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ORIGINAL PAPER

Life cycle assessment on boron production: is boric acid extraction from salt-lake brine environmentally friendly?

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Abstract
No information is currently available on potential environmental impact of boric acid solvent extraction from salt-lake brine although boron production is important for industry, agriculture, and human well-beings. Life cycle assessment (LCA) was firstly used by this study to evaluate the environmental impact of boron production using extraction method with the functional unit of 1-ton boric acid. CO_2 was the pollutant with the highest emission amount among the target pollutants, while both extraction and reverse extraction stages contributed to 61.6% of total emission amount for the boron extraction technique. Global warming potential (GWP) and acidification potential (AP) of producing 1-ton boric acid by extraction technique reached 5.52×10^3 kg CO_2 eq and 28.0 kg SO_2 eq, respectively. Extraction/dry stage contributed to the highest/lowest percentage of environmental impact indices by following the order of extraction > reverse extraction > acidification > dry. Life cycle cost for 1 ton of boric acid was estimated as $1054.83 with 67.5% of internal cost. Approximately 1.59 ton of indirect water and 6010 kWh of electricity were consumed to produce 1 ton of boric acid. The emission amounts of pollutants for nanofiltration boron-production technique were 1.4–1.7 times those for extraction technique. GWP and AP of boron extraction production were comparable with those of the other production processes. The findings of this study will provide the theoretical basis and quantitative data for the sustainable development and cleaner production of boron industry.

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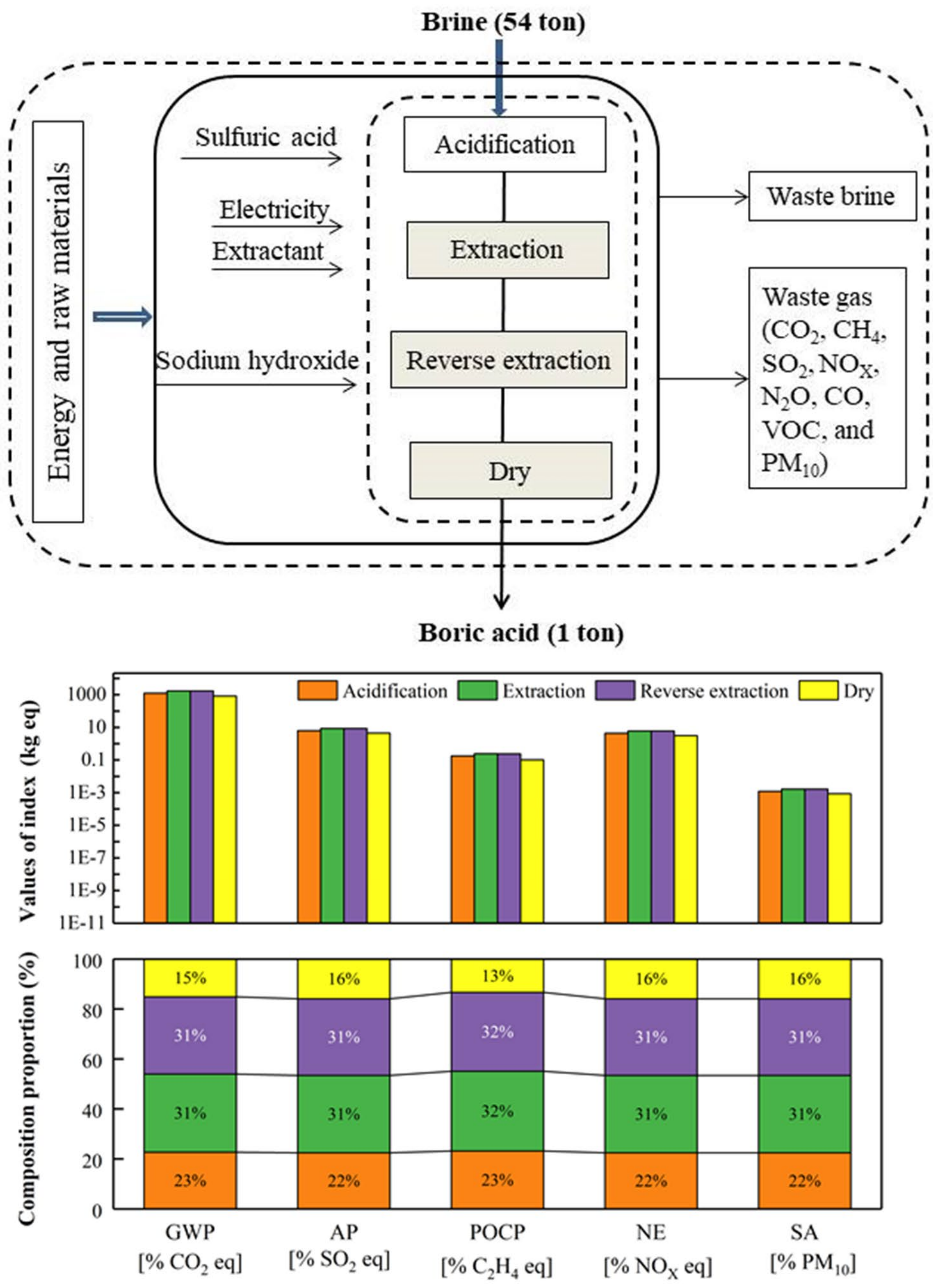
Graphic abstract



