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A review of China's resources of lithium in coal seams

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Lithium gains an increasing importance in new energy vehicles and stationary energy storage, and development and utilization of lithium mines has attracted great attention around the world. In addition to the traditional lithium resources, lithium resources in coal seams have great potential in industrial application. Therefore, how to develop and utilize them is strategically significant for guaranteeing supply of lithium resources in China and promoting clean energy transformation. This paper summarizes the metallogenic ages, occurrence, enrichment factors, availability of lithium resources in coal seams in China. Conclusion are obtained as follows. i. coal-hosted lithium deposits discovered in China so far mainly occur in the Carboniferous-Permian strata of North China. They are less concentrated in smaller range in the Permian strata of Qilian-Qinling. ii. In China, coal-hosted lithium is mainly enriched in aluminum-bearing minerals. Lithium in coal seams mainly occurs in the inorganic matter, and some occurs in the organic matter. iii. Lithium enrichment in coal seams is caused by stable supply of aluminum and lithium-bearing minerals and special structural and geological factors. iv. According to China's national standards on grades of lithium content in coal seams, the metallogenic belts of lithium in coal seams at the southern foothill of Yin Shan and in Qilian-Qinling have the potential of lithium development and extraction, covering Junger mining area in Inner Mongolia, and Pingshuo and Ningwu mining areas in Shanxi.

KEYWORDS

lithium in coal seams, clean energy, China, lithium ore, development potential

1 Introduction

The soaring demand of lithium-ion batteries for new energy vehicles and stationary energy storages (Ma and Li, 2018; Zhong et al., 2018) needs to be supported by more supply of global lithium resources, the development of high-purity lithium products and low-cost lithium extraction methods (Wang and Chao, 2017; Yang et al., 2019). In 2007, the U.S. Congress listed lithium as strategic resources for U.S. economic development (Zhou et al., 2014). In 2009, the European Commission listed lithium as critical material for the economic development of Europe (Wang et al., 2014). The strategic importance of lithium resources has gradually become prominent. How to reasonably develop and utilize lithium resources may become the focus of global new energy competition in the 21st century (Zheng et al., 2007; Seredin et al., 2013; Su et al., 2019; Lunde Seefeldt, 2020). The coal resources in China are abundant and widely distributed. In recent years, lithium, germanium, gallium, rare earth and other strategic mineral resources have been found in coal seams. The comprehensive utilization of these associated resources is of great significance to guarantee the availability of emerging strategic mineral resources for China.

In a very long time, the lithium has not been developed from coal, which has not attracted much attention until 2008. Afterwards, many scholars in China (Liu Gangjun, Zhuang Xinguo, Sun Beilei, Yi Shu, Ning Shuzheng et al.) have analyzed the lithium content in coal with their focus on individual mining areas in China and have found an extraordinary enrichment of associated lithium in No. 4 and No. 9 coal seams of the Pingshuo Mining Area of Ningwu Coalfield, No. 2 and No. 8 coal seams in the Malan Mining Area of Xishan Coalfield, as well as No. 15 coal seam in the southern part of Jincheng Mine in Shanxi Province and No. 9, 10, and 11 coal seams of the Shenghui Mine of the Huoxi Coalfield, etc. By contrast, few scholars (Dai Shifeng et al.) have studied and analyzed the occurrence and distribution of lithium in coal seams in China from a broader perspective, and their studies are far from systematic and comprehensive. There are many deficiencies in basic research and application study, since research in this regard is still at the primary stage and the research issues are complex and difficult.

On the basis of systematic analysis of literature about lithium resources in coal seams, this paper discusses the occurrence, enrichment factors, availability of lithium resources in coal seams in China. It supplement basic research on lithium resources in coal seams in China. According to national standard *Guidance for Utilization and Classification of Content of Valuable Elements in Coal,* the metallogenic belts with highest development potential are determined, which is conducive to the forecast, exploration and development of lithium deposits in coal. This provides a reference to explore, develop and utilize lithium resources in coal seams in China and points out one pathway for circular economy of coal resources, which is of great significance to ensure China's resource security.

