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CARBON FOOTPRINTING

Life cycle assessment for primary gallium production at industrial-scale

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Abstract

Purpose This study aims to provide a comprehensive life cycle assessment (LCA) of primary gallium production on an industrial scale, addressing sustainability concerns due to its intensive chemical and energy consumption. The research question focuses on identifying the environmental impacts across each production process and suggesting mitigation strategies.
Methods Data from a gallium production plant in China was utilized to quantify environmental impacts. The LCA followed the standard four-phase process, including goal and scope definition, inventory analysis, life cycle impact assessment (LCIA), and result interpretation. The ReCiPe 2016 (Midpoint) method was applied for LCIA, and the study considered 14 energy scenarios to assess the carbon footprint under different energy sources.
Results and discussion Key findings indicate that sodium hydroxide and electricity usage are major contributors to environmental burdens such as global warming potential and human toxicity. Data quality analysis highlights the necessity of using high-quality, industrial-scale data in accurate assessment of gallium environmental impacts. In addition, comparison analysis between primary and secondary gallium production shows the challenges of intensive energy and chemical usage during gallium recycling. The study suggests that optimizing production processes and transitioning to cleaner energy sources can effectively mitigate environmental footprints while meeting the growing demand for gallium.
Conclusions The study offers a detailed process inventory for primary gallium production, identifying key emission hotspots and providing insights into potential mitigation strategies. It concludes that significant environmental benefits can be achieved through process optimization and the adoption of renewable energy sources, aligning with global sustainability goals.

Keywords Gallium · Critical materials · LCA · Sustainable production · Carbon footprint

1 Introduction

Gallium is a critical material with applications in many advanced and emerging technologies, attributed to its unique properties, such as a low melting point and good thermal and electrical conductivity (Ge et al. 2013; Butcher and Brown 2014; Grohol and Grow 2023). Gallium-based compounds, such as gallium arsenide (GaAs) and gallium nitride (GaN), can provide high electron mobility, thermal and chemical stability, and possess a direct bandgap (Roccaforte and Leszczynski 2020; Abdul Amir et al. 2021). These properties offer significant advantages over traditional materials in optoelectronic devices, including light-emitting diode (LED), laser diodes, and high-frequency transistors (Sharma et al. 2023). In addition, gallium is also extensively used in photovoltaic (PV) panels because of its ability to improve the efficiency and performance of solar cells. Specifically, the formation of copper-indium-gallium-selenide (CIGS) thin-film solar cells capitalizes on gallium's enhanced solar spectrum absorption, chemical stability, and resilience under diverse environmental conditions (C. B. et al. 2021). Gallium-based compounds' ability to improve the performance, efficiency, and adaptability of semiconductors and PV panels makes gallium a crucial material in driving technology innovations and renewable energy development. The anticipated expansion in sectors such as smartphones, wireless

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technology, electric vehicles, solar energy, and LEDs is likely to increase demand for gallium (USGS 2023).

Since gallium is a critical material for many advanced and emerging technologies, the rapidly growing consumption raises significant concerns about its supply risk. Gallium supply is inherently restricted by the production of its primary carrier metals. Gallium is not found in free form in nature but is typically extracted as a byproduct during the processing of other metals, such as aluminum (95%) and zinc (5%), making its availability rely on the production volumes of these carrier metals (Fthenakis et al. 2009). Consequently, any fluctuations in the primary metal markets can significantly affect the supply of gallium (Løvik et al. 2016). For example, Germany ceased primary production of gallium in 2016 due to economic pressures faced by an aluminum plant (Grohol and Grow 2023). The current gallium production and stock are insufficient to satisfy the surging demand (USGS 2022). Under the global trend toward climate change mitigation, decarbonization, and renewable energy transition, the primary production of aluminum, due to its high energy consumption, is expected to decline, further reducing the availability of gallium (Frenzel et al. 2016). To address these availability concerns, the industry is increasingly focusing on secondary production. The recycling of gallium from industrial waste and end-of-life products, such as LEDs and solar panels, is becoming more widespread.

In addition, China's predominant role in the global gallium supply chain, accounting for the vast majority of production, poses a supply risk (Song et al. 2022). In 2022, global gallium production amounted to 550 tons, with 98% originating from China (USGS 2023). Both Europe and the United States have invested in new gallium recovery facilities to diversify the supply chain and enhance production capabilities outside China, aiming to mitigate this risk. These initiatives, which explore both primary and secondary sources of gallium, not only help address supply shortages but also contribute to securing a more stable and reliable supply of this critical material.

The production of gallium involves multiple stages that may generate significant environmental impacts. The primary production involves gallium extraction from bauxite and zinc ores, which entails large-scale mining operations that disrupt ecosystems, contribute to deforestation, and result in habitat loss (Pathan et al. 2013). The processing and extraction of these ores emit pollutants into the air and water, including heavy metals and toxic chemicals, and are associated with high energy consumption (Fthenakis et al. 2009). Although secondary production mitigates some environmental impacts (e.g., mining operations and resource depletion), it is not without its environmental challenges. This process involves intensive chemical treatments that generate hazardous waste and require considerable energy, contributing to greenhouse gas (GHG) emissions and ecotoxicity (Zhan et al. 2020; de Oliveira et al. 2021). Considering the growing capabilities for gallium production in the near future, both primary and secondary production can have significant environmental footprints. Therefore, an urgent need exists to assess the environmental impacts of gallium production comprehensively. Such assessments are crucial to inform regulations and promote sustainable practices, ensuring a balance between technological advancement and environmental sustainability.

Existing research on the environmental impact assessment of gallium mainly focused on secondary production from LED and PV wastes. For instance, Song et al. (2021) proposed a novel electrodeposition method to sequentially separate Cu-In-Cd-Ga metals from solar cell wastes. Their environmental impact assessment showed that this recovery method could significantly reduce global warming and toxicity impacts, compared with common recycling processes. However, the impact assessment was calculated based on the entire recovery flow without allocation for each recovered metal, leaving the specific impact of gallium recovery from solar cell wastes unclear. de Oliveira et al. (2021) compared multiple methods for recycling gallium from LED wastes. They concluded that the hydrometallurgy process was the most environmentally favorable method. Even so, recycling gallium from LED waste still causes sustainability challenges because of the heavy chemical usage and energy consumption. Liu and Keoleian (2020) compared 16 pathways of metal recovery from LED fixtures and found that recovering one kg of gallium with hydrometallurgical methods may result in 3687 kg $CO_{2\text{-eq}}$ of global warming potentials (GWP). The intensive environmental impacts are due to the low concentration of gallium in LED waste, which requires extensive chemicals for extraction. Despite ambitious recycling efforts for the gallium-included products, current secondary production capability can only make a marginal contribution to supply risks (Grohol and Grow 2023). Therefore, a substantial increase in primary production is essential to meet the rising demand.