Keywords Life cycle assessment · Boron production · Salt-lake brine · Environmental burden

Introduction

Boron (B) with atomic number of 5 and atomic mass of 10.811 g/mol usually exists in nature as solid ores including borax (sodium borate) and borate minerals with 60% of global boron ores in Turkey (Çırak and Hoşten 2015) as well as liquid phase in salt lakes/brines/seawater (Demey et al. 2014). Similar with heavy metals which widely exist in different matrices (Lu et al., 2020; Wen et al., 2019),boron is ubiquitous in the natural matrices such as soil/rock/water/sediment (Uluisik et al. 2018). Boron is beneficial both for animals/plants and humans since boron is capable of providing nutritional benefits, antioxidant properties, and maintenance of bone functions (Başaran et al. 2019). Boron has been widely used in industry and agriculture due to its good property of heat and wear resistance, high rigidity and strength, and fire retardance (Zhang et al. 2016). Boron compounds have been used in production of glass, ceramics, leather, detergents, fertilizers, fire retardants, and disinfectants (Özdemir and Kıpçak 2010). Boron is also a perspective candidate for production of liquid fuel engines (Ojha and Karmakar 2018), anti-cancer or other drugs (Plescia and Moitessier 2020), and advanced energy materials (Zhu et al. 2018). Moreover, boron wastes have been used extensively in construction materials especially cement, asphalt, and brick (Keskin and Karacasu 2019) to achieve recycle of boron resources and sustainability of boron production. Therefore, boron production is important for national/regional economic development and human well-beings.

Compared with exploitation and production from solid ores, extraction from salt-lake brines is more environmental-friendly for boron production. Several methods including acidizing crystallization, solvent extraction (Zhang et al. 2016), adsorption (Wu et al. 2019), and ion exchange (Schilde and Uhlemann 1991) have been used to recover boron from the salt-lake brines. The process of acidizing crystallization is simple and usually used in combination with other methods, while the recovery rate of this method is low (approximately 60–70%). The adsorption and ion exchange methods have high selectivity for boron with recovery reaching more than 90% (Nishihama et al. 2013). However, limited adsorption capacity, low utilization rate, and high energy consumption of these methods may cause high production cost, which make these methods be only applicable in low boron system. Solvent extraction among these methods has been successfully used to recover boron in practical production such as boron extraction from Searles Lake (Garrett 1998). Solvent extraction possesses advantages such as high extraction efficiency, good versatility, and various extractants for choosing (Zhang et al. 2016). Therefore, solvent extraction is still a promising method for recovering boron from salt-lake brines. However, no information is available on environmental burden posed by solvent boron extraction from salt-lake brines. Therefore, it is necessary and important to discuss the potential environmental impact of this technique for the sustainable development of boron production industry.

Life cycle assessment (LCA) is an emerging and promising method for evaluating the potential environmental impact cause by different processes (Li et al. 2020). LCA has been used to determine the life cycle cost and environmental burden of lithium nanofiltration extraction technique (Li et al. 2020), the environmental impact of a small multi-effect distillation plant for treating brackish water (Tarpani et al. 2019), and process innovation evaluation for manufacturing industry (Vinci et al. 2019). LCA provides important information for optimization of production process due to the estimated environmental burden, water/energy consumption, and cost of different stages or production units. No information on environmental burden and costs of boron production is currently available to make the LCA study on boron production necessary.

Therefore, this study performed LCA to evaluate the potential environmental impact of the boron solvent extraction from salt-lake brines. Life cycle inventory, life cycle cost, environmental burden, and water/energy consumption of boron extraction were thoroughly discussed. The final aim of this study is to provide theoretical basis of industrial planning and environmental management for boron production industry.

Materials and methods

Boric acid extraction from salt-lake brine

Boron product in this study was boric acid which was produced by solvent extraction technique (Han et al. 2007). The salt-lake brine which contained boron with concentration of 2.7 g/L was firstly feed into acidification unit in which sulfuric acid was added to adjust brine pH to 3. Then, the acidified brine was feed into extraction unit in which the extractant was added. The extractant was prepared by 2-ethylhexanol and 2-ethyl-1,3-hexanediol with volume ratio of 80:20. Sulfonated kerosene serve as diluent for extractant. The volume ratio of the organic phase and the aqueous phase was 1:2. After extraction, the brine was pumped in reverse extraction unit by using sodium hydroxide as stripping agent. The extraction and reverse extraction were performed 5 times in a multistage centrifugal extractor. The final stage of boron production was product drying.

System boundary and functional unit

The system boundary of boron extraction process referred to Fig. 1. The boron production was composed of 4 processes including acidification, extraction, reverse extraction, and dry. Cost of boron production was affected by raw materials, salt-lake brine, electricity, and chemicals. The environmental impact was influenced by wasted brine and gaseous pollutants including CO_2, CH_4, SO_2, NOx, N_2O, CO, volatile organic compounds (VOC), and PM_{10}. Functional unit of this study was set as 1 ton of boric acid. Approximately 54 tons of salt-lake brine was needed to produce 1 ton of boric acid based on the investigation.