2 Distribution of lithium resources in China

China is rich in lithium resources. According to China Mineral Resources released by the Ministry of Natural Resources, P.R.C., China's lithium reserves in 2022 is 4,046,800 tons (lithium oxide) and is mainly concentrated in Qinghai Province, Sichuan Province and Tibet Autonomous Region, accounting for about 90% of lithium reserves in China. In addition, there are also lithium resources identified in Jiangxi Province, Henan Province, and Xinjiang Uygur Autonomous Region. The salt-lake lithium resources account for more than 80% of the industrial reserves of lithium in China and are mainly distributed in Qinghai and Tibet (Li H et al., 2014). Lithium ore mainly include spodumene and lepidolite, of which spodumene type is mainly distributed in Sichuan Province and Xinjiang Uygur Autonomous Region, and lepidolite type is mainly in Jiangxi Province (Li J et al., 2014; Qi et al., 2014).

Although China is rich in lithium resources, its resource endowment is poor and the industrial development cost is high. Therefore, the development of lithium resources in China stays in a very low level. According to USGS, although China's lithium output ranks third around the world in 2022, it only accounts for about 15% of the total global production (USGS, 2023). The largest granitic pegmatite-type lithium deposit is located in Aba Prefecture and Ganzi Prefecture of Sichuan Province (Liu et al., 2017), but bad transportation along with other constraints of this area hinder the development of lithium resources. In Jiangxi Province, the lepidolite content is quite low and lithium extraction cost is high. In Qinghai Province, there are many associated elements such as boron, potassium, magnesium and sodium in Qinghai Salt Lake, with high magnesium content and low lithium content. Bad weather makes the development of the lithium production in this region discontinuous. The salt lakes in Tibet have high lithium content (Sun et al., 2010), but the climate there is quite harsh.

The biggest problem in the development of lithium resources in salt lakes in China is the high Mg/Li ratio and high lithium extraction cost (Sun et al., 2012), for which technological breakthroughs need to be made. Therefore, the domestic lithium production cannot meet the demand in the short term, and import from overseas market is still needed for a certain period of time in the future.

In recent years, high content of associated lithium have been found in coal seams in China, especially in Junger Coalfield in Inner Mongolia and Ningwu Coalfield in Shanxi Province (Sun et al., 2010; Dai et al., 2012a), which makes associated lithium deposits in coal seams or coal strata an ideal alternative for the exploration of lithium resources. This is of great practical significance for further improving the availability of lithium resources in China.

3 Metallogenic age of lithium resources in coal seams

From the 1950s–1970s, some researchers from coal industry and mineral resources departments of China surveyed elements in coal during geological survey. In the recent 2 decades, people have conducted in-depth research on the enrichment mechanism and environmental impact of trace elements in coal. The metallogenic theories and practical utilization of germanium is the most in-depth studied and best used element among all valuable trace elements in coal. Large or super large coal germanium deposits including those in Lincang, Yunnan Province and Wulantuga, Inner Mongolia have been discovered (Sun et al., 2010; Pu et al., 2012). Many geologists have also analyzed the concentration of lithium in coal. For example, in Junger Coalfield, the average content of lithium in coal seams in the Harwusu Coal Mine is 116 mg/kg (Li H et al., 2014; Ning et al., 2017) and that in Heidaigou Coal Mine is 143 mg/kg. In Guanbanwusu Coal Mine, the average content of lithium in coal seams is 264 mg/kg, and even up to 1320 mg/kg (equivalent to 0.28% Li_2O) in coal ash (Sun et al., 2010; Jin, 2014; Sun et al., 2014). In Jungar No. 6 primary mineable coal bed, there is a super large lithium deposit (Qin et al., 2015; Zhu et al., 2016). Extraordinary enrichment of lithium has also been found in Ningwu Coalfield (Li H et al., 2014; Liu and Ming-yue, 2014; Shu and Wang, 2014), of which the average content of lithium in coal seams No. 4 and No. 9 in Pingshuo Mining Area is 128.27 mg/kg and 152 mg/kg respectively (Liu, 2007; Liu et al., 2019). However, significant progress has not been made in terms of metallogenic theories.

Many Chinese scholars have studied the distribution characteristics of lithium resources. In the first, Sun Shenglin et al. (2014) reviewed the distribution of lithium resources in coal seams in China. Zhu et al. (2016) studied the types and distribution of coal-hosted metal deposits in North China. Ning et al. (2017) made statistics on the lithium content in 25 coal mines along with studies on its metallogenic age and characteristics in Inner Mongolia, Shanxi, Henan, Chongqing and Guangxi Province. The

TABLE 1 Lithium content in coal seams in China (10^{-6}) (Sun et al., 2013a; Li H et al., 2014; Sun et al., 2016; Zhu et al., 2016; Ning et al., 2017).