The environmental impact assessment studies that include primary gallium production in their product scope have relied on very limited data sources. To the best of our knowledge, the ecoinvent database is the sole inventory that can support the life cycle assessment (LCA) of primary gallium production (Wernet et al. 2016). Consequently, all related LCA studies were built up on this database. Vauche et al. (2024) assessed the environmental impacts of producing a GaN semiconductor power device. Despite the collection of detailed empirical data for the manufacturing process, the impact of gallium metal input was referred back to the ecoinvent database. Similarly, LCA studies of CIGS modules for PV cells have also been based on the ecoinvent database (Nuss and Eckelman 2014; Amarakoon et al. 2018). Pallas et al. (2020) conducted an LCA of GaAs/Si nanowire-based tandem solar cells, constructing multiple scenarios in terms of industrial scales, energy consumption, substrate reuse, and other factors to establish benchmarks for future industrialization. The gallium material input was inferred from the ecoinvent database to build their inventory. Additionally, a comparative LCA study of different thin-film solar cells was conducted by Resalati et al. (2022), where they analyzed the environmental impacts of the metals used in the absorber layer (indium, gallium, and germanium) using the economic allocation method outlined in the work of Nuss and Eckelman (2014), which relies on the ecoinvent data. A study by van der Hulst et al. (2020) accounted for the GHG footprint of CIGS solar photovoltaic laminate, demonstrating that the CIGS PV laminate can decrease the GHG footprint by 83% with the process optimization from industrial-scale production. The software (Granta EduPack) they used for the footprint audit also depends on the ecoinvent database for their gallium-compound materials.

Although the ecoinvent is one of the most commonly used databases in LCA studies, there are still some limitations in the existing data entries for gallium production. First, although the production processes are based on data from an operational plant, the information on material consumption, particularly on different chemicals used, is estimated based on the consumption patterns of a laboratory-scale installation (Classen et al. 2009). Laboratory-scale processes differ from industrial processes on scale and operating parameters, and sometimes even different pathways may be adopted for economic reasons. Second, due to limitations in data availability, the energy consumption data in ecoinvent not only relies on proxy data from copper extraction processes for activities such as pumping, mixing, and electrolysis, but also overlooks many other energy-consuming activities that occur in real industrial conditions, such as cooling and heating. The inventory of material and energy consumption from ecoinvent may not accurately reflect the actual conditions of industrial-scale production, potentially leading to biased estimation in environmental impact assessments. This limitation highlights the need for more accurate and comprehensive data that can better represent the complexities and variabilities of industrial-scale gallium production.

To better address the gaps identified in above-discussed literature, this study conducts a gate-to-gate LCA study to evaluate the environmental impacts of primary gallium production in industrial conditions. We used a gallium production plant in China as the case study. This research makes two major contributions. First, we build the inventory using real-world plant data, considering detailed material usage, energy consumption, and waste generation. This inventory can serve as the industrial benchmark for primary gallium production and provide a foundation to support future research in quantifying the environmental impacts of gallium-containing products. Second, the impact assessment results identify key emission hotspots and offer insights into potential mitigation strategies, thereby guiding efforts to reduce the environmental footprint of gallium production.

2 Methods and data

This study uses LCA to evaluate the environmental impacts of primary gallium production. LCA is chosen due to its capacity to provide a comprehensive analysis of environmental impacts across all stages of a product's life cycle, from raw material extraction to disposal, ensuring a thorough understanding of the environmental footprint. The study follows the standard four-phase LCA process as outlined by ISO 14040:2006, which includes goal and scope definition (Sect. 2.1), inventory analysis (Sect. 2.2), and impact assessment (Sect. 2.3) with detailed interpretation (International Organization for Standardization 2006). To evaluate the impact of data uncertainty on the environmental impact assessment, we further conduct an energy scenario analysis (Sect. 2.4).

2.1 Goal and scope definition

The goal of this LCA study is to evaluate the environmental impacts of primary gallium production. As gallium is mainly recovered as a by-product from the aluminum industry, which typically uses the Bayer process, this study focuses on the primary gallium production process from aluminum extraction. Additionally, the study aims to identify the key processes contributing most significantly to environmental impacts and to provide guidance for future improvements in primary gallium production practices.

In this study, we used a primary gallium production plant (80 tons/year) located in Shanxi, China, as a case study. Given that over 90% of the world's gallium production is located in China, data from this Chinese plant provides a representative industrial benchmark for the global gallium industry (USGS 2022). This plant is a by-product factory, associated with an aluminum oxide production plant (800,000 tons/year) in China. The gallium plant receives Bayer Liquor as input from its aluminum production process, extracts gallium, and feeds the Bayer Liquor back to aluminum production. The primary gallium production process takes about 1.23 million tons of Bayer Liquor (containing gallium of 220–240 mg/L) per year. As only 10% of the Bayer Liquor is used for gallium production and is sent back after processing, gallium extraction does not have a significant impact on aluminum production. Therefore, the scope of this LCA study starts from the treatment of Bayer Liquor and ends at outgoing gallium metal (99.99%, 4 N), while ignoring the upstream environmental impacts of the aluminum extraction and downstream subsequent manufacturing processes (Fig. 1). Inbound ground transport of raw materials was excluded in this study. Supporting chemicals that are delivered in bulk may include inbound transport, however, no specific data is available. The functional unit is defined as 1 kg of primary gallium metal. Detailed information on gallium extraction processes, material usage, energy consumption, and final emissions is obtained based on its Environmental Impact Assessment (EIA) Report, which records data under real operation conditions (Shanxi Qingzhe Environmental Protection Science and Technology Co. 2019). This comprehensive data provides a solid foundation for accurately assessing the environmental impacts of primary gallium production under real-world industrial conditions.

2.2 Inventory analysis

The primary gallium production in this study contains 10 processes, including UP1: material preparation, UP2: resin adsorption, UP3: resin washing, UP4: acid making, UP5: leaching, UP6: resin regeneration, UP7: precipitation, UP8: purification, UP9: electrolysis, and UP10: refining. Figure 2 illustrates the detailed extraction process, material flows, and wastes. The following sub-sections introduce the life cycle inventory for material use, waste generation, and energy consumption for environmental impact assessment.

2.2.1 Material and waste

Material preparation, adsorption, and washing The primary raw material for this project is the Bayer Liquor filtered through the disk filters at the aluminum plant. The filtered Bayer Liquor is transported to a plate-and-frame filter for press. Here, the solid waste S1: Filtration residue (mainly containing aluminum hydroxide) is mixed with the remaining Bayer Liquor and fed back to aluminum production.

After filtration, the Bayer Liquor is pumped into adsorption towers for the gallium adsorption process, which employs chelating resin specifically designed to capture gallium. During adsorption, the Bayer Liquor comes into contact with the chelating resin, where gallium ions form stable complexes with the active functional groups on the resin. This process, powered by diffusion and fluid dynamics, allows the gallium ions from the Bayer Liquor to penetrate the microporous structure of the resin and be effectively adsorbed. The adsorption tail liquid (W1), which has passed through the resin and no longer contains gallium, is then directed to the plant's circulating tanks. Since there is no addition of other materials or additives during this process, the only change in the Bayer Liquor is the removal of gallium. This ensures that the process does not interfere with the aluminum production system, which supports our system boundary to exclude upstream impacts. The wastewater (W2) generated from the resin washing section, primarily composed of the residual Bayer Liquor on the resin, is collected and then transported to the aluminum wastewater treatment.

