

Life Cycle Assessment of Boron Industry from Mining to Refined Products

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Table S1. Life cycle inventory for boric acid inputs.

	Input	Output	Amount	Unit	Ref.
Mining inventory for 1 ton of run-of-colemanite	Diesel		0.3769	kgdiesel/tonore	[4]
	Oil		0.0240	kgoil/tonore	[4]
	Dynamite		0.0021	kgdynamite/tonore	[4]
	T.A.N.		0.0454	kgT.A.N./tonore	[4]
	Electric Capsule		0.0028	Piececapsul/tonore	[4]
	Copper (Electric Capsule)		0.00194	gcopper/piececapsul	[5]
	PVC (Electric Capsule)		0.01381	gPVC/piececapsul	[5]
	Energy		0.7017	kWh/tonore	[4]
		Overburden	9.85	tonoverburden/tonore	[2]
Concentrator inventory for 1 ton of concentrate product	Colemanite ore consumption		1.3490	tonore/tonconc	[1]
	Water		4.1797	tonwater/tonconc	[1]
	Diesel		0.4120	kgdiesel/tonconc	[4]
	Oil		0.0417	kgoil/tonconc	[4]
	Electricity		7.4713	kWh/tonconc	[4]
	Water		4.1923	m3/ton/tonconc	[1]
		Water	3.1012	tonwater/tonconc	[1]
		Mineral waste	0.3490	tonwaste/tonconc	*
Refinement inventory for 1 ton boric acid product	Conc. colemanite consumption		1.5	tonconc/tonboric_acid	[3]
	Sulfuric Acid		0.9	tonsulfuric_acid/tonboric_acid	[3]
	Electricity		130	kWh/tonboric_acid	[3]
	Steam		1	tonsteam/tonboric_acid	[3]
	Water		25	tonwater/tonboric_acid	[3]
	Compressed Air		15	m3compressed_air/tonboric_acid	[3]
	Fuel-Oil		48	kmfuel_oil/tonboric_acid	[3]
		Sludge	0.9171	tonsludge/tonboric_acid	*
		Mineral waste	0.4171	tonwaste/tonboric_acid	*

¹ Estimated data are indicated by the * symbol in the reference column.

Calculations for Table S1

(a) Input for Water (in concentrator):

The water used at Bigadiç concentrator facility is 2,250,000 m³/year [1].

The processed run-of-colemanite ore in the concentrator facility is 724,000 ton/year [1].

The produced concentrated colemanite ore is 536,700 ton/year [1].

The water to produce 1 ton concentrated colemanite =
 $(2,250,000 \text{ m}^3/\text{year}) / (536,700 \text{ ton/year}) = 4.1923 \text{ m}^3/\text{ton}$.

(b) Input for run-of-colemanite-ore (in concentrator):

The processed run-of-colemanite ore in the concentrator facility is 724,000 ton/year [1].

The produced concentrated colemanite ore is 536,700 ton/year [1].

The processed run-of-colemanite ore to produce 1 ton concentrated colemanite =
 $(724,000 \text{ ton/year}) / (536,700) = 1.3490 \text{ ton/ton}$.

(c) Output for Waste Water (in concentrator):

The waste water at Bigadiç concentrator facility is 190 ton/hour [1].

Therefore, the waste water $(190 \text{ ton/hour}) \times (24 \text{ hour}) \times (365 \text{ days}) = 1,664,400 \text{ ton/year}$.

The produced concentrated colemanite ore is 536,700 ton/year [1].

The waste water to produce 1 ton concentrated colemanite =
 $(1,664,400 \text{ ton/year}) / (536,700 \text{ ton/year}) = 3.1012 \text{ ton/ton}$.

(d) Output for Overburden (open-pit-mining):

The overburden per run-of colemanite ore at Bigadiç facility is 4.07 m³/ton [2]. The density of run of colemanite ore is 2.42 g/cm³. Therefore the amount of overburden is 4.07 * 2.42 = 9.85 ton/ton.

(e) Output for Mineral Waste (in concentrator):

The processed run-of-colemanite ore to produce 1 ton concentrated colemanite =

$$(724,000 \text{ ton/year}) / (536,700) = 1.3490 \text{ ton (b)}$$

The mineral waste to produce 1 ton concentrated colemanite =

$$(1.3490 \text{ ton run-of-colemanite ore}) - (1 \text{ ton concentrated colemanite}) = 0.3490 \text{ ton/ton. (Assumption)}$$

(f) Output for Sludge and Mineral Waste (refining for sodium perborate):

There is no information about the sludge and mineral waste of boric acid in the literature. Therefore, the assumptions will be done based on borax pentahydrate production.