Province	Coal field/mining area/mine field	Era	Minimum	Maximum	Average
Inner Mongolia	Jungar Mining Area	C_2	1.1	601	114
	Heidaigou Coal Mine in Junger mining Area	C_2	12	657	143
	Guanbanwusu Coal Mine in Junger mining Area	C_2	80	566	264
	Harerwusu Coal Mine in Junger mining Area	C_2	0.1	470	116
	Zhuozi Mountain Mining Field	C_2	38	203	105
Shanxi Province	Pingshuo Mining Area	P_1	13	211	128
		C_2			152
		C_2	94	506	238
	Anjialing Coal Mine Pingshuo Mining Area	P_1	42	196	117
		C_2	60	840	230
	Antaibao Coal Mine Pingshuo Mining Area	P_1	66	141	116
		C_2			144
		C_3	50	141	121
	JingGong No.1 Underground Coal Mine Pingshuo Mining Area	P_1	86	199	141
		C_2			139
	JingGong No.2 Underground Coal Mine Pingshuo Mining Area	P_1	83	211	113
		C_2			176
	JingGong No.3 Underground Coal Mine Pingshuo Mining Area	C_2			96
	Jincheng Mining Area	C_2	183	199	188
	HuoXi Coal Field Shenghui Coal Mine	C_2	65	154	94
	Xishan Coal Field	C_2	259	302	286
Henan Province	ShaanMian-Jiyuan Xin'an Mine	P_1	57	101	83
	Guhanshan Coal Mine in Jiaozuo	P_1	30	97	48
Chongqing	Nanwu Mining Area	P_3	17	257	96
	Nantong Mining Area	P_3	103	171	131
Guangxi Province	Fusui Coalfield	P_3	13	355	188
Gui Zhou Province	Liuzhi-Shuicheng Mining Field	P_3	9	105	28

content of lithium in coal seams in China are shown in Table 1. It is not difficult to know from Table 1 that coal-hosted lithium deposits discovered so far in China mainly occur in the Carboniferous-Permian strata of North China and Permian strata of South China. They are less concentrated in smaller range in the Permian strata of Qilian-Qinling.

4 Occurrence characteristics of lithium resources in coal seams

Some scholars have studied the occurrence and enrichment of lithium resources in coal seams. Zhuang Xinguo et al. (2001) conducted a study on trace element characteristics of Late Permian coal seams of Liuzhi Coalfield and Shucheng Coalfield in Guizhou Province and concluded that lithium in coal seams may have affinity for aluminosilicate; Sun et al. (2012) suggested that high concentration of lithium in coal seams has a close relationship with inorganic matter; Dai et al. (2012b) found that the occurrence of lithium in Guanbanwusu Coal Mine is mainly closely associated with aluminosilicate minerals in coal seams; Liu and Ming-yue. (2014) and Wang, (2018) studied on the enrichment mechanism of lithium in No. 9 stable minable coal of Pingshou Mining Area of Ningwu Coalfield and concluded that lithium is overwhelmingly enriched in inorganic matter and rarely enriched in organic matter. In a study conducted by Lewinska Preis et al. (2009) on trace

TABLE 2 Occurrence of lithium in some coal seams in China.

Scholars	Coal mines	Mechanism of occurrence and enrichment	Relationship with inorganic matter	Relationship with organic matter	Related minerals
Wang and Zhang. (2019)	Guanbanwusu Coal Mine of Junger Coalfield, Ordos Basin	Enrichment of lithium in high-grade coal is related to silicates	Related with silicates	—	Silicate
Dai et al. (2012a)	Guanbanwusu Coal Mine of Junger Coalfield, Ordos Basin	Lithium occurrence is closely related to aluminum silicate	Closely related with aluminum silicate	—	Aluminum silicate
Dai et al. (2012b)	Pingshuo Mining Area in Ningwu Basin	Lithium enrichment is closely related to aluminum containing minerals such as kaolinite	Related with aluminum containing minerals	—	Aluminum containing minerals such as kaolinite
Liu and Ming-Yue. (2014), Wang. (2018)	Pingshuo Mining Area in Ningwu Basin	The vast majority of lithium enrichment is closely related to inorganic matter	Related with inorganic substances and clay minerals	Weak relationship with organic matter	Kaolinite, quartz, calcite, pyriteetc.
Sun et al. (2010), Liu et al. (2017), Shu and Wang. (2014), Zhuang et al. (1998)	Pingshuo Mining Area in Ningwu Basin	Lithium is mainly presented in aluminosilicates, with fewer organically bound lithium elements	Related with iorganic matter, especially silicates; weak relationship with organic matter		Silicoaluminate, organic matter
Sun et al. (2012)	—	High concentration lithium is closely related to inorganic matter	Related with inorganic matter	—	Inorganic matter
Zhuang Xinguo et al. (2001)	Guizhou Liuzhi and Shuicheng Coalfields	Lithium has an affinity for aluminosilicates	Having an affinity for aluminosilicate	—	Inorganic silicoaluminate
Lewinska-Preis et al. (2009)	Spitsbergen District, Norway	Related with minerals	Related with minerals	Having an affinity for organic matter	—
Lucyna et al. (2009), Lei et al. (2015b)	Longyearbyen Mine Norway	72% of lithium combined with organic matter	—	Combining with organic matter	—
Swaine, (1990)	—	Lithium may be absorbed by clay minerals	Related with clay minerals such as kaolinite	—	Clay minerals such as kaolinite