Leaching and resin regeneration Following the resin adsorption, a 4% sulfuric acid solution is employed for the leaching of the resin. This step involves bringing the acid solution into extensive contact with the adsorbed and washed resin to desorb the gallium ions from the resin. In

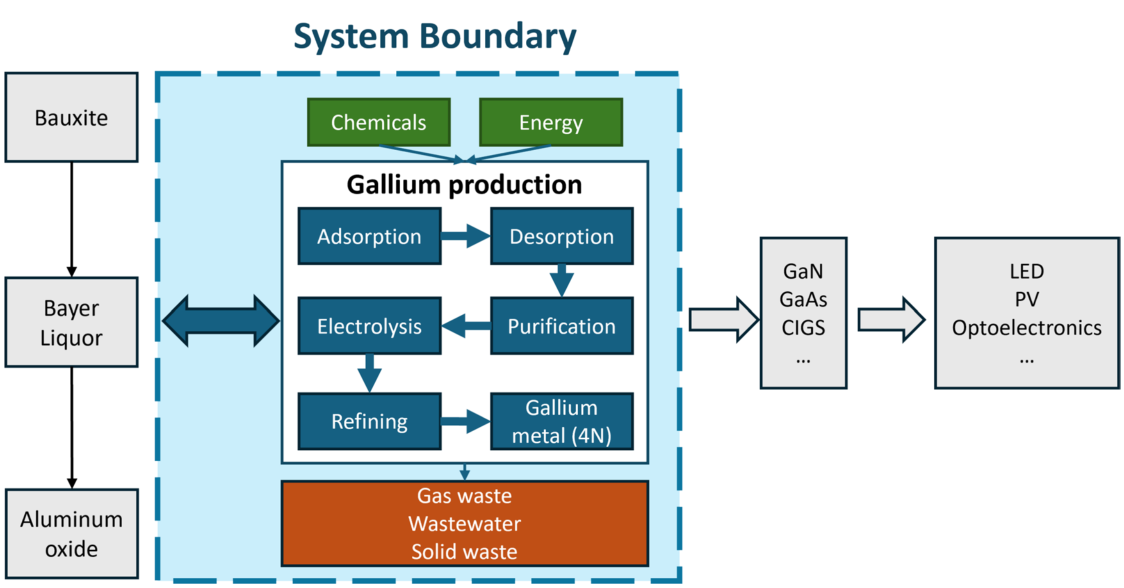


Fig. 1 System boundary of primary gallium production

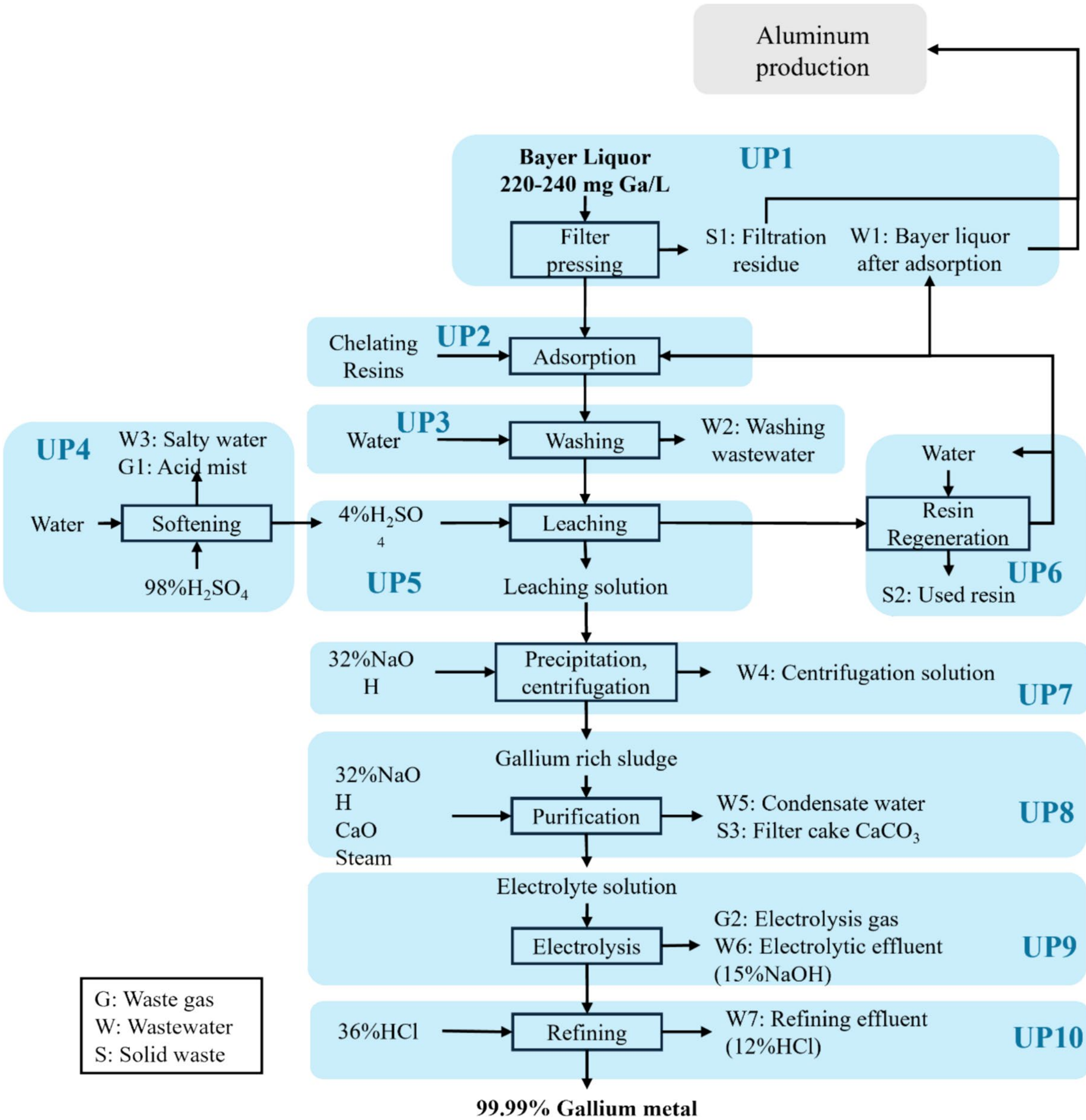


Fig. 2 Primary gallium production processes from Bayer Liquor

such an acidic solution, the hydrogen ions (H^+) lead to electrostatic repulsion with the gallium ions (Ga^{3+}) adsorbed on the resin. This repulsion weakens the stability of the chelation between the resin's functional groups and the Ga^{3+} ions, thereby decreasing the strength of the bond and allowing the gallium ions to be re-solubilized into the acidic solution. The used chelating resins are thoroughly washed with fresh water to remove residual solution and reactivated for reuse. The chelating resins are designed to be reused for around 30 cycles before disposal (S2).

In this project, the 4% sulfuric acid is in situ prepared by diluting 98% industrial-grade concentrated sulfuric acid. An exhaust vent is installed at the top of the desorption solution tank to manage the sulfuric acid mist (G1) produced during the acid mixing process. These acid mists are collected and are ultimately drawn into a spray absorption tower for treatment.