The processed concentrated tincal to produce 1 ton borax pentahydrate = 2.3 ton

The processed concentrated colemanite to produce 1 ton boric acid = 1.5 ton

The sludge waste to produce 1 ton borax pentahydrate = 1.40625 ton/ton.

The sludge waste to produce 1 ton borax decahydrate =

$$(1.5 \text{ ton}) * (1.40625 \text{ ton/ton}) / (2.3 \text{ ton}) = 0.9171 \text{ ton}$$

The mineral waste to produce 1 ton borax decahydrate =

$$(1.5 \text{ ton concentrated colemanite}) - (1 \text{ ton boric acid}) = 0.5 \text{ ton/ton.}$$

The final mineral waste =

$$0.9171 \text{ ton/ton} - 0.5 \text{ ton/ton} = 0.4171 \text{ ton/ton.}$$

Table S2. Life cycle inventory for borax pentahydrate, borax decahydrate, and sodium perborate inputs.

	Input	Output	Amount	Unit	Ref.
Mining inventory for 1 ton of run-of-tincal	Diesel		0.4318	kgdiesel/tonore	[4]
	Oil		0.019	kgoil/tonore	[4]
	Electricity		0.296	kWh/tonore	[4]
	Dynamite		0.076	kgdynamite/tonore	[4]
	T.A.N.		0.003	kgT.A.N./tonore	[4]
	Electric Capsule		0.002	Piececapsul/tonore	[4]
	Copper (Electric Capsule)		0.0014	gcopper/piececapsul	[5]
	PVC (Electric Capsule)		0.00998	gPVC/piececapsul	[5]
		Overburden	9.77	tonoverburden/tonore	*
Concentrator inventory for 1 ton of concentrate product	Tincal ore consumption		3.306	tonore/tonconc	[1]
	Diesel		0.0940	kgdiesel/tonconc	[4]
	Oil		0.0277	kgoil/tonconc	[4]
	Electricity		11.1995	kWh/tonconc	[4]
	Gasoline		0.0036	kggasoline/tonconc	[4]
	Water		4.4673	m3/ton/tonconc	*
		Water	3.375	tonwater/tonconc	[6]
		Mineral waste	0.4375	tonwaste/tonconc	[6]
		Sludge	0.15625	tonsludge/tonconc	[7]
Refinement inventory for 1 ton borax pentahydrate	Conc. tincal consumption		2.3	tonconc/tonborax_pentahydrate	[3]
	Flocculant (nonionic polyacrylamide)		0.3	kgfloc./tonborax_pentahydrate	[3]
	Electricity		130	kWh/tonborax_pentahydrate	[3]
	Steam		5	tonsteam/tonborax_pentahydrate	[3]
	Water		45	tonwater/tonborax_pentahydrate	[3]

		Mineral waste	0.7375	tonwaste/tonborax_pentahydrate	*
		Sludge	1.40625	tonsludge/tonborax_pentahydrate	*
Refinement inventory for 1 ton borax decahydrate	Conc. tincal consumption		1.7	tonconc/tonborax_decahydrate	[3]
	Flocculant (nonionic polyacrylamide)		0.3	kgfloc/tonborax_decahydrate	[3]
	Electricity		125	kWh/tonborax_decahydrate	[3]
	Steam		2	tonsteam/tonborax_decahydrate	[3]
	Water		14	tonwater/tonborax_decahydrate	[3]
		Mineral waste	0.2844	tonwaste/tonborax_decahydrate	*
		Sludge	0.4156	tonsludge/tonborax_decahydrate	*
Refinement inventory for 1 ton sodium perborate	Conc. tincal consumption		1.1	tonconc/tonsodium_perborate	[3]
	NaOH (48 %)		0.3	tonNaOH/tonsodium_perborate	[3]
	H2O2 (70 %)		0.3	tonH2O2/tonsodium_perborate	[3]
	Flocculant (nonionic polyacrylamide)		0.3	kgfloc/tonsodium_perborate	[3]
	Electricity		110	kWh/tonsodium_perborate	[3]
	Steam		1	tonsteam/tonsodium_perborate	[3]
	Water		6	tonwater/tonsodium_perborate	[3]
		Mineral waste	0.269	tonwaste/tonsodium_perborate	*

¹Estimated data are indicated by the * symbol in the reference column.

Calculations for Table S2

(g) Input for Water (in concentrator):

The water to produce 1 ton concentrated colemanite (a) = $(2,250,000 \text{ m}^3/\text{year}) / (536,700 \text{ ton}/\text{year}) = 4.1923 \text{ m}^3/\text{ton}$.

This value assumed the same at Kırka facility to produce tincal, as well.

