Original Article

Global lithium product applications, mineral resources, markets and related issues

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Abstract

Lithium's natural genes, namely its chemical properties, determine its irreplaceable and important role in many fields of modern society, and also determine why it has become one of the hottest green energy metals today and is inseparable from our daily lives. Therefore, lithium deposits and lithium products have become one of the most concerned resources in the world in the past decade, and have also become a hot spot for investment in the international market. During this period, although the price of lithium products has occasionally fluctuated, it has generally been on the rise. Many visionary countries have listed lithium produced locally as one of the critical metals and strategic resources and restricted it to prevent foreign investors from getting involved. As far as the global lithium resources we have mastered so far are concerned, the theoretical quantity is already large enough and seems to be enough for human consumption for a long time. However, many known lithium deposits, especially the brine lithium deposits that account for the majority, are still facing the difficulties of lithium extraction technology and low extraction rate. In other words, for now and in the foreseeable future, the difficulty and urgency of lithium ore prospecting are not as urgent as improving lithium extraction technology as soon as possible. Looking into the future, lithium products will continue to occupy an important position in clean metal energy. Developing the nuclear energy contained in lithium isotopes will be one of the keys to achieving a leap in new energy technology in the future of human society.

Key words: lithium; chemistry and geochemistry; application; resource; extraction and preparation; market

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1 Introduction

In recent decades, people have become more and more dependent on lithium batteries, and most people are becoming more and more familiar with rare metal lithium. The reason is simple. Our daily lives are increasingly closely related to electronic products related to lithium batteries, such as mobile phones, computers and other electronic products, and even the means of transportation that we cannot do without every day, especially various electric vehicles. They are inseparable from us humans and have to be in close contact with them almost every day.

Because of this, human enthusiasm for investing, finding and developing lithium and related metal deposits is getting higher and higher. The price of lithium products is naturally rising. Although there are some fluctuations in a certain period, the general trend has been rising.

The huge business opportunities covered by lithium products have also led more and more mining companies around the world to involve in the exploration and development of lithium deposits. Some internationally renowned mining companies have even turned from traditional bulk mineral deposits to the exploration and development of lithium deposits.

For example, on May 31, 2024, Chile's state-owned company, the world's largest copper miner, Codelco, signed a definitive agreement with the world's second-largest lithium producer, Sociedad Química y Minera de Chile (NYSE: SQM), to jointly develop a giant lithium deposit in Chile's Salar De Atacama. Sources say that the new deal gives Codelco a majority stake[1]. This is undoubtedly one of the key steps in Chilean President Gabriel Boric's strategy to increase government control over lithium production. Prior to this, Chile announced a new policy to nationalize lithium mines. Máximo Pacheco, chairman of Codelco, said in a statement: "Just as we helped Chile become a global leader in copper production, we will now work to make Chile a global leader in lithium production." Sociedad Química y Minera de Chile is a Chilean chemical company and a supplier of plant nutrients, iodine, lithium, and industrial chemicals.

Geologists who study, search, explore and develop different mineral deposits including lithium are also busy. They either help relevant mining companies to diligently search, explore and develop lithium deposits, study the geological and geochemical characteristics of the deposits, and search its mineralization laws in order to find more and better lithium deposits to meet the growing needs of human society. Similarly, mineral processing scientists have been experimenting and looking for the best technology for extracting lithium metal.

Of course, lithium metal is not the only energy metal known to humans. Our scientists are always looking for more efficient and environmentally friendly alternatives. We believe that a new generation of energy metals and/or semi-metals and related batteries will appear in the near future[2].

In any case, lithium is still indispensable in the new generation of energy metal batteries. Therefore, it is of great significance to discuss and summarize the global lithium resources and market status and related issues.

2 Chemistry and geochemistry

Lithium is derived from the Latin word λίθος, which means Lithos, i.e. rock or stone. Its chemical element symbol is Li, and its atomic number is 3. Under standard conditions, pure lithium is the least dense solid silvery-white alkali or lithium family metal. Lithium has a large charge density and a stable helium-type double electron layer, which makes it easy to polarize other molecules or ions, but itself is not easily polarized. Lithium is often in the oxidation state of +1 or 0, and is highly reactive and flammable. It is generally stored in a dry inert gas environment or kerosene in the laboratory. Fresh elemental metallic lithium has a metallic luster, but it quickly turns dark silver-gray in the air and then turns into a black oxide. As the least dense of all elements that are solids at room temperature, lithium can float on the lightest hydrocarbon oils and is one of only three metals that can float on water. Lithium does not occur freely in nature, but occurs mainly as pegmatic minerals, which were once the main source of lithium. Due to its solubility as an ion, it is present in ocean water and is commonly obtained from brines. Therefore, we can separate lithium metal from a mixture of lithium chloride and potassium chloride by electrolysis[3-5].

Lithium metal is soft enough to be cut with a knife. Its melting point of 180.50 °C and its boiling point of 1,342 °C are each the highest of all the alkali metals while its density of 0.534 g/cm3 is the lowest, comparable with pine wood . The nucleus of lithium is relatively unstable. It ranks 26th in content in the solar system and 27th in abundance in nature[3-6].

Although it was synthesized in the Big Bang, lithium, together with beryllium and boron, is markedly less abundant in the universe than other elements. Lithium is also found in brown dwarf substellar objects and certain anomalous orange stars. Certain orange stars can also contain a high concentration of lithium[7-9].

On February 19, 2015, the National Astronomical Observatory of Japan discovered that the nova explosion produced a large amount of lithium when observing the Delphinus Nova. This may mean that nova explosions may be the main mechanism for producing lithium in the universe[8].

Because of its relative nuclear instability, lithium is less common in the solar system than 25 of the first 32 chemical elements even though its nuclei are very light. For related reasons, lithium has important uses in nuclear physics. Lithium is a good conductor of heat and electricity as well as a highly reactive element, though it is the least reactive of the alkali metals. Molten lithium is significantly more reactive than its solid form[3-9].