Precipitation, centrifugation, and purification The desorption effluent is then precipitated and centrifugated for purification. First, the desorption effluent is piped to the neutralization tank and reacts with the sodium hydroxide (NaOH) to neutralize pH and induce precipitation of the gallium-containing compounds. The precipitate is then processed using a centrifuge for solid–liquid separation. The centrifuged solution (W4) obtained in this process is discharged to the wastewater treatment facility in the plant. Meanwhile, the gallium-rich sludge produced by the centrifuge is transferred into a neutralization tank with an additional 32% NaOH solution and calcium oxide (CaO). The addition of CaO, known for its porous properties, allows the adsorption and precipitation of impurities. This helps to further purify gallium by removing unwanted contaminants. Exhausted steam from the plant's evaporator station is used to dissolve and heat the gallium-rich sludge to 100 °C. The purified solution resulting from these processes contains gallium at concentrations of 40–50 g/L, with a significantly reduced impurity content. This high-purity gallium electrolyte is critical for ensuring the efficiency of electrolysis. The residues from the purification process are transferred to a plate-and-frame filter press for further separation. The filter cake (S3), primarily composed of calcium carbonate ($CaCO_3$), is collected and transported for disposal.

Electrolysis and refining In the electrolysis process, crude gallium is produced by applying direct current to the preprocessed electrolyte solution. The plant is equipped with four electrolysis cells (each with a capacity of 2.6 m^3). Both the anode and cathode plates in the electrolysis cells are made of stainless steel. Gallium, which has a low melting point, can be deposited in liquid form at the cathode. A small amount of hydrogen and oxygen gas (G2) produced during the electrolysis process is evacuated and vented through the exhaust system. The gallium content in the electrolytic effluent (W6) can be maintained below 1 g/L, achieving an electrolysis efficiency greater than 95%. The primary reactions during the electrolysis processes are listed below.

$$NaGa(OH)_4 \rightarrow Na^+ + Ga(OH)_4^- \quad (1)$$

$$Ga(OH)_4^- \rightarrow Ga^{3+} + 4OH^- \quad (2)$$

$$Ga^{3+} + 3e^- \rightarrow Ga \quad (3)$$

$$2H^+ + 2e^- \rightarrow H_2 \uparrow \quad (4)$$

$$4OH^- - 4e^- \rightarrow 2H_2O + O_2 \uparrow \quad (5)$$

This stage also involves the further refining and purification processes of the crude gallium with hydrochloric acid to achieve 99.99% purity (4 N). The electrolytic effluent, comprising about 15% NaOH, is piped to a dedicated electrolytic effluent tank for neutralization with the acidic refining effluent (W7).

2.2.2 Energy consumption

Intensive energy consumption has been a major environmental concern for critical material production (Weng et al. 2016). Accurately quantifying the energy consumption in the gallium production process is indeed a crucial step in comprehensively assessing its life cycle environmental impact, especially for global warming consequences. In our case study plant, all facilities, devices, and equipment are powered by electricity. The electricity supply to the primary gallium production plant originates from a 110 kV high-voltage external grid. The overall annual electricity is 8 million kWh, which is obtained based on actual metered consumption recorded at the plant. To better estimate the environmental impacts of each process, we allocated the energy consumption based on the power rate of each device, including electrolysis, pumping, mixing, heating, and cooling. Detailed information on machine types, features, power rates, and counts is listed in Supplementary Information (Table S1).

2.2.3 Waste treatment

All waste streams and emissions generated during gallium production are included within the system boundary, in alignment with Fig. 1. First, all wastewater streams (W1-W7) produced from the processes (e.g., resin washing, acid making, leaching, precipitation, purification, electrolysis, and refining) are collected and piped to the facility's on-site wastewater treatment plant. Second, during acid making, small quantities of sulfuric acid mist (G1) are emitted from the acid dilution tanks. This mist is captured through an exhaust venting system and routed to a absorption tower, where it is neutralized. Third, solid waste streams such as S1 (filtration residue), S2 (used resin), and S3 (filter cake primarily composed of calcium carbonate) are collected, stabilized if necessary, and then either reused (e.g., returned to aluminum production) or sent to disposal facilities. These treatments ensure a comprehensive accounting of all emissions and align with actual plant practices.

The primary gallium production process itself does not generate any further direct, untreated emissions to air or water. All gaseous and liquid waste streams are captured and routed to on-site environmental control systems, including wastewater treatment and acid mist absorption. Therefore, direct process emissions are considered negligible in the process inventory.

2.2.4 Inventory data

With the detailed data on material usage, energy consumption, waste generation, and emissions collected from the plant's production processes, we built the process inventory data using the ecoinvent 3.10 system model (cutoff). Ecoinvent is a comprehensive and widely recognized LCI database in LCA, known for its high-quality, standardized, and transparent data (Wernet et al. 2016). Most of the materials can find the appropriate matched data entry, except chelating resin. We used cationic resin, which is widely used for metal-ion adsorption, as a proxy. Each waste stream is modeled using the closest available proxy in the ecoinvent database, such as "chemical waste, inert" or "limestone waste," based on its composition. Table 1 presents the compiled inventory data, highlighting the inputs and outputs for the primary gallium production process, as well as the ecoinvent entries we selected.

2.3 Life cycle impact assessment (LCIA)

To ensure the implementation of the LCA, we applied the ReCiPe 2016 (Midpoint) method to conduct a midpoint LCIA. ReCiPe 2016 quantifies potential impacts on various environmental categories, including global warming, human toxicity, ecosystem toxicity, water consumption, and land use, quantifies potential impacts on various environmental categories. ReCiPe 2016 is designed for global applicability, providing a broad perspective on environmental impacts with international scope. Through the interpretation of LCIA, we can identify the emission hotspots, such as key material usage, which contribute a lot to the impacts. The LCIA was carried out using OpenLCA v2.4.1.

2.4 Carbon mitigation under energy scenarios

The environmental impact of gallium production can be effectively reduced through adopting cleaner production technologies. With China's commitment to reaching peak emissions before 2030 and achieving carbon neutrality by 2060, its power system will have a profound transformation toward renewable energy sources and advanced carbon mitigation strategies (Liu et al. 2022). To better understand the future dynamics of carbon emissions, we tested its impacts under 14 distinct energy scenarios based on the literature (Zhang and Chen 2022). These hypothetical extreme scenarios incorporate different shares of renewable energy and the adoption of carbon capture systems (CCS). They are not intended to represent feasible energy transition pathways but rather to support researchers and policy-makers to capture the upper and lower bounds of carbon mitigation potential with different energy technologies and provide transparent benchmarks for constructing future energy mixes. For each scenario, we updated all electricity-related process inventory data, including upstream products, with specific greenhouse gas (GHG) emission factors (NREL 2021). The updated inventory was then analyzed through LCIA to capture the influence of these energy transitions on gallium's carbon footprint. In each scenario, we updated the emission factors for both on-site electricity use and all upstream electricity-dependent processes, including the production of sodium hydroxide, hydrochloric acid, sulfuric acid, and etc. Therefore, the global warming mitigation associated with each gallium production inventory reflects cleaner electricity inputs in both in-plant usage and its upstream supply chains.