At Bigadiç, 4.1923 m³/ton water is necessary to process 1.3490 ton run-of-colemanite-ore.

At Kırka, 1.4375 ton run-of-tincal-ore is processed per ton of concentrated tincal.

The water to produce 1 ton concentrated tincal = $(1.4375 \text{ ton run-of-tincal-ore}) * (4.1923 \text{ m}^3/\text{ton water}) / (1.3490 \text{ ton run-of-colemanite-ore}) = 4.4673 \text{ m}^3/\text{ton}$. (Assumption)

(h) Input for run-of-tincal-ore (in concentrator):

The processed run-of-tincal ore in the concentrator facility is 1,150,000 ton/year [4].

The produced concentrated tincal ore is 800,000 ton/year [4].

The processed run-of-colemanite ore to produce 1 ton concentrated colemanite = $(1,150,000 \text{ ton}/\text{year}) / (800,000) = 1.4375 \text{ ton}/\text{ton}$.

(i) Output for Overburden (open-pit-mining): The overburden per run-of colemanite ore at Bigadiç facility is 4.07 m³/ton [2].

This value assumed the same at Kırka facility to produce tincal, as well.

The density of run of tincal ore is 2.4 g/cm³.

Therefore the amount of overburden is $4.07 * 2.4 = 9.77 \text{ ton}$.

(j) Output for Waste Water (in concentrator):

The waste water at Kirka concentrator facility is 2,700,000 ton/year [6].

The produced concentrated tincal ore is 800,000 ton/year [4].

The waste water to produce 1 ton concentrated tincal =
 $(2,700,000 \text{ ton/year}) / (800,000 \text{ ton/year}) = 3.375 \text{ ton/ton}$.

(k) Output for Mineral Waste (in concentrator):

The processed run-of-colemanite ore to produce 1 ton concentrated colemanite is 1.4375 ton (g).

The mineral waste to produce 1 ton concentrated tincal =
 $(1.4375 \text{ ton run-of-tincal ore}) - (1 \text{ ton concentrated tincal}) = 0.4375 \text{ ton/ton}$. (Assumption)

► Second approach:

The waste mineral at Kirka concentrator facility is 350,000 ton/year [6].

The produced concentrated tincal ore is 800,000 ton/year [4].

The mineral waste to produce 1 ton concentrated tincal =
 $(350,000 \text{ ton/year}) / (800,000 \text{ ton/year}) = 0.4375 \text{ ton/ton}$.

(l) Output for Sludge Waste (in concentrator):

The sludge waste at Kirka concentrator facility is 125,000 ton/year [7].

The produced concentrated tincal ore is 800,000 ton/year [4].

The sludge waste to produce 1 ton concentrated tincal =
 $(125,000 \text{ ton/year}) / (800,000 \text{ ton/year}) = 0.15625 \text{ ton/ton}$.

(m) Output for Sludge Waste (refining for borax pentahydrate):

The sludge waste at Kirka refinement facility is 450,000 ton/year. (Approximately 40 % of this sludge is composed of solid waste.) [6].

The produced borax pentahydrate is 320,000 ton/year [6].

The sludge waste to produce 1 ton borax pentahydrate =
 $(450,000 \text{ ton/year}) / (320,000 \text{ ton/year}) = 1.40625 \text{ ton/ton}$.

(n) Output for Mineral Waste (refining for borax pentahydrate):

The sludge waste to produce 1 ton borax pentahydrate =
 $(450,000 \text{ ton/year}) / (320,000 \text{ ton/year}) = 1.40625 \text{ ton/ton}$.

(Approximately 40 % of this sludge is composed of solid waste.) [6].

The solid waste in sludge to produce 1 ton borax pentahydrate =
 $(1.40625 \text{ ton/ton}) * (0.40) = 0.5625 \text{ ton/ton}$

The processed concentrated tincal ore to produce 1 ton borax pentahydrate is 2.3 ton.

The mineral waste to produce 1 ton borax pentahydrate =
 $(2.3 \text{ ton concentrated tincal}) - (1 \text{ ton borax pentahydrate}) = 1.3 \text{ ton/ton}$.

The final mineral waste =

$1.3 \text{ ton/ton} - 0.5625 \text{ ton/ton} = 0.7375 \text{ ton/ton}$.

(o) Output for Sludge and Mineral Waste (refining for borax decahydrate):

There is no information about the mineral waste of borax decahydrate in the literature. Therefore, the assumptions will be done based on borax pentahydrate production.

The processed concentrated tincal to produce 1 ton borax pentahydrate = 2.3 ton

The processed concentrated tincal to produce 1 ton borax decahydrate = 1.7 ton

The sludge waste to produce 1 ton borax pentahydrate = 1.40625 ton/ton.