elements in coal from the Kaffioyra and Longyearbyen coal mines in the Spitz Bergen, Norway, it is shown that lithium in coal from the former is 100% associated with minerals, whereas lithium in coal from the latter shows a high affinity for organic matter (concentration value of 72%). Swaine (1990) held that lithium can be absorbed by clay minerals such as kaolinite.

The research on lithium resources in coal seams at home and abroad is still at the primary stage. According to the existing data, lithium in coal is mainly related to inorganic components in coal, but it is also related to organic matter (Pougnet et al., 1985; PEI et al., 2018). Liu and Ming-yue. (2014) believed that the lithium in No. 9 coal mine in Pingshuo mining area of Wu Coalfield is mainly enriched in inorganic substances while only about 5.5% of lithium has an affinity for organic substances. These inorganic minerals are kaolinite, boehmite, chlorite group minerals, quartz, calcite, pyrite and amorphous clay minerals. In lithium bearing coal seams, lithium may be adsorbed by clay minerals; Dai et al. (2012a) and Wang and Zhang. (2019) also reached a similar conclusion on the enrichment of lithium in Guanbanwusu Coal Mine in Jungar Coalfield and believed that 80% of lithium in high-grade coal is related to silicate, while 60% of lithium in low-grade coal is related to silicate. However, in Longyearbyen Coal Mine in Norway, 72% of lithium is combined with organic matter (Lucyna et al., 2009; Lei et al., 2015a).

According to the existing research findings, among all the lithium bearing coalfields, the Ningwu Coalfield in Shanxi Province is the one that has been thoroughly studied. Particularly, the occurrence of lithium in stable minable coal seams No.4 and No.9 of Pingshuo mining area have been deeply studied by many scholars (Zhuang et al., 1998; Sun et al., 2010; Shu and Wang, 2014; Liu et al., 2017). In Pingshuo mining area, coal seam No.4 is the main minable coal seam (He, 2006; Sun et al., 2013b), of which the maximum value of lithium content is 211.28 mg/kg (Sun et al., 2012); The maximum value of lithium content in coal seam No.9 in Pingshuo mining area is 840 mg/kg, with an average value of lithium content of 152 mg/kg (Sun et al., 2010; Dai et al., 2012b). The results of SCEP analysis of coal samples show that the lithium in coal samples mainly exists in silicate, with a content value up to 482 mg/kg, while the value of lithium bonded in organic matter is only 32 mg/kg. The data show that lithium in coal seam No.9 is closely associated with inorganic matter, especially silicate, but is less closely associated with organic matter (Shu and Wang, 2014) (Table 2).

In a word, coal-hosted lithium often occurs in aluminosilicate minerals. In addition, it may be adsorbed by clay minerals such as kaolinite, boehmite, chlorite group minerals, quartz, calcite, pyrite and clay-like amorphous minerals. In summary, China's lithium in coal seams is mainly enriched in inorganic matter, especially the aluminosilicate minerals, but not likely in organic matter. This study provides the insight into distribution and enrichment of lithium in coal seams and the reference for relevant study.

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5 Geological factors for lithium enrichment in coal seams

According to the existing research findings, coal-hosted lithium mainly occurs in aluminum containing minerals and has similar metallogenic conditions with gallium. The geological factors for lithium enrichment in coal seams are: stable supply of aluminum and lithium sources, special tectonic and geological background, continuously and stable weathering and denudation and continuous movement of surface water. The coal-hosted lithium mainly occurs in aluminosilicate minerals and is greatly affected by weathering crust. It is difficult for lithium element to concentrated in nature and there is a series of long geological process before high concentration of Li occurs. For example, according to research on coal-hosted lithium in Pingshuo mining area by Liu and Ming-yue. (2014), Li H et al. (2014) and Shu and Wang, (2014), Ningwu basin is in an blocked bay where the coal seams have been developed for a long time without or with little interference, and it is a favorable place for peat accumulation and formation of lithium-rich coalfields. (Fan et al., 2018).