3 Results and discussions

This section presents the analysis of the LCIA results based on the data and methods introduced in Sect. 2. The discussion is structured as follows: firstly, we analyze the LCIA results to identify key emission hotspots; secondly, we compare our findings with existing databases to highlight any differences; and finally, we explore potential improvements for the identified hotspots, informed by our sensitivity analysis.

3.1 Environmental impact assessment and emission hotspots

The LCIA results, estimated using the ReCiPe 2016 Midpoint method, cover different impact categories and are based on the inventory data collected from the case study plant (Table 2). With the LCIA results, we can further identify the emission hotspots during gallium production. First, NaOH consumption is one of the primary emission hotspots in gallium production. Figure 3a shows the share of each process in various environmental impact categories. UP8 Purification and UP9 Precipitation are the top two processes that generate more than two-thirds impacts among most categories. This is primarily due to the extensive use of NaOH, with 89 kg of NaOH required per kg of gallium produced. This observation is corroborated by Fig. 3a, which illustrates the share of each process in various environmental impact categories. In addition, the intensive electricity use during production significantly contributes to environmental impacts, particularly global warming. Figure 3b indicates that electricity accounts for over 40% of greenhouse gas (GHG) emissions. Based on the "ReCiPe 2016 (Midpoint)" LCIA method, the carbon intensity for electricity is 1.16 $CO_{2\text{-eq}}$/kWh. This high contribution is largely due to the local power grid, which relies heavily on fossil fuels, with over 98% of the electricity derived from such sources (>96% from hard coal and 2% from natural gas) (Wernet et al. 2016). The leaching process, which is critical for desorbing gallium ions from the chelating resin, requires substantial cooling to maintain the necessary temperature, leading to

Table 1 Life cycle inventory for 1 kg of primary gallium production

Processes	Material and energy	Unit	Consumption	Waste	Ecoinvent
UP1: ingredient preparation	Bayer Liquor	ton	16.03		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	Electricity	kWh	17.23		–
	S1 filtration residue ($Al(OH)_3$)	kg		32.08	market for cationic resin | cationic resin | Cutoff, S—RoW
UP2: resin adsorption	Chelate resin	kg	3		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	Electricity	kWh	11.39		–
	W1 Bayer Liquor after adsorption (for aluminum production)	ton		16.03	electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
UP3: resin washing	Electricity	kWh	3.27		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	Water	ton	1.86		tap water production, conventional treatment | tap water | Cutoff, S—RoW
	W2 wastewater	ton		1.86	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, S—RoW
UP4: acid making	98% sulfuric acid	kg	56		sulfuric acid production, sulfuric acid | Cutoff, S—RoW
	Water	kg	1.65		tap water production, conventional treatment | tap water | Cutoff, S—RoW
	W3 Salty water	kg		329	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, S—RoW
	G1 Acid mist	kg		6.88×10^{-4}	sulfuric acid
	Electricity (cooling for water softening)	kWh	0.72		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	Electricity (cooling for acid dilution)	kWh	1.35		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	Electricity	kWh	9.9		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
UP5: leaching	Electricity	kWh	4.55		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	Electricity (cooling for leaching)	kWh	26.10		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
UP6: resin regeneration	Water	kg	30.9		tap water production, conventional treatment | tap water | Cutoff, S—RoW
	S2 used resin	kg		1.8	chemical waste, inert
	Electricity	kWh	1.98		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC

Table 1 (continued)

Processes	Material and energy	Unit	Consumption	Waste	Ecoinvent
UP7: precipitation	NaOH	kg	44.84		market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, S—RoW
	W4 centrifugate solution	ton		1.25	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, S—RoW
	Electricity	kWh	4.75		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	Electricity (cooling for alkali dilution)	kWh	1.81		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
UP8: purification	Steam	kg	32.25		market for steam, in chemical industry, steam, in chemical industry, Cutoff, S—RoW
	CaO	kg	2		market for quicklime, milled, loose, quicklime, milled, loose, Cutoff, S—RoW
	NaOH	kg	44.16		market for sodium hydroxide, without water, in 50% solution state, sodium hydroxide, without water, in 50% solution state, Cutoff, S—RoW
	W5 condensate water	kg		32.25	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, S—RoW
	S3 filter cake ($CaCO_3$)	kg		2.4	limestone waste
	Electricity (cooling for alkali dilution)	kWh	1.81		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	Electricity	kWh	13.27		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
UP9: electrolysis	Anode (stainless steel)	kg	0		–
	Cathode (stainless steel)	kg	0		–
	Electricity	kWh	3.86		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	G2 electrolysis gas H_2	kg		0.011	hydrogen
	G2 electrolysis gas O_2	kg		0.095	oxygen
	W6 electrolysis waste	kg		263.3	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, S—RoW
UP10: refining	36% HCl	kg	0.012		market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state | Cutoff, S—RoW
	Electricity	kWh	0.29		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
	W7 refining waste	kg		0.018	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, S—RoW
Total electricity		kWh	102.28		electricity, high voltage, production mix | electricity, high voltage | Cutoff, S—CN-NCGC
Final product	Ga metal (99.99%)	kg		1	–

Table 2 Impact assessment of 1 kg gallium metal (4 N) primary production with ReCiPe 2016 (midpoint)

Impact category	Units	Value
Ozone formation, terrestrial ecosystems	kg NO_x-eq	7.36×10^{-1}
Land use	m2a crop-eq	2.03
Terrestrial ecotoxicity	kg 1,4-DCB	1.60×10^{3}
Water consumption	m^3	6.80
Freshwater ecotoxicity	kg 1,4-DCB	1.02×10^{1}
Global warming	kg CO_2-eq	2.82×10^{-2}
Marine eutrophication	kg N-eq	9.47×10^{-3}
Freshwater eutrophication	kg P-eq	7.96×10^{-2}
Human non-carcinogenic toxicity	kg 1,4-DCB	2.75×10^{2}
Human carcinogenic toxicity	kg 1,4-DCB	4.42×10^{1}
Marine ecotoxicity	kg 1,4-DCB	1.48×1
Ozone formation, human health	kg NO_x-eq	7.24×10^{-1}
Terrestrial acidification	kg SO_2-eq	1.53
Fossil resource scarcity	kg oil-eq	6.44×10^{1}
Stratospheric ozone depletion	kg CFC11-eq	7.66×10^{-5}
Ionizing radiation	kBq Co-60-eq	1.22×10^{1}
Mineral resource scarcity	kg Cu-eq	5.57×10^{-1}
Fine particulate matter formation	kg PM2.5-eq	6.42×10^{-1}

