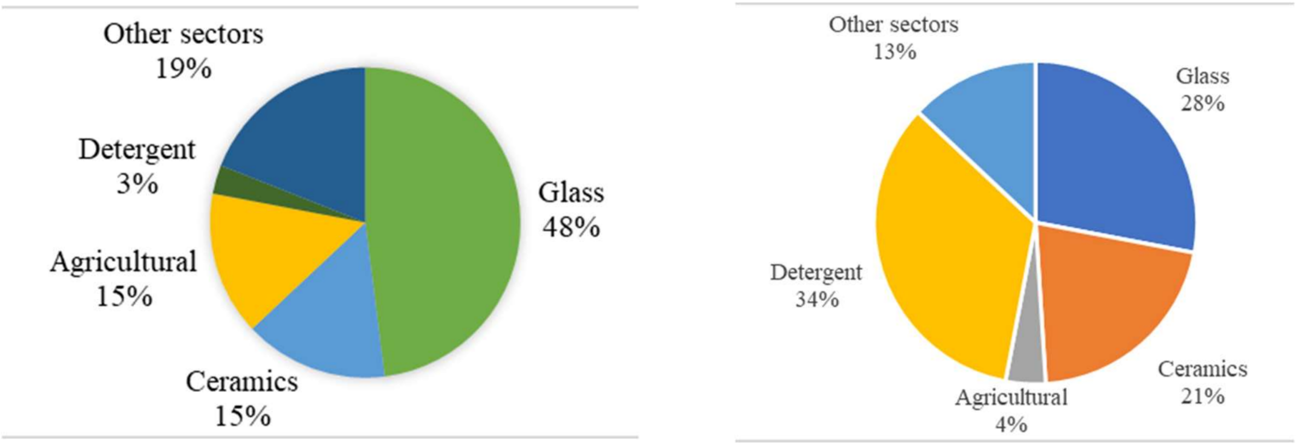


Figure 1. Flow of Boron minerals to usage area.

Approximately 86% of the boron in the world is consumed in four main sectors: glass, ceramics, detergents, and fertilizer. If we look at the distribution of boron products in the world, it is seen that 48% is consumed in the glass sector, 15% in the ceramics sector, 15% in the agricultural sector, 3% in the detergent sector, and the remaining 19% in other sectors (Figure 2a). The most important market of boron is the production of glass fiber. It is also used in products such as borosilicate glasses, LCD glasses, et al. In day-to-day products, boron finds application as composites used in car body panels, in LCD screens, in insulation grade materials, in glass wool for loft insulation, and in other products in the form of ferroboron, borosilicate glass, and fiberglass. The high rate in the glass and ceramics sector directly affects boron usage [11].



(**a**) (**b**)

Figure 2. (**a**) Usage of boron in the world and (**b**) usage of boron in Turkey.

When sectoral usage is examined in Turkey, it is seen that boron is used 28% in the glass sector, 21% in the ceramics sector, 4% in the agricultural sector, 34% in the detergent sector, and 13% in other sectors (Figure 2b). Detergent constitutes the highest rate of domestic use. It is used by converting it into etimatic, which is a tincal–boron detergent product extracted at the Eskisehir–Kirka plant [11].

1.3. Challenges

The challenge today in the extraction and production of boron is obviously the optimization of profits on the one hand (for producers) and the supply of raw materials on the other (for consumer countries).

Today, Europe identifies boron as a critical mineral, especially since Europe mainly consumes boron from Turkey (the world's largest reserve ahead of the USA). Our study, therefore, focuses on identification and an update of boron exports, but also the differentiation of exports between the different types of boron (tincal, ulexite, and colemanite).

Based on the methodology of material flow analysis, we want to provide extraction data on delivery to Europe and the world of boron from Turkey.

These data can be useful for various studies and, in particular, for life-cycle analysis studies or input–output-type economic studies.

2. Materials and Methods

2.1. Materials Flow Analysis

The MFA method aims to determine the past and current flows of materials and produce alternative scenarios for the future. It also helps us to do an economic analysis of the changes in the process of materials. Important points are determined, and the criticality and life cycle of the system are easily explained using this method. It is known that MFA is also frequently used in sustainability and criticality studies in the literature [12–15]. MFA consists of four main steps as a system framework, data collection, calculation, and interpretation. The study has been carried out using the software STAN 2.5 [16] developed by the Technical University of Vienna, Vienna, Austria [17,18].

Today, nobody proposed to study and/or to update the data of boron and most of them come from the USGS (the American Geological Survey) and ETI Maden (the Turkish Government Mining Company, Ankara, Turkey). However, many limitations can be identified. To use boron as a reference can be a mistake, and it would be better to explore and propose an MFA for tincal, colemanite, and ulexite because it is plausible that one of them is more critical than another one.

Extensive desk research was used to collect data on boron fluxes. Boron flux quantification is calculated with the best available estimates due to insufficient and unreliable data. Thanks to government documents, data from scientific articles, and from national and international databases, it is possible for us to identify the volumes of boron potentially exported from Turkey to Europe.

2.2. Scope of the Data Collection

The goal of our study is to update the data and understand the flows of Turkish mining to the exportation stage. Also, boron is almost non-recyclable. Henckens' and others' [9] study about boron stated that the recycling in the life cycle was less than 1%. For this reason, recycling in boron material-flow has been ignored. Boron is also at the forefront of substitute products and material efficiency instead of recycling.

If we were to create an MFA in general terms for boron, it would have been divided into four processes [11,18]. These processes are:

(1) The Mining: Mining is the process of extracting boron ore from the ground. Boron minerals are extracted by means of open-cut operations. Along with the minerals, a significant amount of overburden is also extracted.

(2) The Mineral Processing: The run of the mine is crushed and cleaned in order to remove non-boron materials before refining. For borax (tincal) minerals, this step is only crushing. For other minerals, this step includes crushing and removing non-boron minerals in order to have enriched boron minerals, known as concentrate.

(3) The Refining: At this stage, different refined boron products are produced, employing different processes such as dissolving, crystallizing, filtering, drying.

(4) The Usage Process: This is the process that enables the finished products to be transferred to the necessary sectors [11,18].

Addressing these processes ensures the standardization and comparison of data. Figure 3 shows the generic frame of MFA created for boron with the embedded flow structure. This frame is adapted from Gsodam's and others' study [18], and the description of respective flows is given in Table 1.