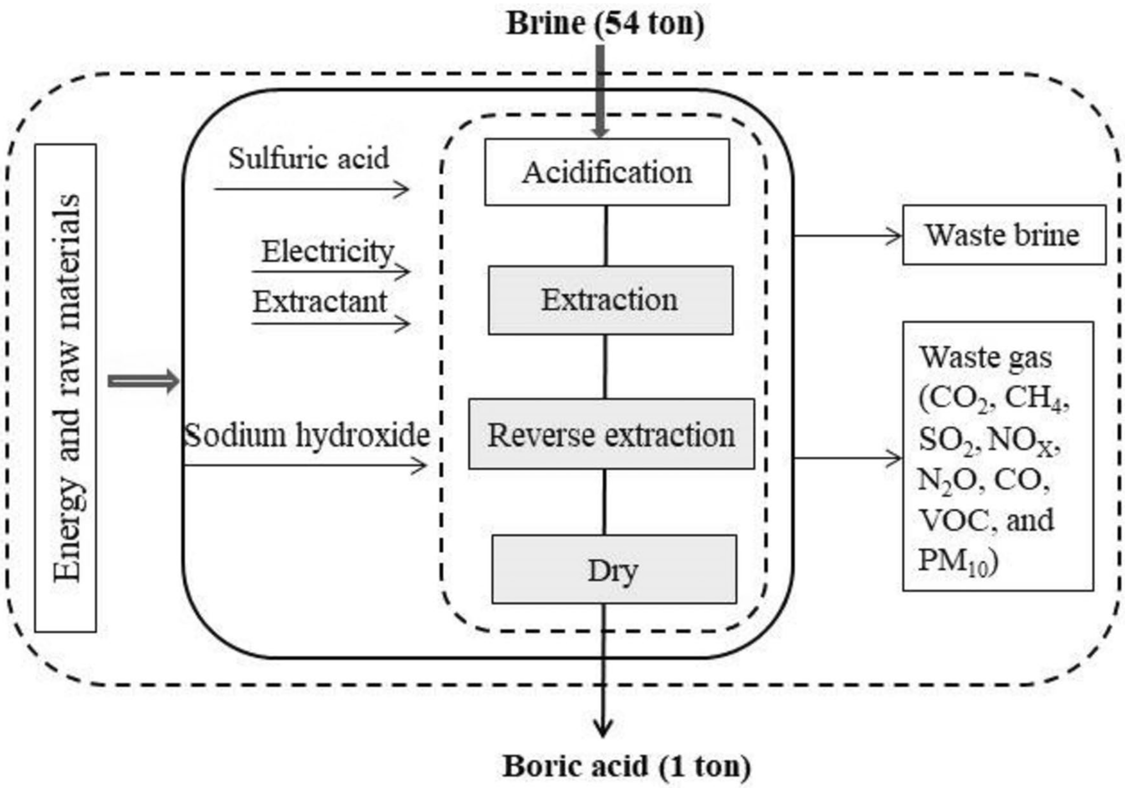


Fig. 1 System boundary and process flow of boric acid production

LCA method, life cycle inventory (LCI), and life cycle cost (LCC)

Boron production from salt-lake brine was generally performed near the salt lakes, and waste brine was recharged into the salt lakes so that impact posed by land occupation, brine transportation, and liquid waste disposal could be ignored. This study selected 5 kinds of indicators including acidification potential (AP), global warming potential (GWP), nutrient enrichment (NE), soot and ashes (SA), and photochemical ozone creation potential (POCP) to evaluate the potential environmental impact of boron production from salt-lake brine. The calculation of AP, GWP, NE, SA, and POCP referred to previous report (Li et al. 2020). In brief, emission of different target pollutant (CO_2, CH_4, SO_2, NOx, N_2O, CO, VOC, and PM_{10}) was estimated by sum of emission in different stages. AP, GWP, NE, SA, and POCP were calculated by sum of different weighed pollutant emission (Li et al. 2020).

LCI of boron production from salt-lake brine included the consumption of brine, electricity, water, extractant, and chemicals used in different stages, which referred to Table 1. LCC was composed by external LCC (LCC_{ex}) that was the monetized environmental impact of the boron production and internal LCC (LCC_{in}) that was the traditional cost of the production process.

Results and discussion

Life cycle pollutant emission of boron production from salt-lake brine

Emission amounts of different pollutants at 4 stages of boron production from salt-lake brine showed significant difference (Fig. 2). Total emission amount of all target pollutants at extraction stage reached the highest with 1633.0 kg while that at dry stage was the lowest with 840.5 kg. Emission amount of all target pollutants at different stages followed the order of extraction > reverse extraction > acidification > dry. Pollutant emission amount of both extraction

Table 1 Life cycle primary inventories of boric acid production (values were presented according to per functional unit)

Categories	Sub-categories	Acidification	Extraction	Reverse extraction	Dry
Materials (t)	Brine	54			
	Sulfuric acid (L)	600			
	Boric acid in the acidizing phase	0.56			
	Residual brine after acidification		35		
	Extractant (L)		20		
	Sodium hydroxide (L)			120	
	Boric acid solution after reverse extraction			0.51	
	Boric acid after reverse extraction				0.44
Energy	Electricity (kWh)	1860	1860	1840	960
Emissions to air (kg)	CO_2	1.17×10^3	1.61×10^3	1.60×10^3	8.33×10^2
	CH_4	3.33	4.58	4.53	2.36
	SO_2	4.00	5.51	5.45	2.84
	NO_X	3.27	4.50	4.45	2.32
	N_2O	1.77×10^{-2}	2.44×10^{-2}	2.42×10^{-2}	1.26×10^{-2}
	CO	2.04	2.81	2.78	1.45
	VOC	0.14	0.19	0.19	9.76×10^{-2}
	PM_{10}	1.21	1.67	1.65	0.86