Sun Y Z et al. (2010) believe that there are three enrichment modes of lithium in coal seams: i. lithium is only enriched in seam roof, seam floor and vein rock, but not enriched in coal seams, such as in the case of the Tongxing Coal Mine in Henan Province; ii. lithium is not only enriched in seam roof, seam floor and vein rock, but also enriched in coal seams, such as in the case of Antaibao Coal Mine in Shanxi Province; iii. the lithium content in both coal samples and gangue samples is rather low, such as in the case of the Adohai Coal Mine.

In sum, lithium enrichment in coal seams is caused by stable supply of aluminum and lithium-bearing minerals and special structural and geological factors such as continuous weathering-denudation. The enrichment patterns vary in different metallogenic belts. Some lithium only occurs in the rock or is enriched both in rock and coal. Understanding these geological factors and enrichment pattern is of great significance for lithium exploration and development.

6 Evaluation of availability of lithium in coal seams

To evaluate the availability of lithium resources in coal seams, the following factors need to be considered: i. Whether lithium is abnormally enriched and whether there is mineralization on a scale; ii. How lithium exists in coal directly affects its availability and thus the difficulty of extraction. It may exist in ionic state, compound form or be adsorbed by certain minerals. Different forms of existence correspond to different levels of likelihood and efficiency of lithium extraction; iii. the behavior of lithium in the combustion process and its degree of enrichment in products of coal combustion. Since lithium is extracted from coal combustion products, the coal ash yield is an important parameter to evaluate lithium grade in coal (Dai and Robert, 2008); iv. Whether it is technically and economically feasible to develop and utilize lithium in coal. The extraction cost and technical feasibility are important factors in availability evaluation. In short, the availability of lithium in coal is affected by many factors, which should be considered for comprehensive evaluation.

Besides, environmental and economic sustainability should be considered in the extraction of lithium from coal. For the environmental aspect, the extraction process has a far-reaching impact on water resources, soil and air, especially when dealing with waste and tailings. In particular, the release of heavy metals may pollute water and affect aquatic ecosystems. A waste management system should be established to effectively separate, categorize and treat waste and tailings. Efficient waste treatment technologies should be adopted, such as solidification and resource recycling, to reduce the negative impacts on water resources, soil and air. In addition, since harmful elements are oftentimes enriched in coal-hosted lithium deposits, their distribution, forms of existence and formation mechanism should be studied to reduce environmental pollution and harm to human health in the process of lithium extraction, development and utilization (Dai et al., 2014). As for the economic aspect, the cost of extraction, technical feasibility, market demand and price fluctuations have a direct impact on economic sustainability. Besides lithium, other beneficial metal elements such as rare earth elements, gallium and silicon should be extracted together with lithium to improve the utilization efficiency of resources, reduce costs and realize industrial production (Xu et al., 2021). In addition, the study on their migration from coal to coal ash, existing forms and availability matters for the comprehensive development and utilization of coal ash and circular economy of coal industry. The advanced technology and experience of lithium extraction at home and abroad should be learned and introduced. In line with the concept of reduction, reuse and zero emission advocated by circular economy, technologies suitable for lithium extraction from coal ash should be effectively applied, which can reduce the cost, increase profit margin, and better serve the national economy.

In summary, a comprehensive evaluation is tremendously required to make extraction of lithium from coal environmentally and economically sustainable in order to gain utmost economic benefits and to protect environment at the same time. This involves scientific and effective waste treatment methods, clear environmental policies, efficient extraction technologies and market surveys. Such a comprehensive evaluation not only helps the sustainability of the extraction process, but also strategically guide the development of related industries.

According to China's *Guidance for Utilization and Classification of Content of Valuable Elements in Coal (GB/T 41042-2021)* published in 2021, basic technological property, major uses, occurrence states of coal, and symbiosis with other elements, and occurrence and distribution of harmful elements hindering extraction of valuable elements should be considered in utilization of coal with extremely high content of valuable elements. The conditions such as seam thickness, occurrence, scale and structure, and effects of production and processing methods on the coal quality should be considered.