Naturally occurring lithium is composed of two stable isotopes, 6Li and 7Li, the latter being the more abundant (95.15% natural abundance). Both natural isotopes have anomalously low nuclear binding energy per nucleon, compared to the neighboring elements on the periodic table, helium and beryllium. Lithium is the only low numbered element that can produce net energy through nuclear fission. The two lithium nuclei have lower binding energies per nucleon than any other stable nuclides other than hydrogen, deuterium and helium. Seven radio isotopes have been characterized, the most stable being 8Li with a half-life of 838 ms and 9Li with a half-life of 178 ms. Lithium isotopes fractionate substantially during a wide variety of natural processes, including mineral formation, metabolism, and ion exchange. Lithium ions substitute for magnesium and iron in octahedral sites in clay minerals, where 6Li is preferred to 7Li, resulting in enrichment of the light isotope in processes of hyperfiltration and rock alteration[8-11].

As a rare element, lithium exists in many rocks and brines, but the content is not high. There are quite a lot of lithium compounds in lithium minerals and brine, but relatively few of them have actual or potential commercial value. So far, we know of more than 30 kinds of lithium minerals, among which the main ones are spodumene, lepidolite, petalite, and hectorite clay. Spodumene and petalite are currently the most reliable commercial sources of lithium. Another important lithium mineral is lithium mica. A new source of lithium is hectorite clay, but currently only the Western Lithium in the United States is actively developing it[9-16].

Lithium constitutes about 0.002 percent of Earth's crust. Lithium is present in various igneous rocks, with the largest concentrations in granites. Granitic pegmatites provide the greatest abundance of lithium-containing minerals, with spodumene and petalite being the most commercially viable sources. Another source for lithium is hectorite clay[10-18].

Almost all vertebrate tissues and body fluids contain 21 to 763 ppb of lithium. Trace amounts of lithium are also found in many plants, plankton, and invertebrates, with concentrations ranging from 69 to 5,760 ppb. Among vertebrates, lithium marine organisms accumulate lithium more readily than terrestrial organisms. In addition, lithium is also present in soil and mineral water, cocoa powder, tobacco leaves, and seaweed. The total content of lithium in seawater is very large, estimated at 230 billion tons, and it exists in a relatively constant content of 0.14 to 0.25 ppm. Higher levels approaching 7 ppm have been found near hydrothermal vents on the seafloor.

In 1800, Brazilian chemist and politician José Bonifacio de Andrada discovered petalite in a mine on the Swedish island of Utö. But it was not until 1817 that Johann Arfvedson discovered the new element while analyzing the mineral petalite in the laboratory of chemist Jöns Jacob Berzelius. The element's compounds are similar to those of sodium and potassium, but its carbonates and hydroxides are less soluble in water and less alkaline. Berzelius named the alkali metal "lithion/lithina", which translates to lithos, to reflect the fact that it was found in a solid mineral[15-18].

Arfvedson later discovered that both spodumene and lepidolite contain this element. In 1818, Christian Gmelin first discovered that the flame color of burning lithium salts is bright red, but neither Arfvedson nor Gmelin were able to separate pure lithium from its salt. It was not until 1821 that elemental lithium was obtained when William Thomas Brand electrolyzed lithium oxide. This method was used by chemist Humphry Davy to separate alkali metals potassium and sodium. In 1855, Augustus Matthiessen produced more metallic lithium by electrolyzing lithium chloride. In 1923, the German company Metallgesellschaft AG borrowed this method to produce commercial lithium by electrolyzing a mixture of molten lithium chloride and potassium chloride. Since then, the production and use of lithium has undergone several drastic changes[17-25].

3 Application

Lithium and its compounds have several industrial applications, including heat-resistant glass and ceramics; lithium grease lubricants; flux additives for iron, steel and aluminium production; lithium metal batteries and lithium-ion batteries. These uses consume more than three-quarters of lithium production. Lithium-based drugs are useful as a mood stabilizer and antidepressant in the treatment of mental illness such as bipolar disorder. Lithium has a mass specific heat capacity of 3.58 kilojoules per kilogram-kelvin, the highest of all solids. Because of this, lithium metal is often used in coolants for heat transfer applications[25].

The first major use of lithium was in high temperature lithium greases for aircraft engines and similar applications during World War II and shortly thereafter. Lithium soaps have a higher melting point than other alkaline soaps and are less corrosive than calcium soaps. The demand for lithium soaps and greases has led to the creation of several small lithium mining operations in the United States[15-26].

Both ^{6}Li and ^{7}Li produce tritium when irradiated by neutrons. As a result, the demand for lithium increased dramatically during the Cold War as nuclear fusion weapons were produced. Lithium can also be used as a solid fusion fuel for hydrogen bombs in the form of lithium hydride. For this reason alone, the United States became the world's leading lithium producer between the late 1950s and the mid-1980s.

When using the Hall-Heroult process, lithium is used to lower the melting temperature of glass and improve the melting behavior of alumina. These two uses dominated the market in the mid-1990s17-19, 23-25 & 27-33. In the mid-1990s, several companies began extracting lithium from brines, which was cheaper than mining solid lithium ore underground or in open pits. However, due to low demand in the local market, most lithium mines closed.

Nuclear weapons manufacture and other nuclear physics applications are a major source of artificial lithium fractionation, with the light isotope ^{6}Li being retained by industry and military stockpiles to such an extent that it has caused slight but measurable change in the 6Li to ^{7}Li ratios in natural sources . The transmutation of lithium atoms to helium in 1932 was the first fully human-made nuclear reaction, and lithium deuteride serves as a fusion fuel in staged thermonuclear weapons[25].

According to the United States Geological Survey34, the global end-use market for lithium in 2019 was: batteries 65%, ceramics and glass 18%, lubricants 5%, polymer production 3%, continuous casting flux 3%, air treatment 1%, and others 5%. Over the past 10 years, the share of lithium consumption in the battery market has nearly tripled. Obviously, batteries are the fastest growing industry for lithium consumption.

In recent years, the need for a green and low-carbon economy and the introduction of relevant international treaties have accelerated the international community's demand for lithium, a resource with good physical and chemical properties. The output and consumption of lithium ore have shown a rapid increase overall, and it has become a strategic critical mineral generally recognized by the international community. It is widely used in emerging fields such as batteries, medicine, nuclear industry, aerospace, new energy vehicles, etc., and has shown great potential in controlled nuclear fusion power generation, because 1 gram of lithium is equivalent to 3.7 tons of standard coal[17-19, 23-25 & 27-34].