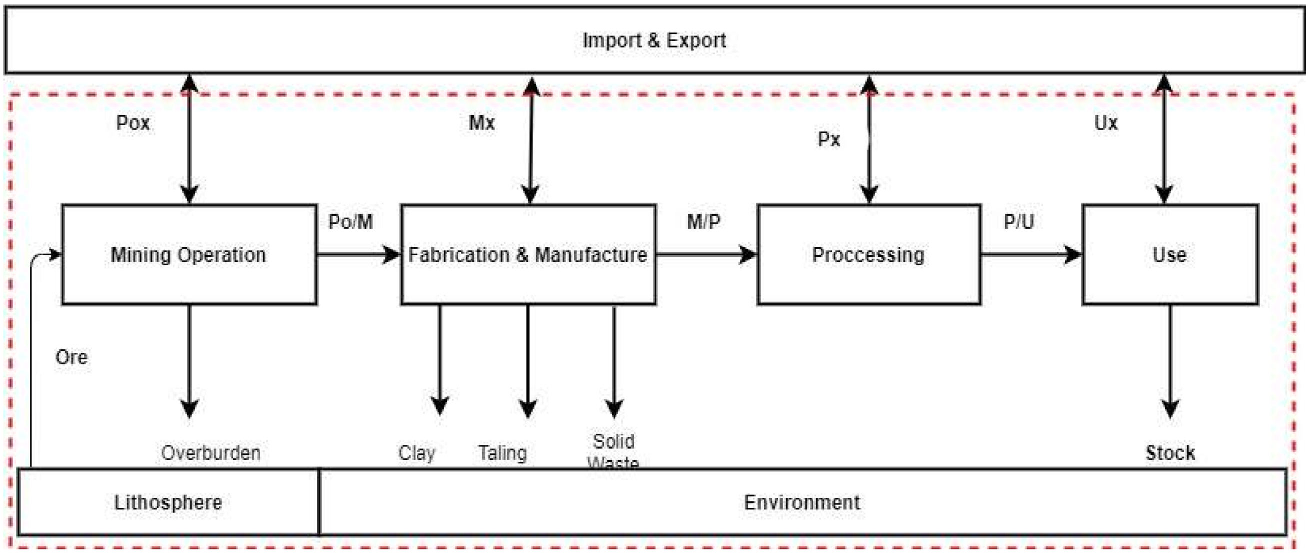


Figure 3. General MFA frame for boron minerals.

Table 1. Flows in the generic MFA framework.

Name	Description
Ore	Boron in ore
Po	Production life stage
M	Fabrication & manufacturing life stage
P	Processing life stage
U	In-use life stage
Pox, Mx, Px, Ux	Respective export and import

2.3. Data Collection

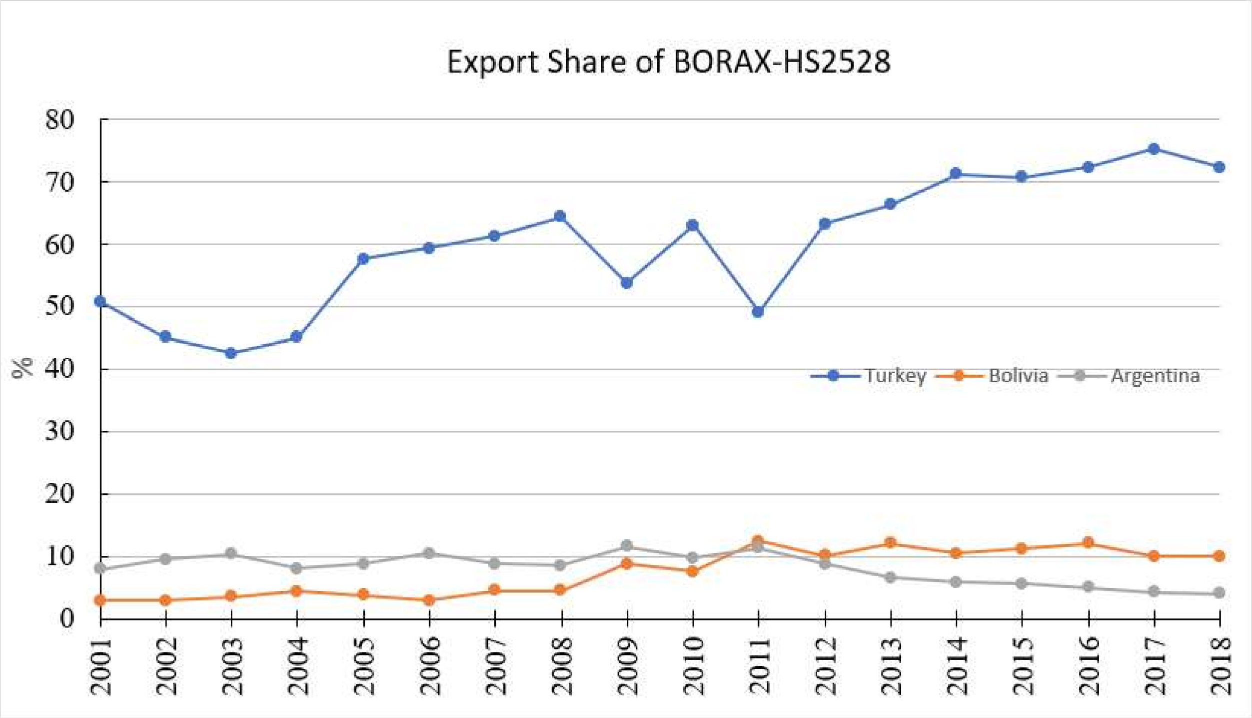
The data used for this study have been extracted from the related web pages. [19] provides the export value of the HS code for boron products. The world trade share of countries is given in Figure 4a–c.

It can be seen from Figure 4 that, as of 2018, Turkey is the biggest exporter of Borax and Borates, at 71% and 45%, respectively. Additionally, Turkey is the second exporter of Boron products. The importing countries are given in Figure 5. As it can be seen in Figure 5, China has the biggest share of importing, at about 30–35% of each boron product. The share of other countries is less than 10%.

The quantity and price of boron products have been obtained from [20]. The value and quantity of each boron product are given on this web page. By using these values, the average price of each boron product is estimated.

$$\text{Average Price} = \text{Total Values}/\text{Quantity}$$

After estimating the average prices of boron products, the total quantity can be estimated.