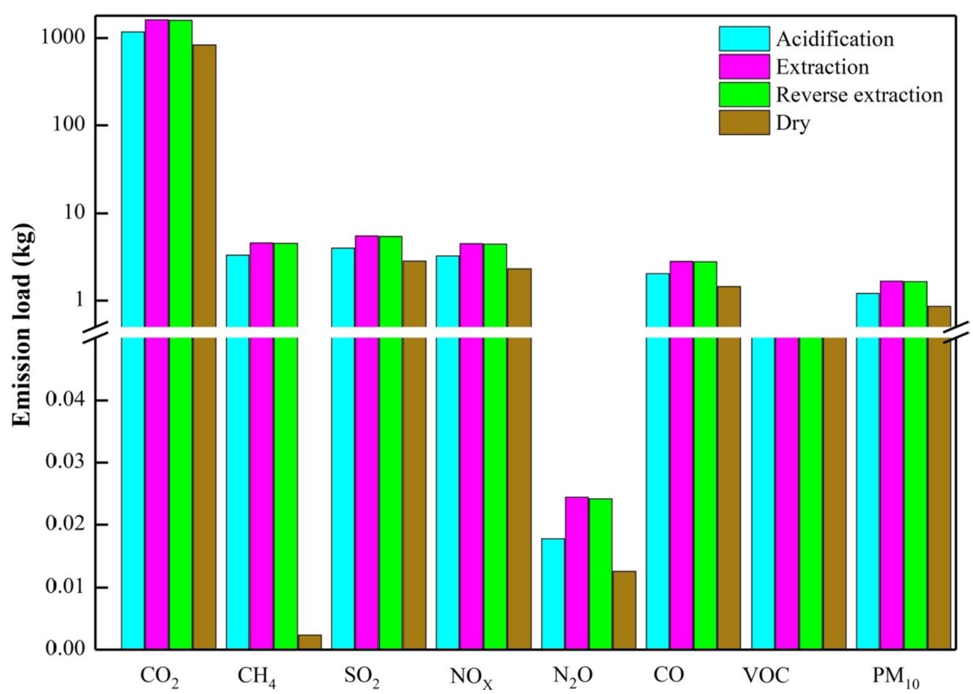


Fig. 2 Pollutant emissions at individual stage of boric acid production

and reverse extraction stages contributed to 61.6% of total emission amount at all boron production processes.

Emission amounts of CO_2 at different stages were significantly higher than those of the other pollutants (Fig. 2). Interestingly, CH_4 emission amount at dry stage was significantly lower than that of other pollutant emission amount. Besides, N_2O emission amounts at different stages were also significantly lower than the other pollutant emission amounts. As far as the same pollutant was concerned, emission amount at extraction stage was slightly higher than that at reverse extraction stage but significantly higher than that at the remaining stages. Emission amounts of CH_4 (excluding at dry stage), SO_2, and NOx were similar at the same stage. Emission amounts of the target pollutants at the same stage followed the order of $CO_2 > SO_2 > NOx > CH_4 > CO > PM_{10} > VOC > N_2O$. The highest emission amount (1613.7 kg of CO_2 at extraction stage) was over 6.8×10^5 times that the lowest emission amount (CH_4 at dry stage), illustrating the effect of production process on pollutant emission. Extraction stage was the most important stage for producing boron using extraction method, while more materials were used in this process to make the pollutant emission higher than the rest of other processes. Accordingly, reverse stage also needed usage of chemicals, water, and energy to produce a lot of pollutants.

Life cycle impact analysis of boron production from salt-lake brine

Five indices were used to evaluate the environmental impact of boron production from salt-lake brine (Fig. 3). Similar to the previous study (Li et al. 2020), GWP was the highest environmental impact index for the boron production from salt-lake brine with 1.25×10^3/1.73×10^3/1.71×10^3/8.37×10^5 kg CO_2 eq at acidification/extraction/ reverse extraction/dry stage, while SA was the lowest index with 1.25×10^3/1.73×10^3/ 1.71×10^3/8.37×10^5 kg at acidification/extraction/reverse extraction/dry stage. GWP and AP for producing 1 ton of boric acid reached 5.52×10^3 kg CO_2 eq and 28.0 kg SO_2 eq, respectively. The index followed the order of GWP > AP > NE > POCP > SA for the different stages of the boron production, illustrating that boron production might exert more effect on climate change. Therefore, technology improvement or innovation of boron extraction production technique will contribute to reduce environmental burden especially climate change burden to great extent.

As far as each index was concerned, extraction/dry stage contributed to the highest/lowest percentage by following the order of extraction > reverse extraction > acidification > dry. Extraction that was the critical process for boron production generally consumed relatively more energy, chemicals, and water as well as emitted more pollutants. Therefore, environmental impact index at extraction stage was higher than that at the other stage. Extraction and reverse extraction were alternately operated so that material and energy consumption as well as pollutant emission of these two stages were similar to cause the similar environmental impact indices.