Lithium has a very small atomic weight, and the battery used as the anode has a high energy density. Lithium can also be used to make low-temperature and/or high-temperature batteries. Lithium batteries used for low temperatures usually use organic solvents as electrolytes, and inorganic salts are added to make them more conductive. Commonly used inorganic salts include lithium perchlorate, lithium hexafluorophosphate, lithium hexafluoroarsenate, and lithium sulfide. The positive electrode materials in secondary lithium batteries are also lithium-containing compounds and their multi-component compounds, such as lithium cobalt oxide, lithium nickel oxide, lithium manganese oxide, lithium iron oxide, etc. The cathode of the battery is lithium, and the anode is often a metal chloride. For example, the battery chemical reaction formula of a lithium-silver chloride battery is: $Li + AgCl \rightarrow LiCl + Ag$. Lithium batteries used for high temperatures usually use molten inorganic salts as electrolytes, but they must be used above the melting point of the salt. The relevant reaction formula is: $2Li + 2Cl \rightarrow 2LiCl$.

There is no doubt that the vigorous development of lithium batteries has dramatically increased the demand for lithium worldwide, and it became the main use of this substance in 2007. With the surge in human demand for lithium batteries, many mining companies around the world have expanded the exploration and mining of brine lithium mines. Some people believe that lithium will become one of the main objects of geopolitical competition in a world dependent on renewable energy and batteries[28-30 & 34-35].

In medical terms, lithium is an effective treatment for seborrheic dermatitis. This may be related to the fact that lithium can inhibit substance-P and all free fatty acids required for the growth of Malassezia yeasts. Some studies have shown that lithium can inhibit many enzymes: such as Na/K ATPase, adenylcyclase, enzymes of the prostaglandins E1 synthesis, and inositol-1-phosphatase. Lithium also has anti-inflammatory and immunomodulatory effects. Oral lithium-containing drugs are mainly used to treat bipolar disorder, but this type of oral drug can cause many side effects on the skin. Relevant research in France shows that lithium-containing hot spring water (Evaux thermal spring water) can improve patients' side effects of skin and nail lesions caused by cancer treatment[17, 25 & 34].

Lithium can also be used as a synthetic raw material, a reducing agent, a catalyst, a heat carrier for manufacturing nuclear reactors in the atomic energy industry, and used to manufacture special alloys and special glasses. It can also be used as a deoxidizer, desulfurizer, and defoamer in the metallurgical industry, as a fuel, and as the red part of fireworks that people love to see. It can also be used to launch weapons such as torpedoes. Alloys doped with lithium have the characteristics of high strength, low density, and high temperature resistance. Some people have also used lithium to synthesize lithium-lead liquid semiconductor alloys.

4 Resource

According to statistics from the United States Geological Survey, the total global lithium reserves are approximately 31,000 tonnes25 & 34. Other researchers have given similar results on the reserves (Figure 1)[35].

Chile is estimated to have the largest reserves by far (9.2 million tonnes), and Australia the highest annual production (40,000 tonnes). One of the largest reserve bases of lithium is in the Salar de Uyuni area of Bolivia, which has 5.4 million tonnes. Other major suppliers include Australia, Argentina and China25 & 34-38. As of 2015, the Czech Geological Survey considered the entire Ore Mountains in the Czech Republic as lithium province. Five deposits are registered, one near Cínovec is considered as a potentially economical deposit, with 160,000 tonnes of lithium[12, 25 & 34].

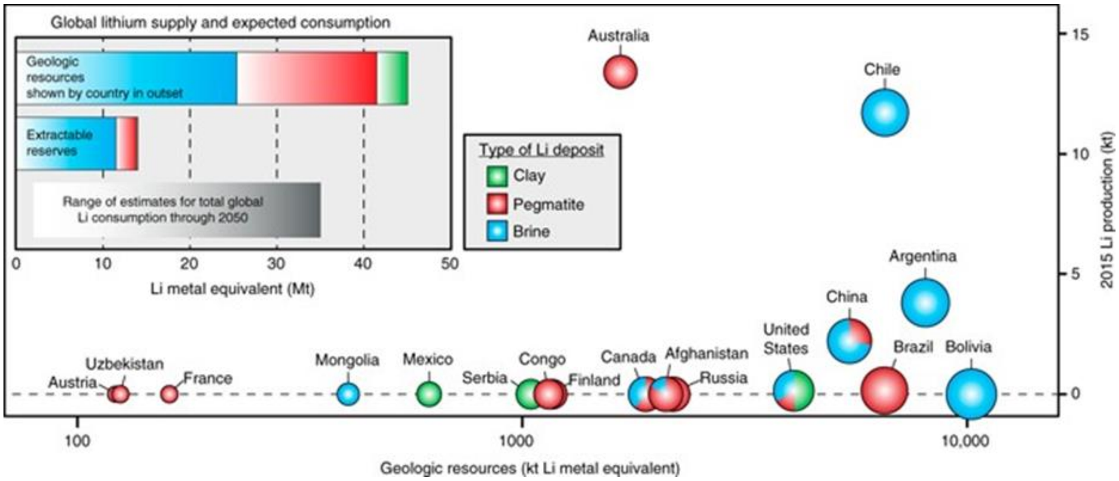

Figure 1. Global lithium resources and total 2015–2050 estimated consumption

Estimates for global Li resources are ~45 Mt Li and include brine, pegmatite, and clay resources. Global Li reserves (the amount of the resource that is currently economically extractable) are estimated at ~14 Mt Li, primarily from brine and clay deposits. Future Li consumption (2015–2050) estimates range anywhere from 3–35 Mt Li, depending on the efficiency of Li extraction and projections for electrification of the automobile industry, highlighting the need to explore for new resources of Li[35]

In June 2010, The New York Times reported that American geologists were conducting ground surveys on dry salt lakes in western Afghanistan believing that large deposits of lithium are located there. These estimates are "based principally on old data, which was gathered mainly by the Soviets during their occupation of Afghanistan from 1979–1989". The Department of Defense estimated the lithium reserves in Afghanistan to amount to the ones in Bolivia and doubled it as a potential "Saudi-Arabia of lithium"39 & 40. In Cornwall, England, the presence of brine rich in lithium was well known due to the region's historic mining industry, and private investors have conducted tests to investigate potential lithium extraction in this area[25].

The total lithium content of seawater is very large and is estimated as 230 billion tonnes, where the element exists at a relatively constant concentration of 0.14 to 0.25 ppm, higher concentrations approaching 7 ppm are found near hydrothermal vents[25 & 34].