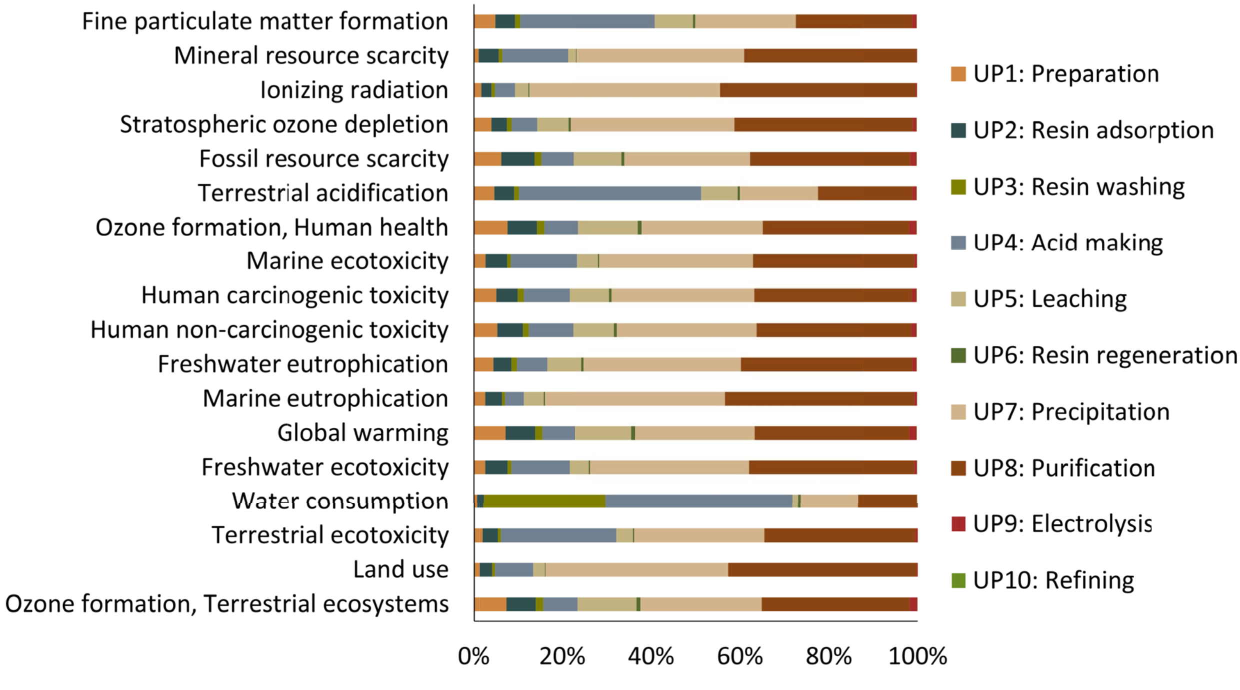
high energy consumption with a cooling capacity of 290 kW. In summary, NaOH and electricity consumption have been identified as the two major emission hotspots contributing significantly to the environmental burden of gallium production. Addressing these areas through process optimization and the adoption of cleaner energy sources is essential to mitigate the environmental footprint of gallium production.

3.2 Comparison analysis with similar studies

3.2.1 Comparison with 6 N primary gallium production from ecoinvent

To further validate the environmental impact, we assessed based on our case study plant, we compared our results with the gallium metal (Gallium (99.9999%), semiconductor-grade {GLO}| production | CUTOFF) in ecoinvent v3.10, which has been widely used in LCA studies for gallium-based materials. Similar to our study, the system boundary starts from Bayer Liquor treatment, excluding all the upstream impacts. Although the gallium output in the ecoinvent data has one extra purification process (i.e., fractional crystallization) to improve the purity from 4 to 6 N, the process only consumes a trace amount of energy (0.0465 kWh/kg). Compared with the energy consumption of primary gallium process (102 kWh/kg) in our study, this extra purification process introduces only a negligible difference in total energy use and environmental impacts. Therefore, despite the additional step, the overall system boundaries in terms of system boundaries and environmental burden can be considered comparable. Figure 4 shows the environmental impact comparison across different categories using the ReCiPe method (with detailed results listed in Table S2). The comparison shows notable differences in the impact distribution between our study and the ecoinvent database. In four out of eighteen categories—mineral resource scarcity, marine eutrophication, terrestrial toxicity, and land use—gallium production in our study generates fewer impacts compared with the ecoinvent database. However, our study shows higher impacts in the remaining 14 categories.

The disparities in LCIA results mainly come from (1) the extraction process differences and (2) data quality. First, gallium production in this study uses the resin (chelating resin) adsorption process, while ecoinvent data entry refers to the solvent extraction process using Kelex 100 as the chelating agent (Bautista 2003). These two processes differ significantly in their consumption of chemicals and energy, leading to different environmental impacts. Second, ecoinvent data entry involves too many approximations and assumptions. First, the data was collected based on the laboratory-scale installation rather than actual plant-scale operations. For energy consumption, the ecoinvent data was inferred from a copper extraction process to estimate the electricity consumption for the gallium extraction process due to the data limitation. However, copper and gallium production processes are quite different. Such approximation may result in inaccuracy (Krauss et al. 1999). Moreover, the electricity consumption data they referred to only considered the electrolysis process (2.63 kWh/kg Ga), ignoring many devices in real-world plant operation, such as mixing, pumping, filtering, heating, and cooling (Dresher 2001; Meijer et al. 2003). The total electricity consumption of this study is around 102 kWh/kg Ga, wherein the electrolysis only consumes 3.86 kWh, and facilities in other processes consume most of the energy, which cannot be ignored. In contrast, our study provides a more comprehensive analysis by quantifying energy consumption for all working devices and equipment under real-world plant conditions. For material usage, the gallium production inventory in ecoinvent relies on many approximations for chemical usage. For example, it used ethylenediaminetetraacetic acid (EDTA), adipic acid, and fatty alcohol to approximate Kelex 100, versatic acid 10, and n-decanol, respectively. These approximations can significantly influence the impact categories. For example, certain chemicals, such as EDTA, contribute substantially (> 80%) to many impact categories. Such approximation diminishes data quality and result robustness. In addition, some chemicals, such as lime, were estimated based on theoretical calculation (i.e., neutralizing pH), instead of empirical data. These approximations may add greatly to the uncertainty of the LCIA results. The inventory data from this study is more comprehensive and reliable, covering more plant operation details



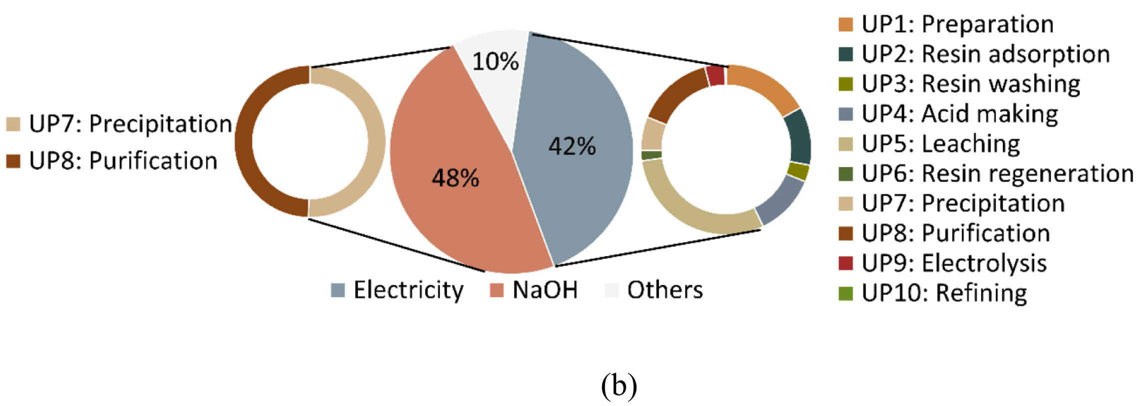


Fig. 3 **a** Share of impact assessment of primary gallium production for each process. **b** GHG emission hotspots

and including very limited approximations. The inventory analysis and LCIA results from our study provide a more accurate and detailed benchmark for primary gallium production compared with the ecoinvent database, making our findings a valuable resource for future research and policy development.