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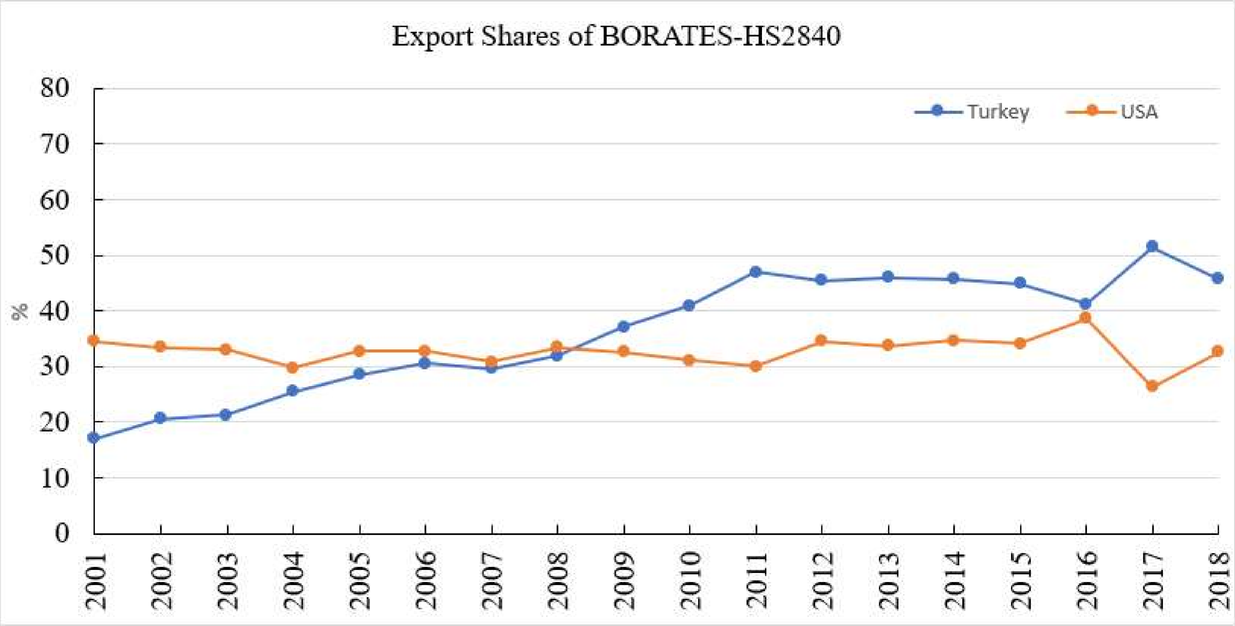
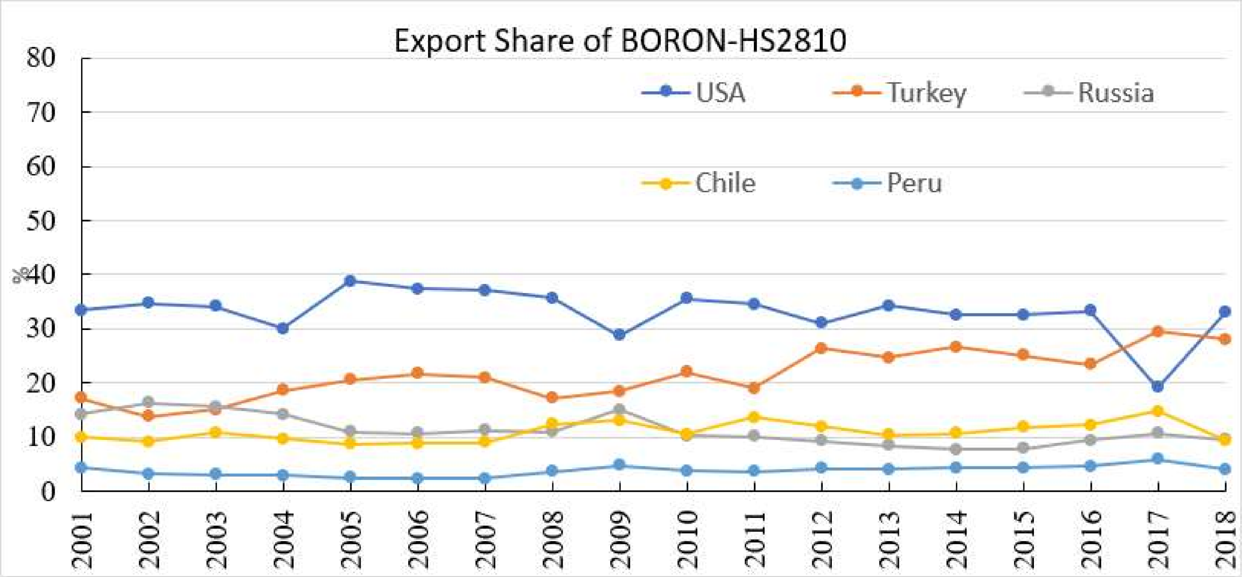