The world's lithium resources are rich but highly concentrated, with 73% of lithium resources distributed in South America and North America. Oceania, Asia, Europe and Africa have relatively few lithium resources, accounting for 8%, 7%, 7% and 5% respectively (Figures 1 & 2). In terms of countries, lithium resources are mainly distributed in Bolivia, Chile and Argentina in the "Lithium Triangle" region of South America. It is currently known that lithium mines around the world are distributed in 6 large concentration areas, belonging to 23 countries.

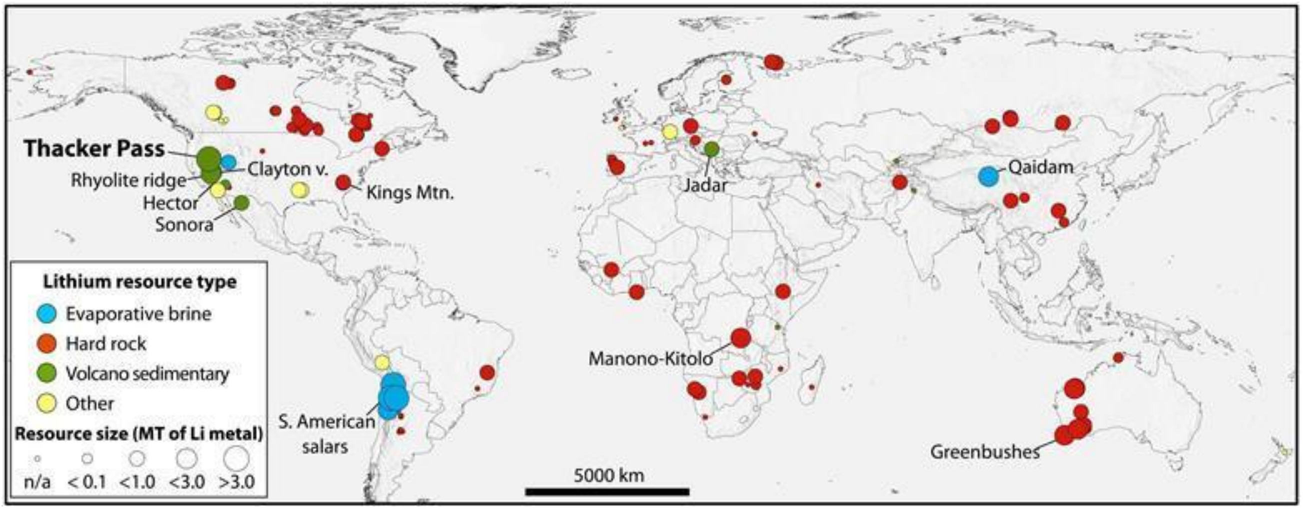

Figure 2. Map showing type and relative size of global lithium resources[41]

Current production is predominantly spodumene from pegmatites in Australia (47%) and brines underlying salt flats in Chile (30%), China (12%), and Argentina (5%)

In terms of reserves, the world's proven lithium reserves were 17 million tons in 2019. Among them, Chile's lithium reserves ranked first in the world, about 8.6 million tons, accounting for 50.59% of the world's total reserves, far ahead of other countries. Australia ranks second, about 2.8 million tons, accounting for 16.47% of the world's reserves. Argentina ranks third, about 1.7 million tons, accounting for 10.0% of the world's reserves. China ranks fourth, about 1 million tons, accounting for 5.88% of the world's reserves. The lithium reserves of the above four countries account for about 85% of the world's total reserves. It is followed by the United States, Canada, Zimbabwe, Brazil and Portugal (Figures 1, 2 & 3)[25, 34-36 & 40-47].

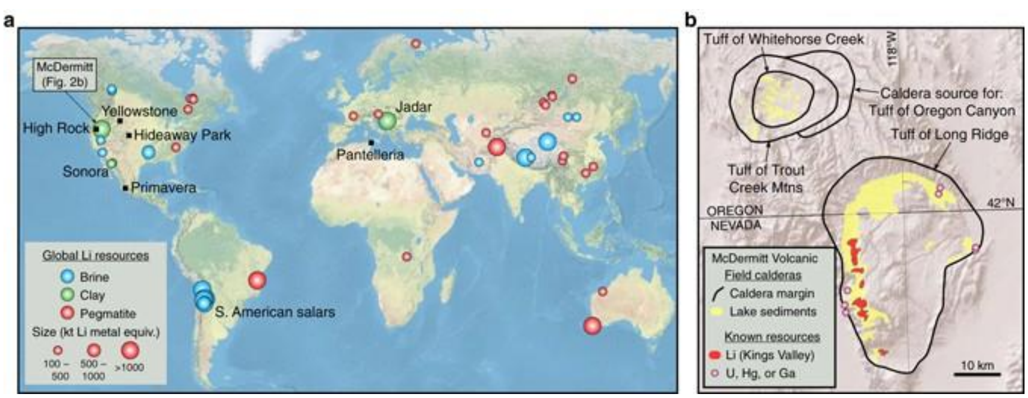

Figure 3. Location maps of global lithium resources and McDermitt volcanic field

a. Map of worldwide Li brine, clay, and pegmatite resources larger than 100 kt Li and locations of volcanic systems analyzed by Benson et al. (black squares). b. McDermitt Volcanic Field calderas and associated caldera-forming ignimbrites. Also shown are outcrops of caldera lake sediments and locations of the Kings Valley Li deposit and Ga, U, and Hg resources in the McDermitt Caldera[35]

In terms of lithium resources, 58.75% of the world's lithium is concentrated in the "Lithium Triangle" countries in Latin America, and the lithium resources in the United States, Australia and China account for 8.5%, 7.9% and 5.6% of the world's total, respectively.

Comparing the two different sets of data on reserves and resources, it can be seen that the United States, China, Bolivia and Argentina have great potential for the development and utilization of lithium deposits.

It should be pointed out that although lithium resources are very rich, many lithium resources cannot be converted into lithium reserves due to mining conditions and lithium extraction technology. For example, Uyuni, the world's largest known lithium mine, has a huge amount of lithium resources that cannot be included in lithium reserves because there is no economically feasible method for extracting lithium salts at this time[40-47].

Currently, nearly 30 countries around the world are conducting lithium exploration activities. Among them, Australia, the United States and Canada are the three most active countries in lithium exploration activities, with about 210 related exploration projects. In addition, there are 21 in Latin America, 25 in Africa, 24 in Europe, and only 6 in Asia excluding China.