Life cycle cost of boron production from salt-lake brine

Life cycle cost for 1 ton of boric acid was estimated as \$1054.83 with external cost of \$343.08 (Fig. 4).

Internal cost at extraction stage contributed to 47.8% of total internal cost, while internal cost at different stages followed the order of extraction > reverse

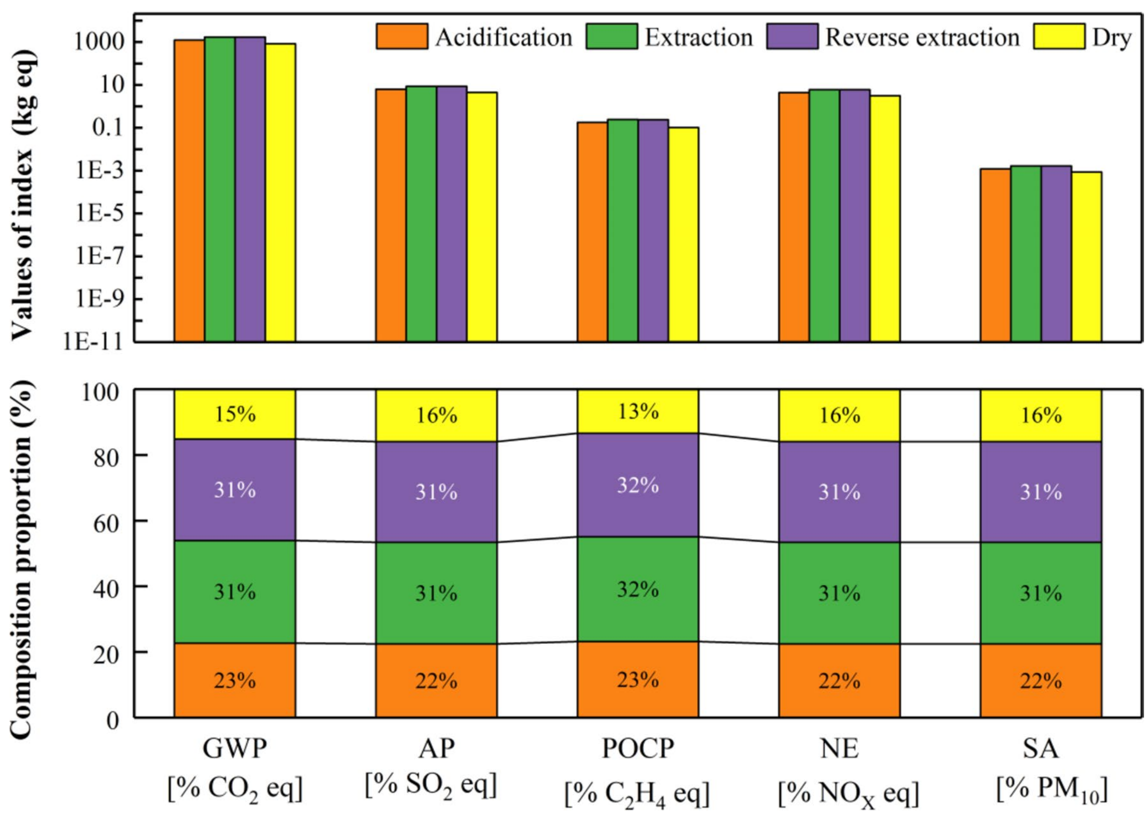


Fig. 3 Distribution and contribution percentage of environmental impact indices at individual stage of boric acid production