3.2.2 Comparison with gallium secondary production

The comparison of LCIA results between primary and secondary gallium production is crucial in understanding the environmental trade-offs and identifying opportunities for sustainability improvements across both pathways. As the demand for gallium continues to rise, driven by its critical role in advanced technologies such as semiconductors, LEDs, and photovoltaic cells, such comparison analysis becomes increasingly important. While secondary production offers the potential for resource recovery and circular economic benefits, its environmental advantages are not always guaranteed, when considering the energy and chemical-intensive processes involved. Therefore, we compared our results with a secondary production LCA study, which recovered gallium from linear LED lamp waste via leaching and solvent extraction (Liu and Keoleian 2020). To the best of our knowledge, this is the only detailed LCA studies on gallium secondary recovery at this time. Thus, their study

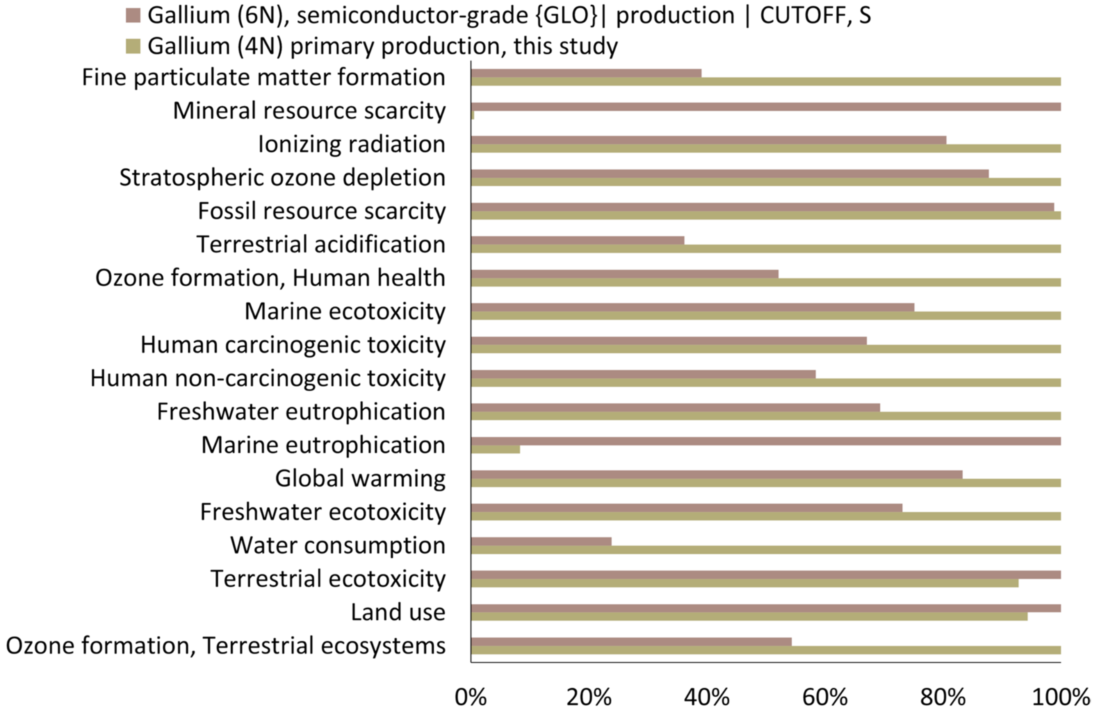
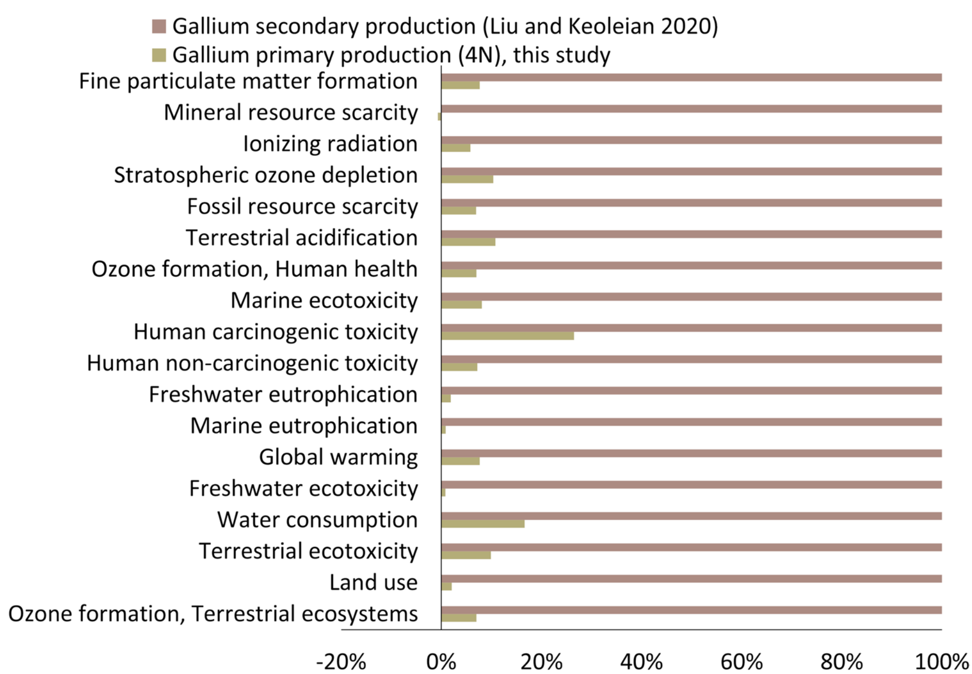


Fig. 4 Impact assessment comparison with ecoinvent database

provides the only available reference for secondary gallium recovery in an LCA framework. This analysis not only supports industrial decision-making and policy formulation but also highlights pathways for process optimization and cleaner production technologies.

The comparative LCIA results between primary and secondary gallium production are significantly different (Fig. 5, with detailed results listed in Table S2). Surprisingly, most environmental impact indicators for secondary gallium production are higher than those for primary

Fig. 5 Impact assessment comparison with gallium secondary production



production. A notable exception is the negative value of "mineral resource scarcity" associated with secondary gallium production, which reflects the benefits of metal recycling. In terms of chemical usage, NaOH dominates the environmental impact of primary production, while hydrochloric acid (HCl) is the primary contributor in secondary production, with significant contributions from water and Cyanex 923. These findings suggest the importance of minimizing chemical reagent usage in both production routes. However, the requirements of NaOH and HCl in precipitation, purification, and acid-leaching processes in both methods present inherent challenges to substantial reductions. A more practical approach would involve addressing the environmental impacts linked to the upstream production processes of these reagents. Furthermore, secondary gallium production may generate higher GHG emissions, due to an extensive network of energy and material flows. Among these, electricity consumption and sodium hydroxide usage are significant contributors, both of which are utilized in the high-temperature annealing process. Transitioning from energy-intensive high-temperature roasting to hydrometallurgical methods offers a promising pathway for environmental impact reduction. Additionally, the inherently low concentration of gallium in electronic waste further amplifies the environmental footprint of secondary production. Therefore, future improvements in gallium recycling should focus on simplifying process flows to minimize material and energy inputs while promoting cleaner production technologies, such as renewable energy, for key chemical reagents.