The top ten lithium deposits in the world are Bonnie Claire, Vulcan, Clayton Valley, Kachi, Mt Holland-lithium, Pozuelos, Phyolite Ridge, Cuenca Centenario-Ratones, Tetra and Pastos Grandes (Figures 2 & 3).

China has discovered 153 lithium deposits/showings in more than 10 provinces (regions). Solid lithium deposits are mainly distributed in 14 provinces (regions), including Inner Mongolia, Henan, Shanxi, Jiangxi, Sichuan, Fujian, Xinjiang, Guizhou, Yunnan, Shaanxi, Guangxi, Guangdong, Hubei and Hunan. Liquid brine lithium deposits are concentrated in 6 provinces (regions), including Xinjiang, Qinghai, Tibet, Sichuan, Inner Mongolia and Hubei[47-53].

According to the information currently available, there are a total of 6 important lithium mining belts in all continents of the world[40-53].

4.1 North American lithium belt

- Whabouchi pegmatite lithium deposit in Quebec, Canada, with a total resource of 49.12 million tons, containing 744,800 tons of lithium and a grade of 1.52%.
- The pegmatite-type lithium deposits in Quebec, Canada and its northern James Bay have lithium resources of approximately 47 Mt (average lithium content of 0.23%, equivalent to 0.11 Mt lithium) and 22.20 Mt (average lithium content of 0.58%, equivalent to 0.13 Mt lithium), respectively.
- King Mountain pegmatite lithium deposit in Cleveland, North Carolina, USA, estimated at 20% spodumene content, ore Li_2O content is about 1.5%, the entire North Carolina pegmatite belt Li_2O reserves are about 1 Mt.
- Kings Valley sedimentary lithium deposit in Nevada, USA, with a total resource of 234 million tons, containing 1.560 million tons of lithium, a total reserve of 27.14 million tons, containing 231,000 tons of lithium, and a lithium grade of 0.85%.

- Silver Peak salt lake lithium mine in Nevada, USA, with Li_2O reserves of about 115,000 tons.

4.2 Oceania lithium belt

- Green bushes pegmatite lithium deposit in Yelgon Province, Australia, with lithium ore resources of 7.1 Mt, Li_2O grade of 4.06%; tantalum ore of 47 Mt, Ta grade of 0.06%; niobium ore of 10.8 Mt, Nb grade of 0.42%; tin ore of 4.7 Mt, Sn grade of 0.24%; kaolin ore of 2.3 Mt, kaolin grade of 30.00%.
- Mount Myrion pegmatite lithium mine in Yelgon Province, Australia, with spodumene reserves of 1 Mt and an average Li_2O content of 1.7%.
- Pilgangoora pegmatite lithium deposit in Australia, with a lithium resource of 983,000 tons.

4.3 African lithium belt

- The Bikita pegmatite lithium deposit in Fort Victoria, Zimbabwe, is divided into two mining sections: Bikita and El Hait. The Bikita mining section has a lithium ore reserve of 6 Mt and an average Li_2O content of 2.9%, mainly mining lepidolite; the El Hait mining section focuses on mining petalite, with a lithium ore reserve of 2.6 Mt and an average Li_2O content of 4.1%.
- Kamativi pegmatite lithium deposit in Zimbabwe, with an estimated resource of 100 Mt, an average lithium content of 0.28%, equivalent to 0.28 Mt of metallic lithium.
- The Manono and Kitotolo pegmatite lithium deposits in Katanga Province, Congo (DRC) have an estimated Li_2O resource of 11.45 million tons, of which Manono contains 835,000 tons of Li_2O resources and Kitotolo contains 310,000 tons of Li_2O resources.

4.4 European lithium belt

- Jadar sedimentary lithium deposit in Belgrade, Serbia, with a total resource of 125.3 million tons, 2.26 million tons of lithium and a lithium grade of 1.8%.
- The Cinovec pegmatite lithium deposit in the Bohemian Plateau of the Czech Republic has a lithium resource of 1.19 million tons.
- Wolfsberg pegmatite lithium deposit in Austria, with a lithium resource of 264,000 tons.

4.5 Latin America and South America lithium belt

This lithium ore belt is mainly rich in liquid brine lithium deposits, including the internationally renowned "Lithium Triangle". However, the author believes that large solid lithium deposits will be discovered in South America in the near future.

4.6 Asian lithium belt

The so-called Asian lithium mining belt is currently mainly concentrated in China. China's lithium reserves and resources are among the highest in the world, but it lacks high-grade, high-quality lithium deposits. The country's lithium resources are mainly concentrated in Qinghai, Tibet, Sichuan, Jiangxi, Hubei and Hunan provinces. The lithium resources in these regions account for 99.9% of China's proven resources. Among them, solid lithium deposits are concentrated in Sichuan, Jiangxi, Hunan, Xinjiang and other provinces (regions), while salt lake brine-type lithium deposits are concentrated in Qinghai, Tibet and Hubei provinces (regions). China's salt lake brine-type lithium deposits have low lithium content, and most of them are distributed in the plateau areas such as Qinghai and Tibet with weak infrastructure and poor mining conditions. This has led to a low development and utilization rate of lithium resources in China, and a significant lack of self-sufficiency[28, 34-36, 38, 40-45 & 47-54].