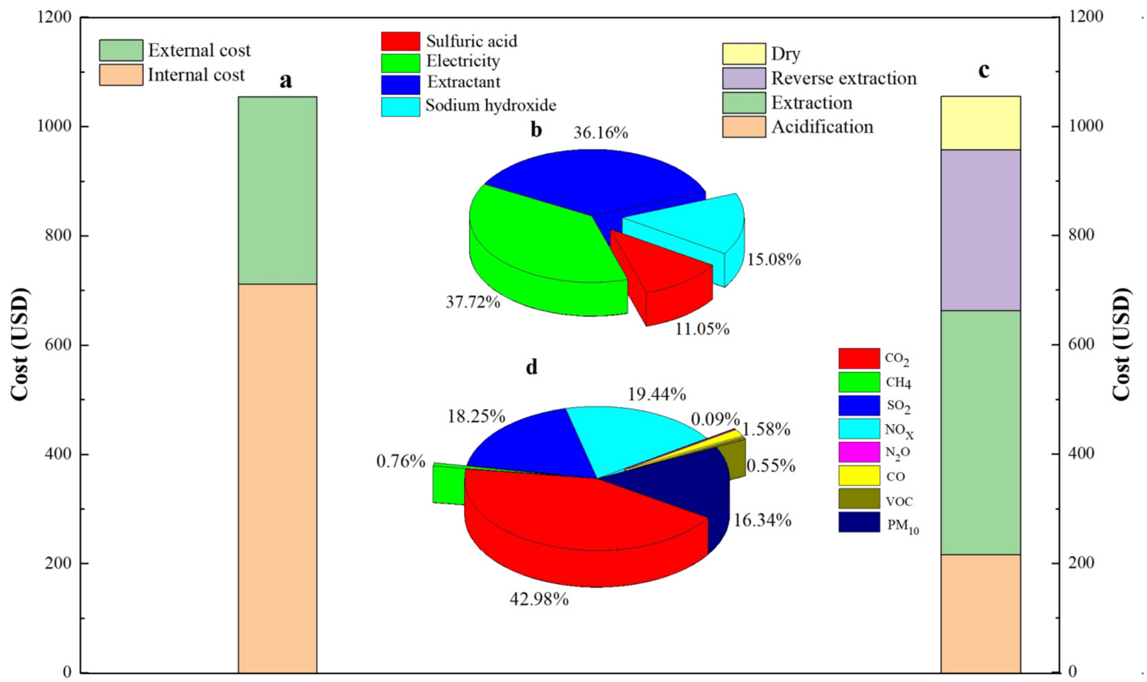


Fig. 4 The total life cycle cost **a** the internal life cost composition **b** the external life cost composition **c** and life cycle cost at different stages **d** of boric acid production

extraction > acidification > dry. Electricity cost accounted for 37.7% of internal cost, while electricity cost at extraction and reverse extraction stages was higher than that at the remaining stages. Chemicals including extractant, acid, and alkali accounted to about 62.3% of the internal cost, illustrating that dosage reduction and technological improvement might reduce the internal cost of boron production to great extent. For example, internal cost will be reduced by 20% or more if the improved technique makes the extraction-reverse extraction perform 4 times.

External cost at extraction/reverse extraction stage covered about 31.0%/30.7% of total external cost (Fig. 4). External cost at different stages also followed the order of extraction > reverse extraction > acidification > dry. Cost of CO_2 accounted for 43.0% of external cost, while cost of N_2O only covered about 0.1% of total external cost. External cost of different pollutants followed the order of $CO_2 > NOx > SO_2 > PM_{10} > CO > CH_4 > VOC > N_2O$.

Water and energy consumption of boron production from salt-lake brine

Consumed amount of indirect water which was water consumed for energy production reached 1.59 tons for producing 1 ton of boric acid (Fig. 5). Indirect water at extraction/reverse extraction accounted for 30.8%/30.4% of total consumed water. Indirect water at dry stage was lower than that at the other stages. Consumption of direct water was very limited for boron production from salt-lake brine.

Consumed electricity reached 6010 kWh for producing 1 ton of boric acid. Electricity at extraction/reverse extraction accounted for 30.9%/30.6% of total consumed power (Fig. 5). Electricity at dry stage was also lower than that at the other stages. Interestingly, water/electricity consumption for producing 1 ton of boric acid was much lower than 1 ton of lithium using nanofiltration technique, which might be caused by different requirements for water and electricity of different techniques. Nanofiltration technique generally has more demand on water and power, while extraction technique has special requirements on chemicals.

Feasibility of alternative technique for boron production

The alternative technique of boron production will be helpful for sustainable development of this industry and innovation of corresponding technology. The alternative techniques for boron production from salt-lake brine have been investigated although solvent extraction has been widely used for practical production for decades (Cao et al. 2018). Nanofiltration has been successfully used for lithium production with relatively low environmental burdens (Li et al. 2020) to make it possible for lithium cleaner production. Moreover, nanofiltration technique has also been proposed and recommended for boron production