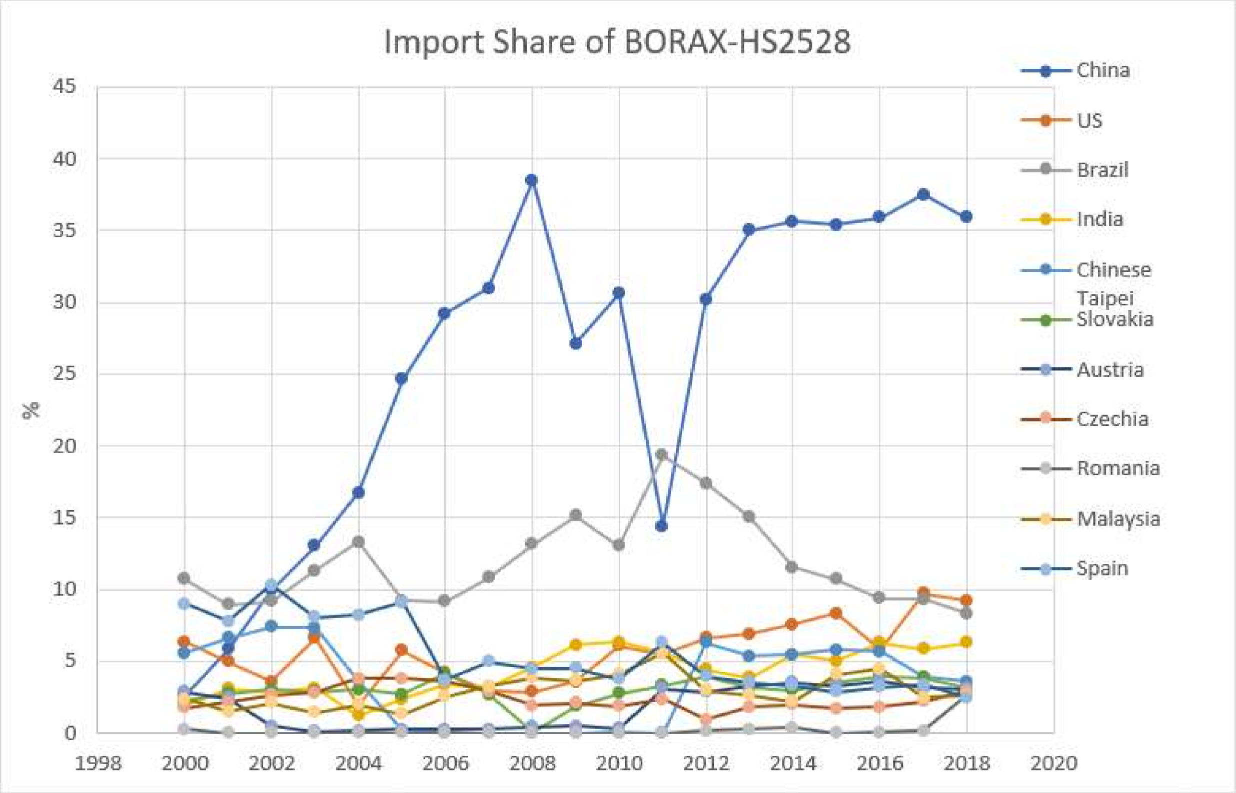
(**b**)

Figure 4. *Cont.*



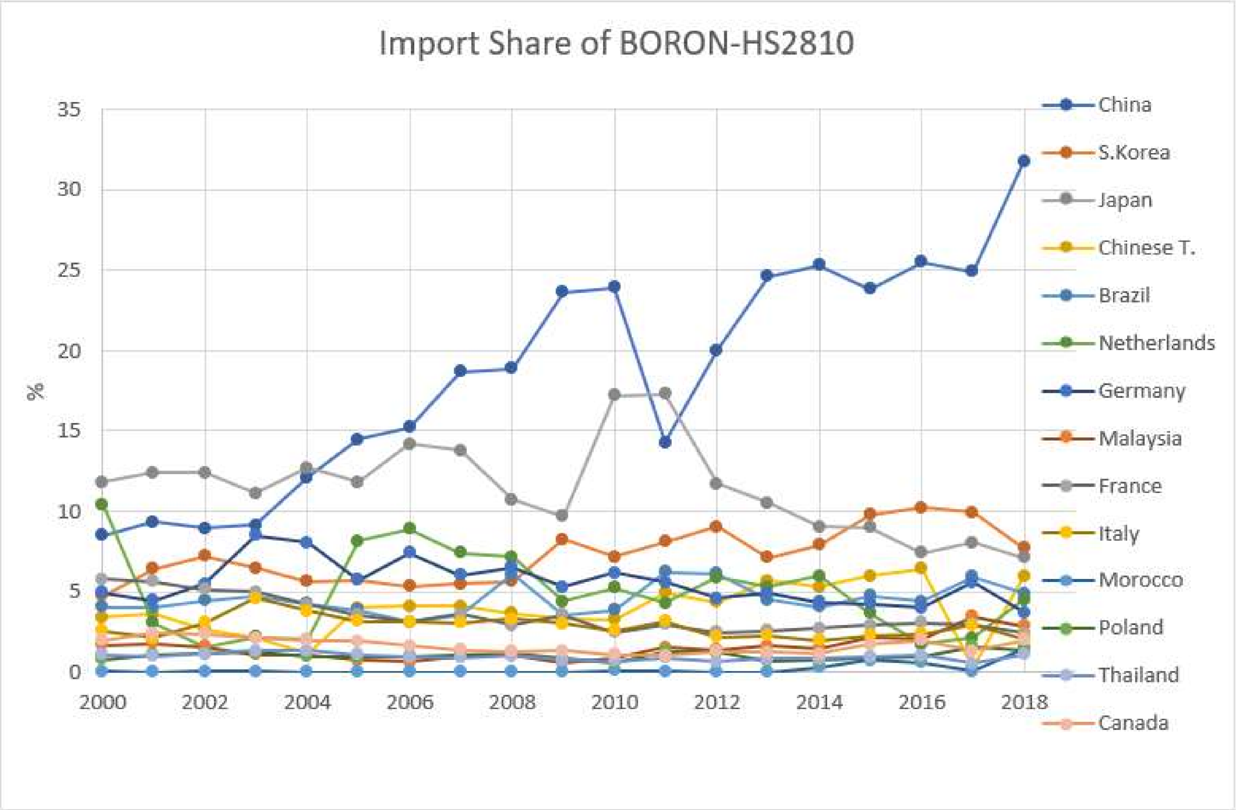
(**c**)

Figure 4. Boron products' exportation. (**a**) Export Share of BORAX-HS2528; (**b**) Export Shares of BORATES-HS2840; (**c**) Export Share of BORON-HS2810.



(**a**)