5 Extraction and preparation

5.1 Extraction[17-18, 25, 34, 51-53 & 55-62]

- **Sulfate method**: After spodumene and potassium sulfate are sintered together, potassium will replace lithium to form lithium sulfate that is soluble in water. The chemical reaction equation is as follows: $2LiAl(SiO_3)_2 + K_2SO_4 \rightarrow Li_2SO_4 + 2KAl(SiO_3)_2$. For a long time, sulfate extraction was the only method for industrial preparation of lithium. This method is not only applicable to spodumene, but can also be used to treat lithium mica, etc.
- **Lime method**: Lime or limestone is sintered with lithium ore at a temperature of 1,000°C and then treated with water. The leaching solution is evaporated multiple times to crystallize lithium hydroxide. The chemical reaction formula is as follows: $2LiAl(SiO_3)_2 + 9CaO \rightarrow Li_2O + CaO{\bullet}Al_2O_3 + 4[2CaO{\bullet}SiO_2]$. The advantages of this method are: strong applicability and ability to decompose almost all different kinds of lithium ores; the reaction does not require scarce raw materials; and lime and limestone are both cheap and easy to obtain. The disadvantages are: a dilute solution is obtained after leaching, and evaporation consumes a lot of heat and takes a long time.
- **Sulfuric acid method**: Ellestad and Leute first developed this method. The sulfuric acid method is applicable to β-spodumene and lepidolite. Under the temperature conditions of 250-300 ℃, the relevant lithium minerals react with sulfuric acid as follows: $2LiAl(SiO_3)_2 + H_2SO_4 \rightarrow Li_2SO_4 + H_2O{\bullet}Al_2O_3{\bullet}4SiO_2$. The problem with this method is that sulfuric acid only reacts with β-spodumene, but not α-spodumene. Direct decomposition of uncalcined spodumene with sulfuric acid only extracts 4% of the total lithium.
- **Extraction of natural brine**: The processing process is to precipitate the lithium in the natural brine into Li_2NaPO_4, and then convert it into lithium carbonate, which can be used as a raw material to process other lithium compounds. Processing natural brine can also produce by-products such as borax, potassium carbonate, sodium chloride, sodium sulfate and magnesium chloride.

5.2 Preparation of lithium metal[17-18, 25, 34, 51-52 & 55-62]

At present, there are the following methods for preparing metallic lithium:

- **Electrolysis**: Metallic lithium is obtained by electrolyzing molten lithium chloride. Graphite is used as the anode, low-carbon steel is used as the cathode, and the electrolytic cell pressure is 6.0-6.5 V. This will produce lithium with a purity of 99%. Metallic lithium obtained by electrolysis usually contains impurities such as Na, K, Mg, Ca, Fe, Si and Al, and needs to be purified. These impurities can be filtered out by remelting and using the difference in specific gravity. As for the sodium and potassium that are difficult to remove, they can be removed by hydrogenation.
- **Thermal reduction method**: The chemical reaction formulas are: $3Li_2O + 2Al \rightarrow 6Li + Al_2O_3$，$2Li_2O + Si \rightarrow 4Li + SiO_2$. Reduction of lithium oxide is an endothermic reaction and can only be carried out at high temperature and high vacuum。

6 Market[34, 41, 43-53 & 63-66]

As an important new energy metal, lithium plays an increasingly important role in lithium batteries, new energy vehicles and controlled nuclear fusion. Due to its important strategic significance, the world has set off a wave of exploration and development of lithium mineral resources. Some people even call 2016 the "Global Lithium Mineral Exploration Year". Compared with the sluggish market of bulk minerals, lithium mineral resources have become a hot spot in the market.

The global lithium consumption has steadily increased from 113,000 tons of lithium carbonate equivalent in 2010 to 310,000 tons of lithium carbonate equivalent in 2019. It has increased by 174.3% in the past 10 years. In recent years, the global lithium salt consumption has shown a more rapid growth momentum, with an average annual growth rate of 17.6% (Figure 4).

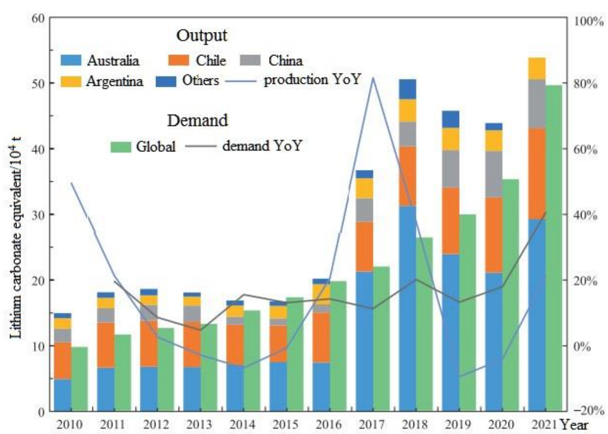

Figure 4. Lithium product production, demand and comparison of major countries in the world from 2010 to 2021[28 & 34]

In the foreseeable future, global consumption of lithium products will continue to grow (Figure 1).

Lithium products refer to metal lithium and lithium compounds such as lithium carbonate, lithium hydroxide and lithium chloride. Among them, lithium carbonate is the most direct lithium product formed after lithium ore mining and processing.

Before 2016, although lithium products were widely used in metallurgy, ceramics, glass, lubricants, organic chemistry, pharmaceutical products, mobile phone batteries and other fields, the usage was small and the price has been hovering at a low level. In recent years, the battery field has become the core driving force for the growth of lithium demand, and the scale of new energy vehicles has expanded significantly, driving lithium prices to continue to rise.

Since 2016, the global supply of lithium products has been tight and prices have risen rapidly. Since 2018, lithium products have experienced excess production capacity, and lithium product prices have fallen. Affected by the epidemic in the first half of 2020, lithium product prices fell to a low point. Starting from the second half of 2021, countries have increased their emphasis on new energy technologies, and the global new energy market has exploded. Demand for lithium products has continued to remain high, and as a result, supply has been insufficient, and prices have continued to rise and premiums have appeared.

In addition to lithium concentrate, the historical price trends of lithium products such as lithium carbonate and lithium hydroxide are basically the same whether in Asia, Europe or North America. The price was at the bottom in October 2020 (about US$10,000/ton), and then increased rapidly, once exceeding US$50,000/ton in 2022. Among them, the Chinese market price leads the way, once exceeding US$75,000/ton.

Australia is the world's largest supplier of lithium concentrate and the main source of China's spodumene concentrate imports, accounting for 95.4% of China's total lithium concentrate imports in 2021. More than 95% of the world's lithium concentrate is imported by China, increasing from 5.0×10^4 tons in 2012 to 26.3×10^4 tons in 2021, an increase of 426%. Among them, 95.4% of lithium concentrate in 2021 came from Australia, and the remaining 4.6% came from Brazil.

Before October 2020, due to factors such as oversupply and the COVID-19 pandemic, the long-term price of Australian lithium concentrate continued to decline to US$385/ton. After that, it bottomed out and grew rapidly. It reached US$3,700/ton in May 2022, an increase of 861%. Since 2021, Pilbara Mining has completed spot auctions of lithium concentrate through the BMX platform many times. Among them, the prices of the first four auctions were 70%, 121%, 83% and 69% higher than the long-order prices of the day, respectively. They played a significant guiding role in the price expectations of the lithium market and quickly pushed up the prices of lithium products.