The delineation of metallogenic belts of coal-hosted lithium provides a basis to evaluate the feasibility in tapping the potential of lithium resources in coal seams. According to study on China's coal-hosted metal metallogenic belts by Ning et al. (2019), the lithium resources in coal seams are divided into three metallogenic belts: i. the metallogenic belt at the southern foothill of Yin Shan. This metallogenic belt contains the southern Inner Mongolia Autonomous Region, the northern Shanxi Province, as well as a

TABLE 3 Grades of lithium content in coal seams.

Grades	No.	Lithium content in coal seams ω(Lid)/(μg/g)
Low lithium-content coal	Li-1	ω(Lid)≤10
Medium lithium-content coal	Li-2	10<ω(Lid)≤50
High lithium-content coal	Li-3	50<ω(Lid)≤120
Extra high lithium-content coal	Li-4	ω(Lid)>120

TABLE 4 Classification of lithium content in coal seams of some mining areas in China.

Classification	Province	Coalfields/mining areas/mine fields	Average value
Extra high lithium-content coal	Inner Mongolia	Heidaigou Coal Mine in Junger Mining Area, Guanbanwusu Coal Mine in Junger Mining Area	143,264
	Shanxi	Pingshuo Mining Area, Anjialing Coal Mine in Pingshuo Mining Area, Antaibao Coal Mine in Pingshuo Mining Area, JingGong No.1 Underground Coal Mine In Pingshuo Mining Area, JingGong No.2 Underground Coal Mine in Pingshuo Mining Area, Jincheng Mining Area, Xishan Coalfield	128, 152, 238, 230, 144, 141, 139, 176, 188, 286
	Chongqing	Nantong Mining Area	131
	Guang Xi	Fusui Coalfield	188
High lithium-content coal	Inner Mongolia	Jungar Mining Area, Harwusu Coal Mine in Junger mining Area, Zhuozi Mountain Coalfield	114, 116, 105
	Shanxi	Anjialing Coal Mine of Pingshuo Mining Area, Antaibao Coal Mine of Pingshuo Mining Area, JingGong No.2 Underground Coal Mine of Pingshuo Mining Area, Jing Gong No.3 Underground Coal Mine of Pingshuo Mining Area, Shenghui Coal Mine of HuoXi Coalfield	117, 116, 113, 96, 94
	He Nan	ShaanMian-Jiyuan Xin'an Mine in Henan	83
	Chongqing	Nanwu Mining Area	96
Medium lithium-content coal	Henan	Guhanshan Mine in Jiaozuo	48
	Guizhou	Liuzhi-Shuicheng Coal Field	28

part of Hebei Province. It includes the coal bearing belt at the north edge of North China, the Yimeng coal bearing belt, the northern Xian Province coal bearing belt, the western Xian Province coal bearing belt, and the western edge of the Erdesian basin coal bearing belt (Zhu et al., 2016). ii. the Qilian-Qinling metallogenic belt. This metallogenic belt contains the western Henan, central Shaanxi, Gansu, and Qinghai Province, including Songqi coal bearing belt, Weibei coal bearing belt, west edge of the Erdos Basin coal bearing belt, Qilian coal bearing belt and the Chaibei coal bearing belt. The lithium outlier in coal seams is mainly distributed in the Permian coal beds of Shandong and Henan Province. iii. the metallogenic belt in Sichuan, Yunnan, Guanxi Province. This metallogenic belt is located in the southwestern part of China, mainly including Sichuan, Chongqing, Guangxi, Guizhou, and contains Longmenshan inverted depression coal bearing belt, uplift coal bearing belt in central and southern Sichuan, Kangdian fault uplift coal bearing belt, fold coal bearing belt in eastern Yunnan, and the Youjiang fold coal bearing belt. The lithium outlier in coal seams is mainly distributed in the Permian seams in Chongqing, Guangxi and Guizhou (Liao et al., 2020).