Figure 5. *Cont.*



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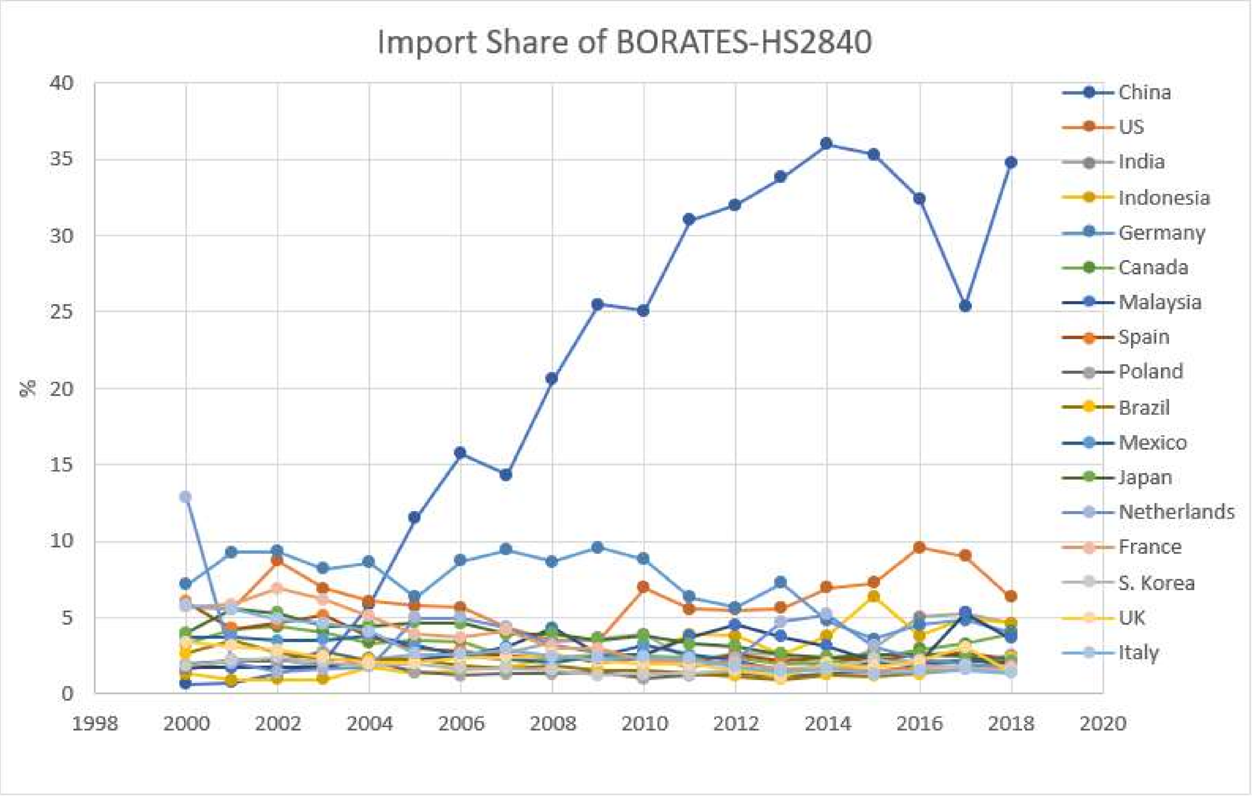

(**c**)

Figure 5. Boron products' import share of countries. (**a**) Import Share of BORAX-HS2528 (**b**) Import Share of BORON-HS2810 (**c**) Import Share of BORATES-HS2840.

Boron demand forecasting data have been obtained from [21]. The results are given in Figure 6. As it can be seen in Figure 6, the boron demand for glass fiber will be almost twice by 2024. The increase in other areas is relatively low, at about 25%. Almost 81% of boron products have been used in these four areas: glass fiber, ceramics, agriculture, and detergent. The total demand for these will be about 2 million tons. After adding the other usage, the total demand for boron products will be 2.4 million metric tons. That means the total demand for boron products will increase about 25% by 2023.

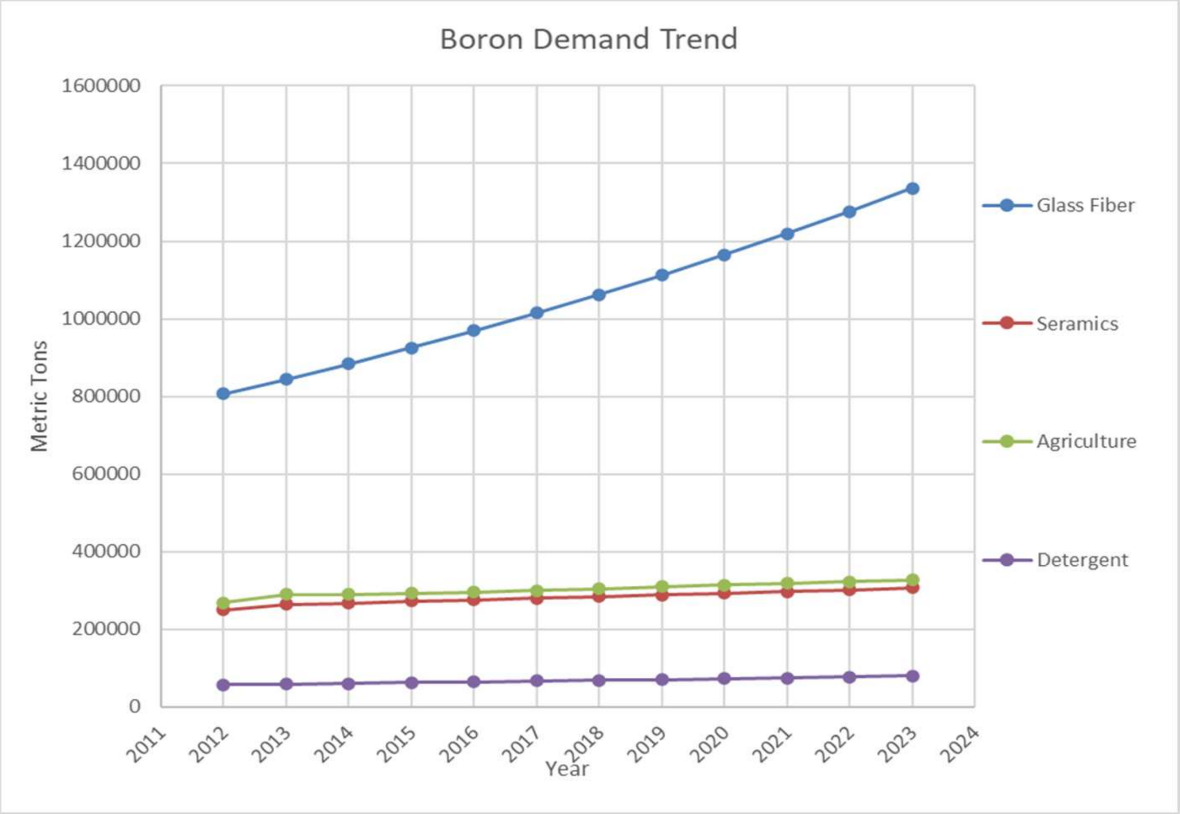

Figure 6. World demand for boron products.

Based on the trade market/price and the materials flow analysis principles (mass balance), we evaluated the quantity in mass.

There are no compatible or reliable data for boron production and boron reserves. According to the given literature, the boron reserves of Turkey is 1.1 B tons, of the USA is 40 M tons, of Russia is 40 M Tons, of Chile is 35 M tons, of China is 24 M tons, and of Peru is 4 M tons [21]. However, there is no additional information about the amount of borate minerals in situ or the amount of borate products possible that can be obtained. Demand figures are the amount of boron products. All the previous data can be found in the Supplementary Materials.