In 2021, the United Kingdom and the United States successively launched lithium futures markets, continuing to increase their influence and voice on lithium pricing. Although China has also begun to plan its own lithium pricing and trading methods, its pace is relatively backward. In July 2021, Wuxi Electronic Trading launched a lithium carbonate forward contract, but the lithium carbonate contract is not a futures contract in the traditional sense. In November of the same year, the relevant person in charge of the Guangzhou Futures Exchange said that the exchange's lithium futures had been approved by the China Securities Regulatory Commission, but it would take some time to go online.

China is the world's largest lithium trading and consumer country, but its influence on the international pricing of lithium is limited. Since 2007, China's net imports of lithium carbonate have generally been on the rise. From 2007 to 2017, the total net imports of lithium carbonate in the country were 102,700 tons, of which the net imports in 2017 reached 29,200 tons. 63.70% of the imports came from Chile and 29.80% from Argentina. From 2010 to 2021, China's lithium carbonate imports grew rapidly, from 0.64 × 10^4 tons in 2010 to 8.1 × 10^4 tons in 2021, an increase of 11.7%.

In addition, as the main raw material for the production of metallic lithium, China's domestic lithium chloride production is extremely small and relies heavily on imports. From 2009 to 2015, the country's cumulative net import volume reached 21,800 tons.

From 2007 to 2017, China's total lithium product consumption reached 624,300 tons, with an average annual growth rate of 19% in 11 years. Among them, China's lithium product consumption in 2017 was 124,700 tons, accounting for about 52.48% of the world's total consumption of 237,600 tons that year. Compared with the consumption of 22,800 tons in 2007, it increased by 101,900 tons, an increase of 81.72%. In China's lithium product consumption in 2017, lithium used in the battery field ranked first, accounting for as high as 67%. Glass ceramics, medicine, grease and catalyst ranked second, third, fourth and fifth, accounting for 7%, 6%, 6% and 3% respectively, and the five together accounted for about 86% of the total lithium consumption.

Comparing the production and consumption of lithium products in China from 2007 to 2017, it can be seen that the domestic production of lithium products is significantly lower than the consumption, but both maintain a rapid growth trend. Over time, the gap between the production and consumption of lithium products will continue to widen.

China is rich in lithium resources, but battery-grade lithium carbonate, high-purity lithium carbonate, anhydrous lithium chloride and high-purity metallic lithium with high technical content still need to be imported in large quantities, reflecting the low efficiency of China's lithium resource development and utilization and the severe situation of resource security.

Since 2019, China's consumption of lithium products has exceeded 55% of the world's total, making it the world's largest consumer of lithium products. In recent years, China's imports of lithium carbonate and lithium concentrate have ranked first in the world. In 2021, China's lithium product consumption was about 39.3 × 10^4 tons of LCE, accounting for about 72% of the world's total production. Among them, China's domestic production was 13.0 × 10^4 tons, and imports were 34.7 × 10^4 tons. The external dependence of lithium resources was as high as 67% (external dependence = (consumption-production)/consumption).

As the world's largest consumer of lithium products, China's domestic lithium ore quality is poor and the development cost is high, which has caused the spot price of lithium products in China to be higher than the international level.

In contrast, China's lithium carbonate exports have remained at a low level. Before 2018, the annual export volume was less than 0.5 × 10^4 tons, and it increased slightly after 2018.

China's lithium hydroxide imports have always been at a low level. The average annual import volume from 2010 to 2021 was only 0.07 × 10^4 tons, accounting for less than 1% of global imports each year.

In contrast, as one of the world's most important lithium salt production bases, China's lithium hydroxide exports continue to increase. In addition to meeting domestic demand, the lithium hydroxide it produces is also exported in large quantities, and China's lithium hydroxide exports have ranked first in the world. In 2016, 9,800 tons of lithium hydroxide were exported, an increase of 6,100 tons from 3,800 tons in 2007, an increase of 61.51%. Then it increased from 0.25 × 10^4 tons in 2010 to 7.36 × 10^4 tons in 2021, an increase of nearly 28 times. It supplies more than 80% of the lithium hydroxide currently needed in the world.

The main reason for this phenomenon is that lithium hydroxide is mainly derived from spodumene, and the mineral processing and extraction process of brine-type lithium ore requires the preparation of lithium carbonate first, and then the generation of lithium hydroxide. Restricted by development conditions, technology, cost and other factors, the mining of brine lithium deposits in China has developed slowly and there is a large gap in the output of lithium carbonate. However, the lithium hydroxide produced by the country's pegmatite-type lithium mines has cost advantages, resulting in a situation where its lithium hydroxide imports are low and exports are high.

Europe and the United States have obvious resource advantages and a vast terminal automobile market. They are currently working hard to increase processing capacity and try to build their own supply chain closed loop.

There are many problems in China's lithium product market, including but not limited to the following aspects: most lithium deposits have poor development conditions, low lithium deposit development and utilization rates, serious homogeneity of lithium battery companies, low industrial concentration, insufficient extension of the industrial chain, uneven development of various links, imperfect industrial chain structure, and low degree of integration. In addition, China's financial support for promoting international capacity cooperation is insufficient, and the financial market has insufficient development, high financing costs, single channels, high thresholds for equity funds, imperfect financial infrastructure, lagging financial services development, and lack of effective regional financial markets. Furthermore, China's lithium product companies have serious inadequacies in internationalization capabilities and mutual coordination between companies, and have not formed a joint force. Basically, they are fighting alone.

Stimulated by the current high lithium price, the supply side of lithium products continues to expand, the investment in lithium ore exploration has increased significantly, the beneficiation and processing and salt lake lithium extraction technologies have achieved breakthroughs and improvements, and the secondary recycling industry has developed rapidly.

It is believed that in the next 3-5 years, the commissioning or increased production of lithium mines such as Greenbush, Wogina, Mt. Holland in Australia and Tres Quebradas (3Q), Cauchari, and Cionbre Muerto in South America will effectively increase the global supply of lithium products. The global supply and demand pattern may be greatly improved as a result, and it is expected to change from shortage to oversupply, thereby driving down the price of lithium products.