The sludge waste to produce 1 ton borax decahydrate =
 $(1.7 \text{ ton}) * (1.40625 \text{ ton/ton}) / (2.3 \text{ ton}) = 1.039 \text{ ton}$

(Approximately 40 % of this sludge is composed of solid waste.) [6].

The solid waste in sludge to produce 1 ton borax decahydrate =
 $(1.039 \text{ ton/ton}) * (0.40) = 0.4156 \text{ ton/ton}$

The mineral waste to produce 1 ton borax decahydrate =
 $(1.7 \text{ ton concentrated tincal}) - (1 \text{ ton borax decahydrate}) = 0.7 \text{ ton/ton}$.

The final mineral waste =

$0.7 \text{ ton/ton} - 0.4156 \text{ ton/ton} = 0.2844 \text{ ton/ton}$.

(p) Output for Sludge and Mineral Waste (refining for sodium perborate):

There is no information about the mineral waste of sodium perborate in the literature. Therefore, the assumptions will be done based on borax pentahydrate production.

The processed concentrated tincal to produce 1 ton borax pentahydrate = 2.3 ton

The processed concentrated tincal to produce 1 ton sodium perborate = 1.1 ton
The sludge waste to produce 1 ton borax pentahydrate = 1.40625 ton/ton.
The sludge waste to produce 1 ton sodium perborate =
 $(1.1 \text{ ton}) * (1.40625 \text{ ton/ton}) / (2.3 \text{ ton}) = 0.6725 \text{ ton}$
(Approximately 40 % of this sludge is composed of solid waste.) [6].
The solid waste in sludge to produce 1 ton sodium perborate =
 $(0.6725 \text{ ton/ton}) * (0.40) = 0.269 \text{ ton/ton}$
The mineral waste to produce 1 ton sodium perborate =
 $(1.1 \text{ ton concentrated tincal}) - (1 \text{ ton borax decahydrate}) = 0.1 \text{ ton/ton.}$
The final sludge waste =
 $0.1 \text{ ton/ton} - 0.269 \text{ ton/ton} = -0.169 \text{ ton/ton.}$
The result is minus here. Therefore, only solid mineral waste will be used for sodium perborate production.

Table S3. Impact assessment of 1 ton boric acid, borax decahydrate, borax pentahydrate, and sodium perborate production (characterization).

Impact category	Unit	BA	BD	BP	SP
Climate change	kg CO2 eq	495,3125	566,0345	1262,956	1701,519
Ozone depletion	kg CFC-11 eq	0,000121	4,89E-05	0,000113	0,000347
Human toxicity, non-cancer effects	CTUh	0,000329	6,58E-05	0,000117	0,000389
Human toxicity, cancer effects	CTUh	3,08E-05	1,31E-05	2,29E-05	0,000149
Particulate matter	kg PM2.5 eq	0,902737	0,559895	0,98549	1,61663
Ionizing radiation HH	kBq U235 eq	53,79986	14,93264	33,79421	164,2083
Ionizing radiation E (interim)	CTUe	0,000286	6,83E-05	0,000152	0,000447
Photochemical ozone formation	kg NMVOC eq	2,624189	1,25554	2,627465	4,533912
Acidification	molc H+ eq	10,42143	3,254536	6,912963	10,95829
Terrestrial eutrophication	molc N eq	7,414589	3,96172	8,030616	14,31164
Freshwater eutrophication	kg P eq	0,28392	0,138333	0,214044	0,529216
Marine eutrophication	kg N eq	0,950391	0,538293	1,024098	2,74009
Freshwater ecotoxicity	CTUe	8941,028	1623,265	2810,016	13586,87
Land use	kg C deficit	1701,39	539,525	1203,997	1673,557
Water resource depletion	m3 water eq	14,57281	5,599342	20,66463	12,75312
Mineral, fossil & ren resource depletion	kg Sb eq	0,242378	0,001981	0,003545	0,037245

The Pedigree Matrix is prepared for Table S1 and S2. Since all the literature sources for the data are the same, same Pedigree Matrix is used for mining, concentrating and refining, see Table S4.

Table S4. The Pedigree Matrix.

Indicator Score	1	2	3	4	5	Comments
Reliability		X				The data was taken by the literature. Since it is not taken by the company, they are still not totally reliable.
Completeness		X				Because it is representative selection of boron

						mining located in Turkey.
Temporal Correlation					X	Age of data is more than 15 years old.
Geographical Correlation	X					Boron mining was investigated in this study and the data of Eti Mine was used (using the literature).
Further technological correlation	X					The data found in the literature of Eti Mine Company were used. The data is only related boron mineral processing. The other mineral processes were not used as a reference.

References

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