The question is that in order to obtain one unit of boron products, how many units of boron minerals are needed to be extracted? This depends on the boron minerals and processes. The answer to this question enables us to set up a relationship between reserves and demand.

The aim of the following part of this study is to try to define the relationship between boron minerals and boron products.

3. Results

This study focuses on the production, processing, and usage of boron minerals. There are two boron minerals considered in this study, namely tincal (Borax) and colemanite. The flow of both minerals differs from each other. Therefore, two different MFA have been carried out in this study.

3.1. MFA for Tincal

The tincal ore reserves of Turkey are in Kırka, Turkey. Tincal ore production is estimated to be around 2,500,000 tons, with an overburden ratio of 2.2. The MFA model of tincal ore is given in Figure 7. The model consists of four (4) main processes connected to each other by flows. These processes are mining operation, crushing-dissolving operation, refining process, and production process. Tincal ore is extracted from the ground by means of open-pit mining. The ore, then, must be crushed to reduce the size below 100 mm. Crushed ore is mixed with hot liquor, a combination of borates and water, and dissolved in water before it can be refined. Insoluble rocks, sand, and other solids are removed using screens of about 51% of fed ore. Then, the saturated borate solution is pumped to the refinery. The refinery refines the boron ore into refined borates. As a result of refining, borax pentahydrate and borax decahydrate are produced. Following this operation, some amount of borax pentahydrate is used to produce anhydrous borax with another process. Borax decahydrate is used to produce detergent as an end-use product.

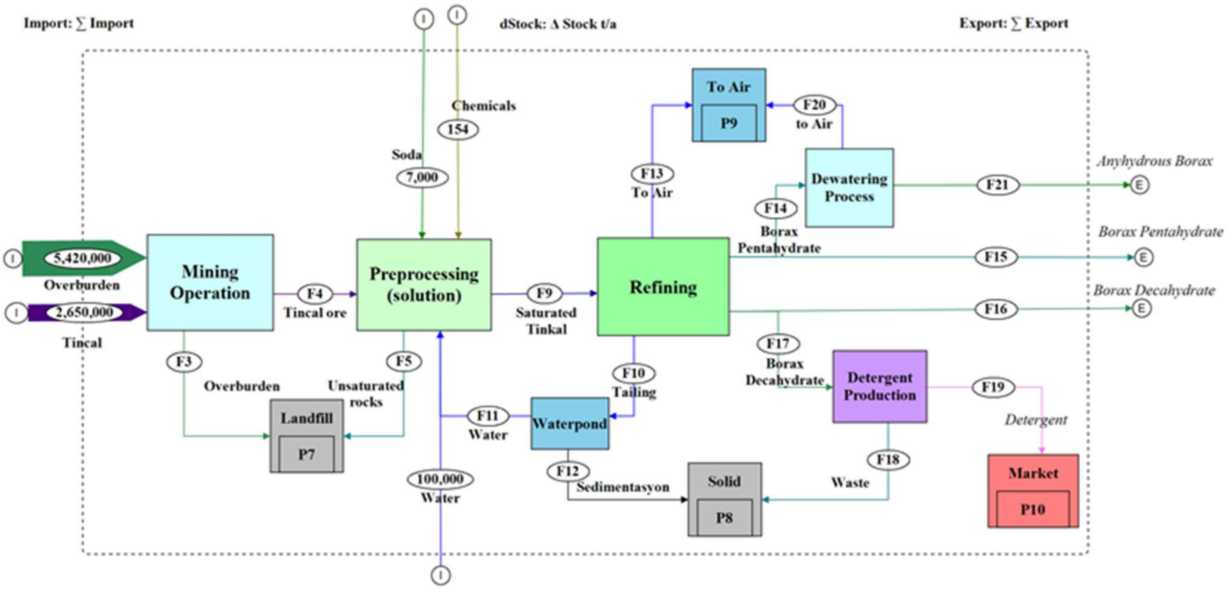

Figure 7. MFA modes of tincal and the processes and flows.

The input of the system is tincal ore, water, soda, and some chemicals. The input–output ratios of each process are reconciled values obtained from the literature with some estimation. The results of the MFA performed with STAN 2.5 are shown with the Sankey diagram in Figure 8. The width of the flows is proportional to the numerical values of the flows.

The MFA of tincal ore indicates that almost 25% of extracted ore is converted to a refined product (19% of it borax pentahydrate and 5% of it anhydrous borax), and 5% of it is used to produce end-use products, such as detergent.

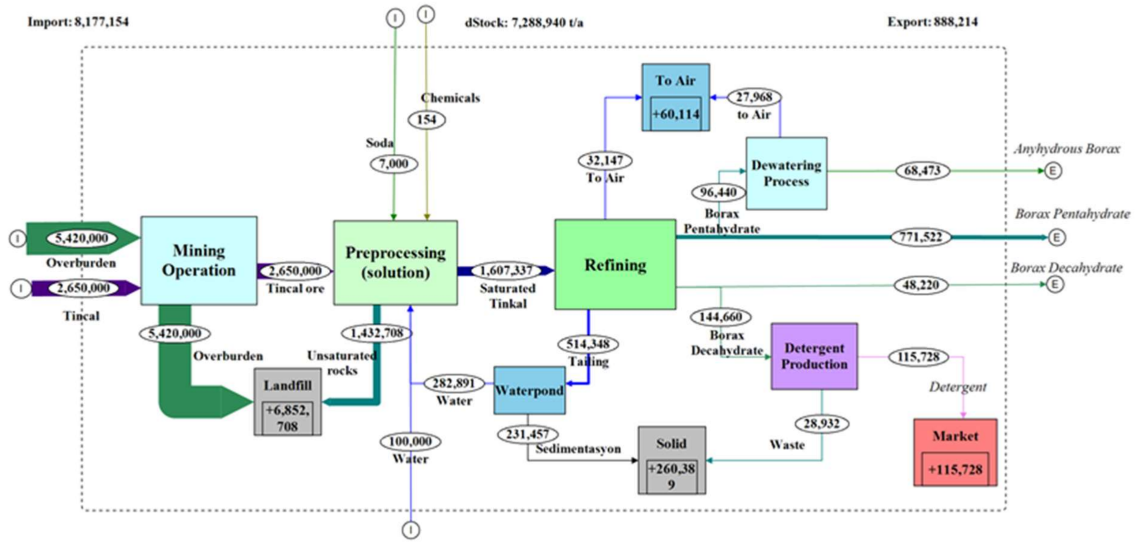

Figure 8. Tincal ore MFA model structure and respective flows are shown in the Sankey diagram.