Since 2007, China's lithium product output has grown rapidly, with an average annual growth rate of 128%. From 2007 to 2017, the country's cumulative lithium production was 573,500 tons (lithium carbonate equivalent LCE, the same below). Among them, the national lithium product output in 2017 reached 96,000 tons, accounting for about 41.9% of the world's total output of 229,000 tons that year. However, China's demand for lithium products still mainly depends on imports. In 2017, China's lithium supply structure was as follows: 79,200 tons of spodumene ore was imported from Australia, accounting for 57%; 35,600 tons of high-concentration brine lithium ore was imported from Latin America, accounting for 23%. In 2018, China's lithium ore output reached 80,000 tons, a year-on-year increase of 17.6%. However, most lithium deposits are distributed in the Qinghai-Tibet Plateau, and the magnesium/lithium ratio of brine lithium ore in the Qaidam Basin in Qinghai is high, and the lithium extraction technology is not yet mature.

The development and utilization of lithium deposits are subject to dual constraints of the environment and technology, so the raw ore is highly dependent on foreign countries.

7 Discussion

There is no doubt that with the passage of time and the rapid rise of the three major industries of new energy, new materials and new medicines, the development and utilization of lithium resources, as a new clean green high-energy metal and known as "white oil", will surely receive more and more attention and importance from major countries in the world.

In addition, more and more governments and mining companies will further increase the exploration and development of lithium deposits. There will also be more countries that control and reserve lithium as a critical metal and strategic resource.

Whether it is lithium mining technology or mineral processing and extraction technology, innovation and breakthroughs are needed. In particular, for those brine lithium deposits with high magnesium/lithium ratios and many associated elements, breakthroughs in this area need to be made as soon as possible. Otherwise, these liquid lithium deposits with huge potential lithium resources can only become idle and waste deposits and cannot be mined and utilized. In other words, it is necessary to increase the innovation of brine lithium extraction technology in order to achieve large-scale production of lithium resources in difficult areas such as the Qinghai-Tibet Plateau.

China's salt lake lithium resources account for about 80% of the country's total lithium reserves, but China's salt lake lithium extraction capacity accounted for only 21.5% in 2020. Limited to brine lithium extraction technology, a large amount of salt lake lithium deposits in the country have not been developed and utilized. Therefore, breakthroughs in salt lake lithium extraction technology will greatly increase the supply of China's salt lake lithium resources. It is believed that the innovation of brine lithium extraction technology will change the supply pattern of lithium products and the international trade ecology. The release of China's brine-type lithium mine production capacity may become the main growth pole in the future, thereby reducing the country's dependence on foreign lithium resources.

The development technology of lithium in controlled nuclear fusion will become a new technology that countries are competing to develop and is highly confidential. The maturity and widespread use of this technology in the future will greatly change the way people live, especially the way new energy is used in the future. By then, severely polluted coal mines may be permanently closed. The problem of insufficient natural gas will also be solved. With the help of lithium controlled nuclear fusion, an economical, environmentally friendly and long-lasting new energy source, space travel may become a commonplace in people's daily life.

The recycling and utilization of lithium batteries will become an emerging industry. In the future, the lives and even survival of more people will be closely related to this industry.

The international trade futures market for lithium products will become more and more prosperous. Accordingly, the formulation of global international trade rules and conventions for lithium products will soon be on the agenda. Countries that actively participate, or even promptly initiate and participate in the formulation of relevant international trade rules will have the right to speak and bargain in the corresponding trade negotiations, and even become the leaders and controllers in this regard.

At present, China, Japan, and South Korea are the largest regions for lithium product consumption in the world, while Australia and Chile in South America are important lithium product suppliers. If these countries unite to initiate relevant multilateral trade agreements and conduct trade negotiations on the import and export of lithium products, they will definitely occupy the commanding heights of bargaining power in the future global lithium product trade and improve the international competitiveness of their respective lithium product-related companies.

Obviously, lithium resources will have an increasingly close relationship with the financial system. Whoever takes the lead in this regard may become an emerging capital power or even an emerging hegemon in the future.

In fact, some countries with strategic vision have consciously deployed and controlled overseas high-quality lithium resources with the help of relevant domestic institutions and enterprises. They use investment and mergers and acquisitions to target high-quality potential areas with rich lithium resources but not yet developed on a large scale, select overseas lithium deposits with lithium resource advantages and relatively mature exploration, plan and layout in advance, and strengthen international mining investment and development cooperation, so as to maximize the use of overseas lithium products.

8 Conclusions

Lithium's natural genes, that is, its chemical properties, determine its widespread use in many fields today, especially in related fields such as electronic products and electric vehicles. This has also triggered a global boom in its search, exploration and development, and has led to the worship and pursuit of it by the capital world.

We believe that in the near future, international rules and regulations on lithium product trade will definitely be released and regulate people's related trade in this product. At the same time, lithium resources and related products may assume some of the functions of international currencies, just like gold. The country that has more lithium mineral resources and related products will have the international pricing power of lithium products, and even have the right to speak in other international affairs. In other words, lithium resources and products may change a country's national destiny and world status to a certain extent.

The lithium futures and auction pricing models that have emerged in recent years will not only continue to impact the traditional mainstream long-term contract pricing model, but will also become more prosperous and have the potential to replace the traditional pricing model. It should be noted that the new pricing model may intensify the supply and demand tension and continue to push up the price of lithium products.

In the foreseeable future, the global supply and demand of lithium products will continue to grow rapidly. Australia, Chile, and Argentina will continue to be the main suppliers of lithium products in the world in the next few decades. The four countries once accounted for more than 95% of the global share. This situation will continue for a long time. China, Japan and South Korea were once the main demand sides of lithium products, accounting for more than 70% of the three countries. In the future, this trend will fluctuate due to international political games, but there will be no fundamental changes.

At the same time, driven by policies, markets and environment, the global new energy industry will continue to flourish. In response to this, the investment in lithium exploration funds will continue to grow, and the transaction of lithium mining rights will also be very prosperous, especially in underdeveloped regions such as Africa, South America and Eastern Europe. Because so far, many countries in these regions have not raised lithium resources to a strict national strategic level.

With the turmoil and changes in international politics, China's situation as the world's largest lithium product consumer and trading country will change, and the situation of insufficient domestic lithium resource supply and high external dependence will also change accordingly. However, the country's low level of development of brine-type lithium deposits, imperfect industrial chain structure of lithium resource market, lagging construction of lithium futures market and related financial system, and weak international competitiveness of related enterprises and financial institutions will still exist.

Lithium will occupy an increasingly important position in the new generation of clean and efficient energy metals, and will attract more and more people's attention.

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Data availability

The data that support the findings of this study is available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.