Lithium content in various mining areas was analyzed with consideration of aforementioned delineation of metallogenic belts of coal-hosted lithium and grades of lithium content in coal seams (Table 3). It is found that extra high lithium-content coal, high lithium-content coal, and medium lithium-content coal are distributed in all metallogenic belts (Table 4). The extra high lithium-content coal is distributed in the metallogenic belt at the southern foothill of Yin Shan and in Qilian-Qinling and is concentrated in Junger Mining Area in Inner Mongolia, Pingshuo Mining Area in Shanxi, Nantong Mining Area in Chongqing, and Fusui Coalfield in Guangxi. The high lithium-content coal is distributed in the metallogenic belt at the southern foothill of Yin Shan and in Qilian-Qinling, covering Junger Mining Area in Inner Mongolia, Pingshuo Mining Area in Shanxi, ShaanMian-Jiyuan Xin'an Mine, and Nanwu Mining Area in Chongqing. The medium lithium-content coal is distributed in the metallogenic belts in Qilian-Qinling and in Sichuan-Guizhou-Guangxi, covering Guhanshan Mine in Henan and Liuzhi-Shuicheng Coalfield in Guizhou. According to the requirements of content $\omega(Li_d)>50$ μg/g for lithium extraction in the standard, the average content of 50 μg/g in extra high and high lithium-content coal meet the requirements for extraction, while the average content less than 50 μg/g cannot meet the requirements for extraction. The metallogenic belts of lithium in coal seams at the southern foothill of Yin Shan and in Qilian-Qinling have the potential of lithium development and extraction. In addition, according to previous research, China's Junger Coalfield, Ningwu Coalfield, and Qinshui Coalfield have great potential in commercial development of lithium in coal seams. The predicted lithium resources in Junger Coalfield is about 3 million tons; The associated lithium ore reserves in coal seam No. 9 in Pingshuo Coalfield is about 560,000 tons (Dai et al., 2014); the resource of Li_2O in No. 15 coal seam in Qinshui Basin is 55,600 tons (Lei et al., 2022). Thus, the belts with development potential are distributed in Junger Mining Area in Inner Mongolia, Pingshuo Mining Area, Ningwu Coalfield, Qinshui Coalfield in Shanxi, ShaanMian-Jiyuan Xin'an Mine in Henan, and Nantong Mining Area in Chongqing.

7 Conclusion

1. China's lithium resources in coal seams are mainly hosted in the Carboniferous Permian coal in North China and secondarily in the Late Permian coal in South China. They are less concentrated in smaller range in the Permian strata of Qilian-Qinling.
2. Coal-hosted lithium is often enriched in aluminum containing minerals. Lithium in coal seams generally occurs in inorganic matter, with a small part occurring in organic matter. These inorganic minerals are kaolinite, boehmite, chlorite family minerals, quartz, calcite, pyrite, and amorphous clay minerals.
3. Lithium enrichment in coal seams is caused by stable supply of aluminum and lithium-bearing minerals and special structural and geological factors such as continuous weathering-denudation. The enrichment patterns vary in different metallogenic belts. Some lithium only occurs in the rock or is enriched both in rock and coal.
4. Based on previous delineation of metallogenic belts of coal-hosted lithium and grades of lithium content in coal seams, the metallogenic belts at the southern foothill of Yin Shan and in Qilian-Qinling have the potential of lithium development and extraction, covering Junger Mining Area in Inner Mongolia, Pingshuo Mining Area, Ningwu Coalfield, Qinshui Coalfield in Shanxi, Shanmian-Jiyuan Xin'an mine in Henan, and Nantong Mining Area in Chongqing. This finding provides the insight into theoretical study and exploration and development of lithium in coal seams. It is recommended to focus on these two metallogenic belts in exploration and carry out geological survey in Junger Mining Area in Inner Mongolia and Pingshuo Mining Area in Shanxi. In addition, a comprehensive survey of metal elements associated with coal, gangues, and argillaceous rocks in coal seams should be conducted in all large-scale coal fields in China. In such a survey, attention should be paid to aluminous strata. In addition to lithium, other resources which include germanium, gallium, rare earth and other scattered rare metals should also be surveyed so as to find their new metallogenic prospects and ensure the sustainable exploration and development of these resources. It is suggested that belts for development and utilization of lithium and other scattered rare metals in coal seams should be strategically proposed in China as soon as possible with scientific planning and optimization of resources. In this way, associated elements in coal can be utilized to support comprehensive development of strategic emerging mineral resources. And last but not least, industrial structure should be adjusted and improved through the horizontal synergy of multiple industries, the vertical extension of the industrial chain, and the improved waste recycling system. Large poly-generation strategic bases should be established to extract strategic metals from coal, so as to promote the utilization of multiple resources and efficiency in resource utilization, waste recycling, and by-product utilization. In doing so, environmental pollution can be reduced, and the efficient use of clean energy and strategic transformation can be promoted.