3.2. MFA for Colemanite

The colemanite ore of Turkey is in Bigadic and Emet. Mined ore is sent to the concentrator to be enriched. The enriched ore is classified into three sizes: −3 mm, +3–25 mm, and +25–100 mm. The concentrate of +3 mm is sent either to the boric acid factory or to sale. Colemanite ore production is estimated to be around 2,240,000 tons, with an overburden ratio of 2.2. The MFA model of colemanite ore is given in Figure 9. The model consists of four (4) main processes connected to each other by flows. These processes are mining operation, mineral processing operation, and production process. Colemanite ore is extracted from the ground by means of open-pit mining. The mineral processing operation consists of crushing, screening, washing, and classification sub-processes. The output of the mineral processing process is concentrated colemanite. Concentrated colemanite is used for direct sale as a concentrate and sent to the boric acid facility to produce boric acid (Figure 9).

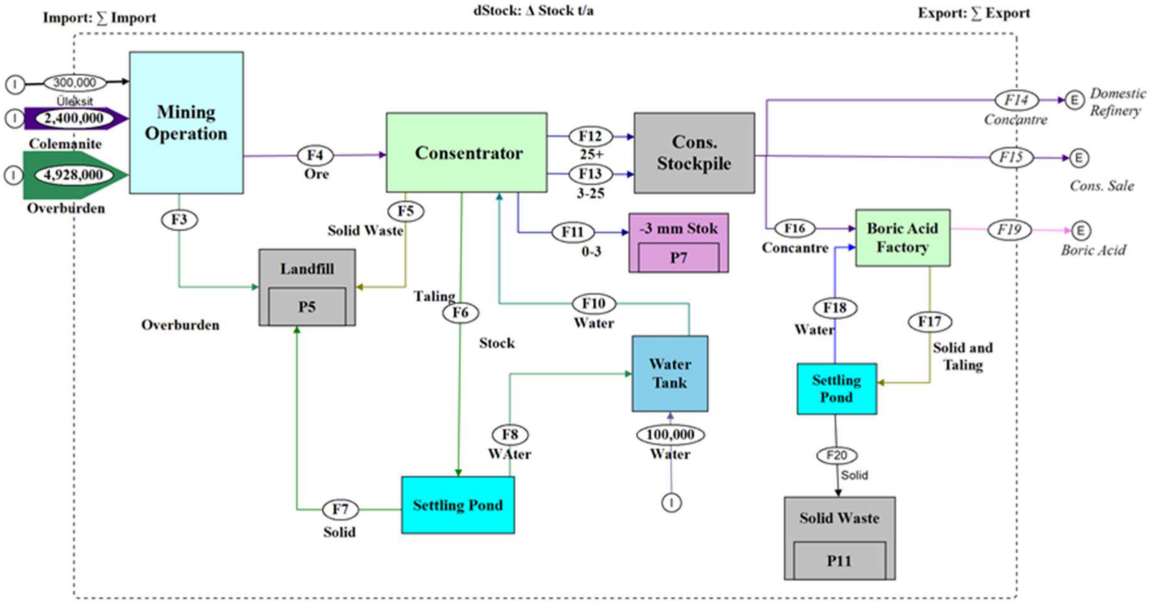

Figure 9. MFA modes of colemanite and the processes and flows.

The input of the system is colemanite ore and water. The input–output ratios of each process are estimated values obtained from the literature. The results of MFA performed with STAN 2.5 are shown with the Sankey diagram in Figure 10. The width of flows is proportional to the numerical values of the flows.

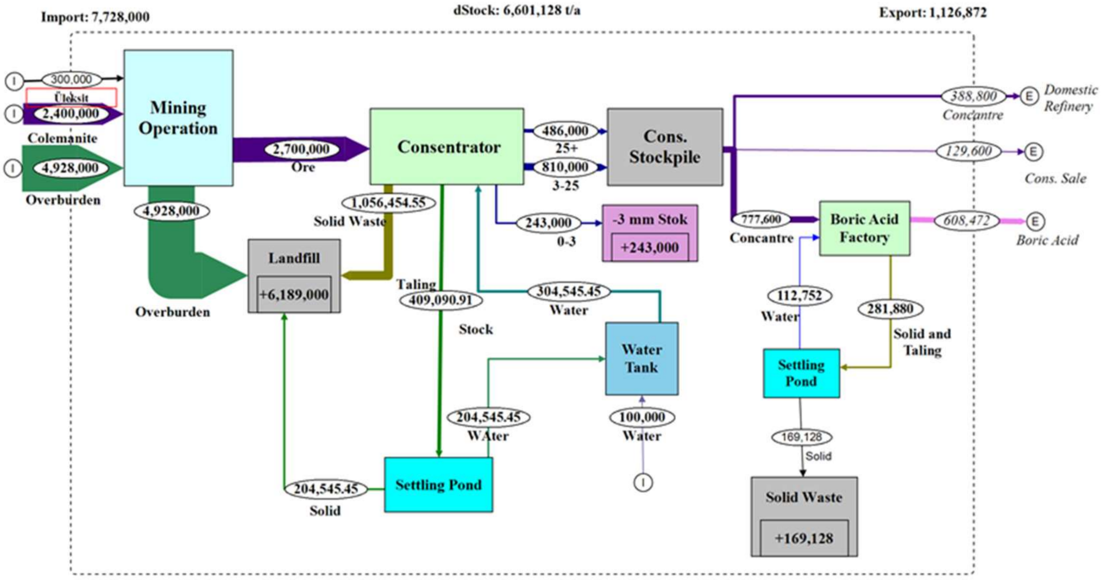

Figure 10. Colemanite ore MFA model and respective flows are shown in the Sankey diagram.

As shown in Figure 10, about 42% of the total ore input to the system comes out as an economical product.

3.3. Global MFA of Boron from Turkey

In 2019, 56% of the world's boron demand was provided by ETI Maden. ETI Maden exports almost 95% of its refined and concentrates' production. Only 5% of the boron production is consumed domestically. The MFA diagram was drawn to show the flow of boron from Turkey to the world (Figure 11). The average of five years (2015–2019) data, taken from the observatory of economic complexity [22], was the export values. HS2840_Borates has the biggest share in export value with 52.6% and 33.3% of the export value coming from HS2528_Borax, and 14.1% of it coming from the sale of HS2810_Boron.