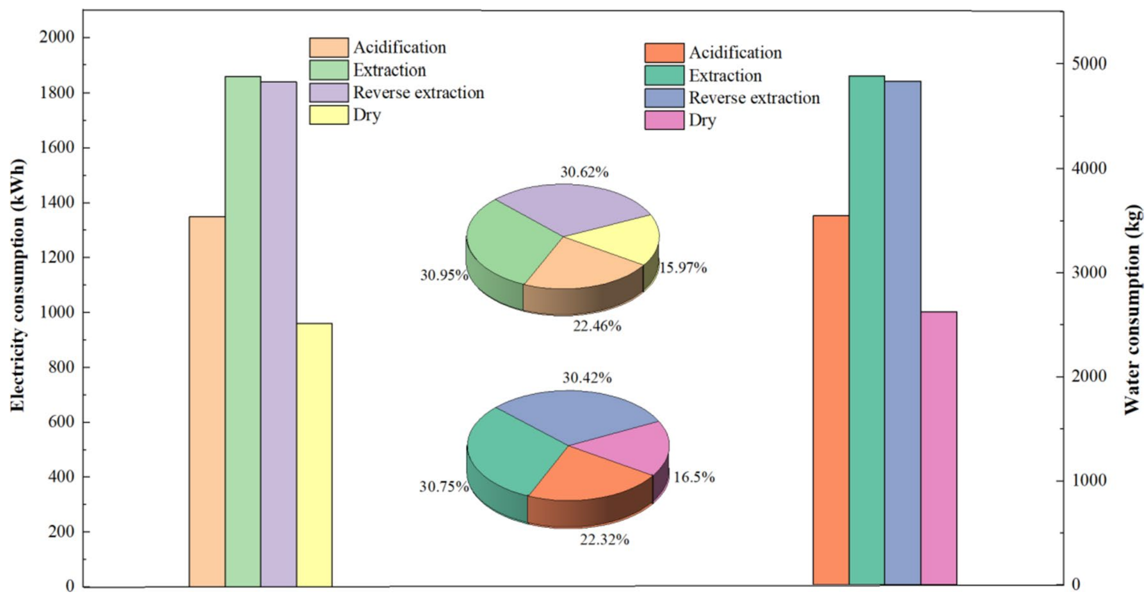


Fig. 5 Water and energy consumption of boric acid production

(Cao et al. 2018) although the practical production is still in plan. Therefore, a comparative investigation was performed to discuss the feasibility of boron extraction technique and its alternative method from the point view of LCA (Fig. 6). Pollutant emissions of two techniques for boron production were compared (Fig. 6a). It was interesting that all pollutant emissions of extraction technique were lower than those of nanofiltration technique. The main contributor to the higher pollutant emission of nanofiltration technology was the consumption of electricity. Nanofiltration membrane technology in the process of boron separation requires the use of high-pressure pumps to pump the brines into the nanofiltration membrane module, which consumes a relatively large amount of electricity compared to extraction technology. The emission amounts of pollutants for nanofiltration technique were 1.4–1.7 times those for extraction technique. Three-stage nanofiltration was used for boron production so that power consumption was relatively high to further cause relatively high pollutant emission. Nanofiltration stage mainly contributed to the pollutant emissions for nanofiltration technique, while acidification was the main producer of pollutant for extraction technique. The environmental indices of two techniques also showed significant difference (Fig. 6b). GWP/POCP of nanofiltration technique was 1.44/1.47 times that of solvent-extraction technique and the remaining indices of nanofiltration were also higher than those of extraction technique.

Extraction and reverse extraction stages were the major contributors for environmental burdens of extraction technique, while the contribution percentage of different stages followed the order of extraction > reverse extraction > acidification > dry. Nanofiltration was still the major contributor for environmental burdens of nanofiltration technique, while the contribution percentage of different stages followed the order of nanofiltration > acidification > evaporation > dry. Therefore, the current extraction technique might be still feasible for boron production by considering the environmental burdens of different techniques. It is still suggested that novel production techniques should be developed for cleaner boron production.

Besides developing the novel techniques, improvement on current extraction technique is also necessary and feasible for boron production from salt lakes. Usage of new environmentally friendly solvents/extractants and more advanced extraction-reverse process might greatly decrease consumption of water/energy/material to further reduce production cost and environmental burden.

Environmental impact comparison with other production processes

Environmental burdens posed by boron production from salt-lake brine were compared with those caused by the other processes (Table 2). Different production processes exerted different burden to the environment due to difference in raw materials, technique, and application. As far as industrial production was concerned, all environmental impact indices of boron production from salt-lake brine were 1–2 magnitude higher than those of lithium nanofiltration