3.3 Global warming impacts under different energy scenarios

The substantial variations in carbon footprints under different energy scenarios suggest the importance of quantifying the impacts of energy sources and technologies on the life cycle emissions of gallium production (Fig. 6). Renewable energy sources, particularly solar, wind, hydro, and geothermal, show the lowest greenhouse gas (GHG) emissions, with carbon footprints significantly reduced by over 50% compared with the current coal-based scenario. Among non-renewable sources, scenarios with CCS, such as biomass CCS and natural gas CCS, also demonstrate notable emission reductions, highlighting the potential of CCS technologies in mitigating GHG emissions. Electricity-related consumption plays one of the most significant role in the carbon footprint of gallium production. Transitioning from current coal-based to low-carbon or renewable electricity sources provides a lot of savings, followed by modest reductions in emissions associated with sodium hydroxide (NaOH) use and other upstream processes. The baseline coal scenario represents the highest emissions, emphasizing the critical

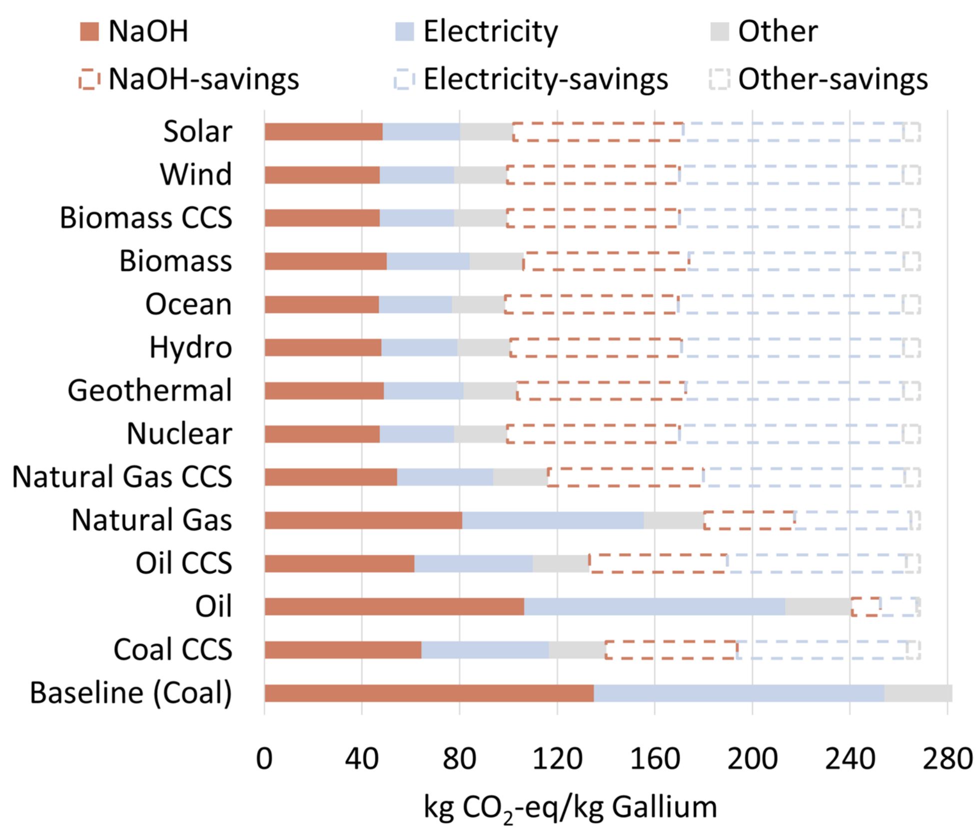


Fig. 6 Global warming impacts of gallium production under different energy scenarios

need for a shift to cleaner energy systems to achieve sustainable gallium production. Overall, the analysis indicates the great potential of clean energy transition into the production process to minimize environmental impacts effectively. By exploring these scenarios, this analysis provides valuable insights into the pathways for decarbonizing gallium production and supports informed decision-making for achieving sustainability goals.

4 Conclusions

This study analyzed the gate-to-gate life cycle environment impact of primary gallium production, using detailed operational data from a real-world plant in China to build the process inventory. LCIA results indicate that the massive NaOH used in gallium-rich solution precipitation and sludge purification processes is one of the emission hotspots, contributing the highest impact across multiple impact categories. In addition, the intensive energy consumption for stirring, pumping, and temperature control (e.g., cooling), especially under the current grid mix, has led to substantial carbon footprints and GWP impacts. Analysis also indicates that these environmental impacts can be significantly mitigated through process optimization, material recycling, and renewable energy adoption.

The contributions of this study include two facets. First, we constructed a comprehensive process inventory for primary gallium production using high-resolution data from an industrial-scale plant. Compared with the existing related database, our inventory may have better data quality and representativeness because (1) we minimized the use of assumptions and approximations and (2) we used industrial scale–production data instead of laboratory-scale installations. The inventory data from this study can serve as a benchmark for the gallium industry to better facilitate the environmental impact assessment of materials and products containing gallium compounds. Second, the identification of key emission hotspots and the results from energy scenario analysis provide valuable insights for decision-makers. These findings can inform both process optimization, such as improving efficiency in chemical usage and energy consumption, and mitigation policies such as transitioning to renewable energy sources and implementing material recycling practices.

Although this study has the merit of providing a systematic LCA for gallium production, several limitations should be noted. First, due to the lack of LCI data on the chelating resin, we had to use a similar resin as an approximation, which may decrease the accuracy of the LCIA results. The production process and environmental footprint of the specific chelating resin used in gallium extraction need further quantification. This resin is also widely used in the extraction of other critical materials (Page et al. 2017; Hermassi et al. 2021). In addition, this study does not include inbound ground transport of chemicals due to a lack of site-specific transport data. While this is unlikely to change the major findings of our study, future studies should incorporate transport modeling when such data becomes available to enhance completeness. Second, this LCA was constructed using data from a specific gallium production plant, which may not fully represent the industrial standard for gallium production globally. The global gallium industry employs various extraction technologies, depending on the source metals (e.g., aluminum or zinc) and the concentration of gallium (de Oliveira et al. 2021). These differences can lead to significant variations in environmental impacts across different plants and production processes. More empirical studies are needed to gather real-world data from gallium plants worldwide. Collecting data across different contexts and scenarios would provide a more comprehensive and representative understanding of the environmental impacts of the gallium industry.

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Data availability All data supporting the findings of this study are already available within the paper and supplementary information.

Declarations

Conflict of interest The authors declare no competing interests.

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