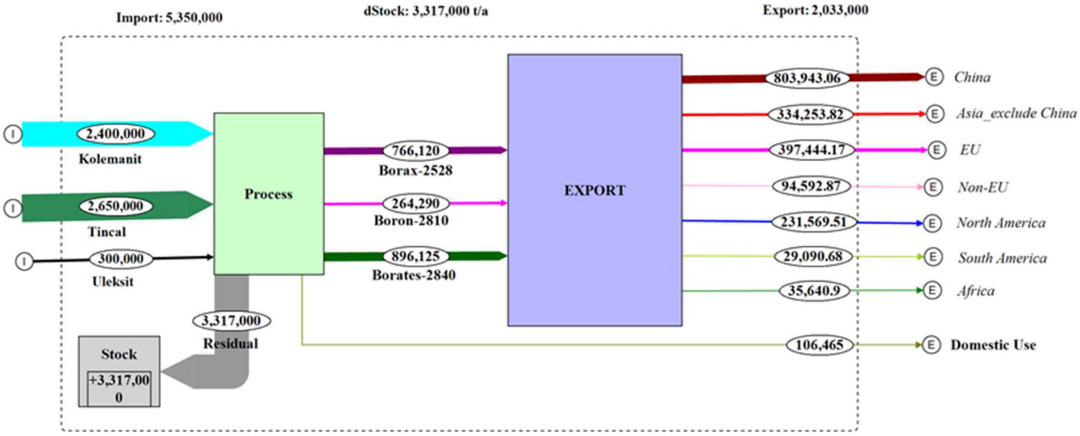

Figure 11. MFA of boron from Turkey to the world.

In order to get the quantity, the approximated prices were used, as given in Table 2. Since the total export value is known, the quantity can be estimated easily.

Table 2. Turkey's boron export for the year of 2019.

	Export Values (×1000, 1000 USD, 2019)									
	Ratio	**World**	**China**	**Asia-Ex. China**	**EU**	**Nom EU**	**N. America**	**S. America**	**Africa**	**Other**
Borax-2528	33.34%	256.80	112.42704	50.17296	48.97775121	8.228352	27.00	3.19	5.458	1.325
Boron-2810	14.04%	108.14	36.291784	24.408216	26.1146351	4.65954176	8.126	2.742	4.364	1.43
Borates-2840	52.63%	405.40	168.88964	57.51036	86.23056	21.0998528	58.40	6.172	4.52	2.58
TOTAL	100.00%	1770.34	317.608464	132.091536	161.322707	33.9877466	93.526	12.104	14.342	5.40
	Estimated Export Amount (Ton, 2019)									
	Price ($/tom)	**World**	**China**	**Asia-Ex. China**	**EU**	**Nom EU**	**N. America**	**S. America**	**Africa**	**Other**
Borax-2528	310	828,387	362,668	161,848	157,992	26,543	87,097	10,290	17,606	4342
Boron-2810	540	200,259	67,207	45,200	48,360	8629	15,048	5078	8081	2655
Borates-2840	450	900,889	375,310	127,801	191,623	46,889	129,778	13,716	10,044	5728
TOTAL		1,929,535	805,185	334,849	397,976	82,060	231,923	29,084	35,732	12,726
Share			41.73%	17.35%	20.63%	4.25%	12.02%	1.51%	1.85%	0.66%

As it can be seen from Table 2, the total value of export is 770.34 million USD, and the total amount of boron is 1,929,535 tons for the year 2019. 33.3% of the export value comes from concentrate boron, which amounts to 43% of the total quantity. 52.6% of export values come from refined boron products.

Turkey exports 20.63% of refined and concentrated boron to the EU, and this is almost 98% of the boron demand of the EU. China is the leading country, with a 41.73% share. Turkey provides 70.5% of Borax_HS2528, 43.4% of Borates HS2840, and 23.3% of Boron HS2810 demand of the world.

4. Discussion and Conclusions

The biggest difficulties in this study were collecting the data, many references propose different values and some of them are contradictory. All Turkish mine facilities are managed by the government and the data collection is, then, extremely sensitive. In this work, there have been many assumptions, especially to estimate the waste generation.

In this study, the MFA for different boron minerals in Turkey was carried out. The results of the MFA reveal that Turkey exports the biggest portion of its different kinds of boron. This resource is exported mostly to China and the European Union. Most of the transformation is conducted outside of Turkey (e.g., the transformation for glass and fertilizers). Moreover, boron cannot be recycled, and the mineral is automatically dissipated [23–26]. One can also mention that the boron resources are concentrated in mostly two countries (Turkey and the USA) and that a geopol-risk indicator could be considered [27].

For two years, boron has been identified as a critical material, and it seems that the management of boron is crucial in order to save the resource for Turkey but also to save the business for a long period. As an example, Norway set a strong petroleum business model in order to have regular benefits for a long period.

However, this study is an important step in order to understand the potential depletion of boron [28] and, also, to understand the dissipation of this resource over the exportation and sectors [29]. Boron recycling is not a question now, as no technology is made to recycle different boron components (e.g., the colemanite extracted from the glass). Today, the main problem of boron is its dissipation and its loss in different sectors and compartments (air, water, and soil). Additionally, this study can help for our future work that consists of the implementation of the abiotic depletion indicator for the life cycle assessment. The methodology presents two main mistakes: the data source (global ore and global extraction) used in order to calculate the characterization factor [30] and, also, the methodology that uses boron as a resource; however, databases like ecoinvent use the boron type (e.g., colemanite, ulexite, et al.), or, in other terms, when one assesses the environmental impact of glass, the impact of boron is not considered.

Additionally, our next work will focus on the estimates of boron production to meet European needs depending on the sectors of activity. This work will identify more precisely the potential depletion of boron in Turkey. The MFA dynamic methodology can be used for this type of estimation, as Panasiuk [31] was able to do for iron.

Moreover, one investigates the quantity and the characterization of the waste generated in order to foresee the potentiality to reuse this waste as a by-product instead of landfilling it and also estimate the volume generated. One can see that in some regions in Turkey, it has produced ceramics with some residues that contain a lot of clay [32] and, also, tile production [33] but it is a marginal production.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/mining2020009/s1, Data for Estimation of the Turkish Boron Exportation to Europe.xls.

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