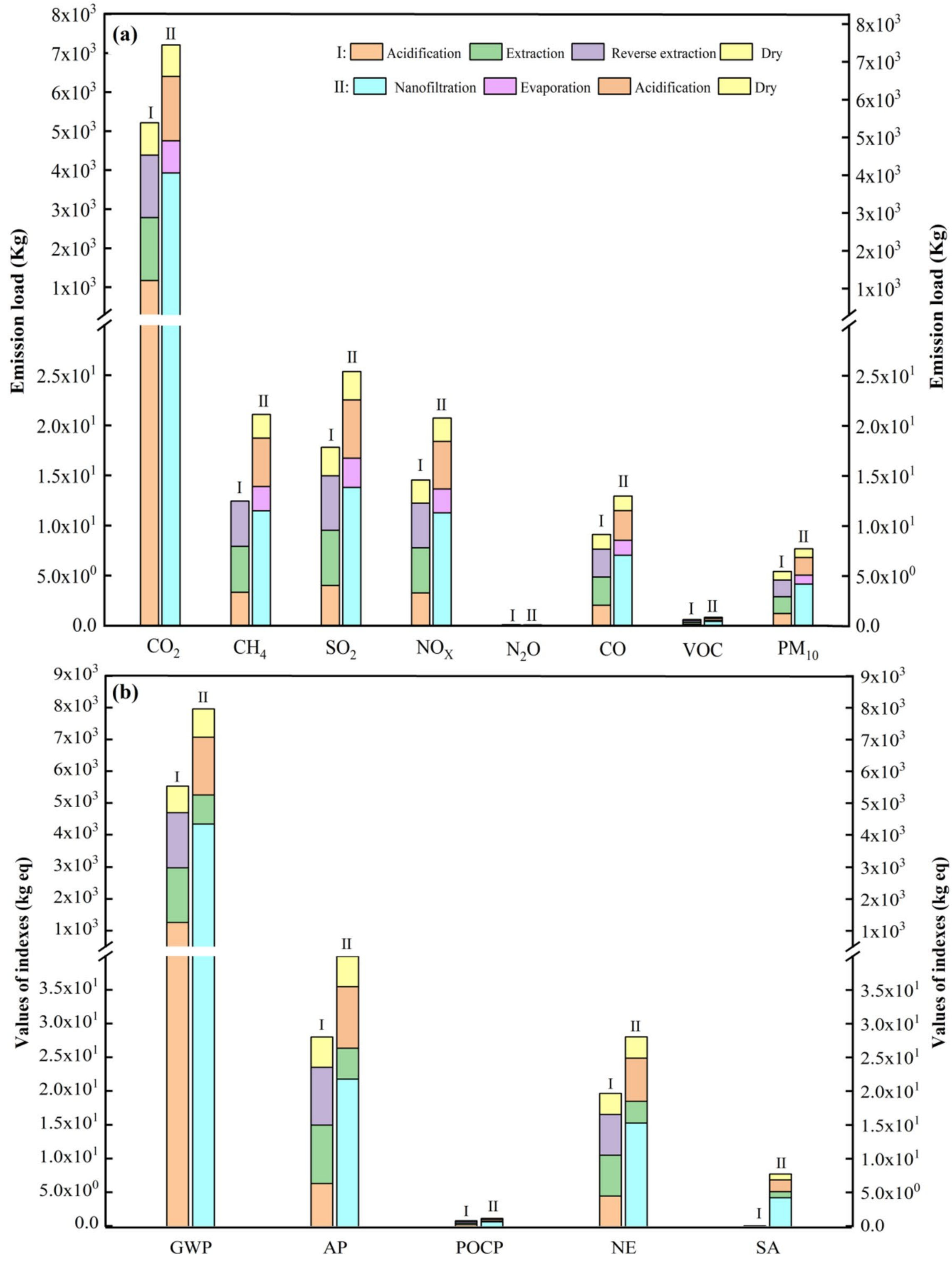


Fig. 6 Pollutant emissions (**a**) and environmental impact indices (**b**) with functional unit of 1-ton products by using extraction technique (I) and nanofiltration technique (II)

process (Table 2). Interestingly, environmental burdens of boron nanofiltration technique were much lower than those of lithium nanofiltration technique. Compared with magnesium electrolytic/thermal production process (Cherubini et al. 2008), GWP and AP of boron production were much lower than those of magnesium production, while only

Table 2 Environmental burden of different processes

GWP (kg CO_2 eq/kg product)	AP (kg SO_2 eq/kg product)	POCP (kg C_2H_4 eq/kg product)	NE (kg NO_X eq/kg product)	SA (kg/kg product)	Process
5.52	2.80×10^{-2}	7.64×10^{-4}	1.96×10^{-2}	5.40×10^{-6}	Boric acid solvent extraction [a]
7.96	4.00×10^{-2}	1.12×10^{-3}	2.80×10^{-2}	7.71×10^{-3}	Boron production by nanofiltration[a]
3.2×10^{-2}	1.55×10^{-4}	4.26×10^{-6}	1.09×10^{-4}	3.85×10^{-5}	Lithium production by nanofiltration[b]
24.5	9.85×10^{-2}				Magnesium production by electrolytic process[c]
10.4–42.0	2.07×10^{-2}-0.30				Magnesium production by thermal processes[c]
9.6–57.9	-4.9×10^{-2}–0.114				KNO_3 production[d]
0.87					Bio-based succinic acid production[e]
1.75–5.48	$(2.0–7.0)\times10^{-2}$				Strawberry production in the USA[f]
0.6–1.3					Lettuce production in Greece[g]

[a]This study; [b](Li et al. 2020; [c]Cherubini et al. 2008; [d]Mohammed et al. 2016; [e]Moussa et al. 2016; [f]Tabatabaie and Murthy 2016; [g]Foteinis and Chatzisymeon 2016)

AP of magnesium thermal production using briquetted process in Brazil was lower than that of boron production. GWP of boron production was much lower than that of KNO_3 production, while AP of boron production was lower than that of KNO_3 production with ozone oxidation but much higher than that with H_2O_2/NaClO oxidation (Table 2).

GWP of boron production was much higher than that of bio-based succinic acid production and lettuce production (Table 2). Interestingly, strawberry production in the USA showed the similar GWP and AP with boron production (Table 2). Strawberry production in North Carolina was similar with that of boron production, while AP of strawberry production in North Carolina or Oregon was higher than that of boron production (Tabatabaie and Murthy 2016). LCA results showed that boron industrial production might not cause lots of environmental burdens in comparison with the other industrial/agricultural processes.

Conclusions

This work could be the globally first study on life cycle analysis of boron production using extraction technique from salt lakes to provide novel insights on cost, water/energy consumption, and environmental burden of boron production. Both extraction and reverse extraction stages of boron production from salt-lake brine contributed to major emissions of pollutants, while CO_2 was the main pollutant with the largest emission amount during boron production. Individual environmental impact index at extraction stage was higher than that at the other stage. Internal cost of boron production was almost twice external cost, while both extraction and reverse extraction stages were still the main contributor of life cycle cost of boron production. Water/energy consumption at both extraction and reverse extraction stages accounted for over 60% of total consumed amount. The environmental load caused by boron extraction technology was lower than that of nanofiltration technique. Comparative study on LCA of all different boron production methods might still need further investigation to identify the optimal boron technique. GWP and AP of boron extraction production were comparable with those of the other processes, illustrating that boron production from salt-lake brine might still be feasible and sustainable for the local development. The findings will provide important data on life cycle impact and cost evaluation of boron production and the related industries. The corresponding data will instruct and improve the boron production activities. This study will also lay a scientific basis for environmental management in salt-lake areas and similar regions.

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Author contributions Jun Wu contributed to original draft preparation, conceptualization, writing—reviewing and editing, supervision. Baolan Li contributed to methodology, investigation. Jian Lu contributed to original draft preparation, conceptualization.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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