Author contributions

CL: Conceptualization, Writing–original draft, review and editing; TZ: Writing–review and editing, Supervision, Funding acquisition; GW: Conceptualization, Formal analysis; DC: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Dai, S. F., Jiang, Y. F., Ward, C. R., Gu, L., Seredin, V. V., Liu, H., et al. (2012b). Mineralogical and geochemical compositions of the coal in the Guanbanwusu Mine,Inner Mongolia,China: further evidence for the existence of an Al (Ga and REE) ore deposit in the Jungar Coalfield. *Int. J. Coal Geol.* 98, 10–40. doi:10.1016/j.coal.2012.03.003

Dai, S. F., Ren, D. Y., Zhou, Y. P., Vladimir, S., Li, D. H., Zhang, M. Q., et al. (2014). Coal-hosted rare metal deposits:Genetic types,modes of occurrence,and utilization evaluation. *J. China Coal Soc.* 39 (8), 1707–1715. doi:10.13225/j.cnki.jccs.2014.9001

Dai, S. F., and Robert, B. (2018). Coal as a promising source of critical elements: progress and future prospects. *Int. J. Coal Geol.* 186, 155–164. doi:10.1016/j.coal.2017.06.005

Dai, S. F., Zhang, W. G., Colin, R., Seredin, V. V., Hower, J. C., Li, X., et al. (2012a). Mineralogical and geochemical anomalies of late Permian coals from the Fusui Coalfield, Guangxi Province, southern China: influences of terrigenous materials and hydrothermal fluids. *Int. J. Coal Geol.* 105, 60–83. doi:10.1016/j.coal.2012.12.003

Fan, E., Yang, Z., Gao, Y., et al. (2018). Tectonic characteristics and their control on coal in the north of Ningwu coalfield. *Coal Geol. Explor.* 46 (04), 8–16. doi:10.3969/j.issn.1001-1986.2018.04.002

He, S. (2006). Occurrence law of coal seams in Pingshuo mining area, Ningwu coalfield, Shanxi Province. *J. Shanxi Inst. Energy* (03), 123–124. doi:10.3969/j.issn.1008-8881.2006.03.069

Jin, Y. (2014). Main achievements in the research on the enrichment regulaton and exploitation and utilization of associated minerals in coal in China. *Manag. Res. Sci. Technol. Achiev.* (2), 86. doi:10.3772/j.issn.1673-6516.2014.02.037

Lei, Z., Colin, W., David, F., and Graham, I. (2015a). Major and trace element geochemistry of coals and intra-seam claystones from the songzao coalfield, SW China. *Minerals* 5 (4), 870–893. doi:10.3390/min5040531

Lei, Z., Colin, W., David, F., Graham, I. T., Dai, S., Yang, C., et al. (2015b). Origin of a kaolinite-NH 4 -illite-pyrophyllite-chlorite assemblage in a marine-influenced anthracite and associated strata from the Jincheng Coalfield, Qinshui Basin, Northern China. *Int. J. Coal Geol.* 185, 61–78. doi:10.1016/j.coal.2017.11.013

Li, H., Xia, X., and Yang, K. (2014). Lithium and gallium resources metallogenic geological characteristics in coal No. 4 Pingshuo mining area, Shanxi. *Coal Geol. China* 26 (12), 17–19. doi:10.3969/j.issn.1674-1803.2014.12.04

Li, J., Liu, X., and Wang, D. (2014). Summary of the metallogenic regularity of lithium Ore in China. *J. Geol.* 88 (12), 2269–2283. doi:10.19762/j.cnki.dizhixuebao.2014.12.009

Liao, J., Mengdie, W., and Liang, X. (2020). Analysis on late permian heshan formation coal accumulating basin lithium resource features in Guangxi. *Coal Geol. China* 32 (09), 122–127. doi:10.3969/j.issn.1674-1803.2020.09.21

Lithium. Jinchuan Technology (2019). *Lithium. Jinchuan technology* (1), 49.

Liu, B. J., and Ming-yue, L. (2014). Enrichment mechanism of lithium in coal seam No. 9 of the ping-shuo mining district. *Ningwu Coalf. Geol. Explor.* 50 (06), 1070–1075. doi:10.13712/j.cnki.dzykt.2014.06.007

Liu, D. (2007). *The study of coal petrology and coal geochemistry in permo- carboniferous coal form datong coalfield [D]*. Taiyuan University of Technology. Available at: https://kns.cnki.net/kcms2/article/abstract?v=JTjHPEokuYSwyfp-OBE6y3WXoHgJZpfCKIST4g2TFkc0eXR6a43ZkrN4G1Za4ciYZ4Frg-UCx1bcK37xSt00n-G04gurhFyg8yALcY_P082lwdHaqkNNwp_QjrdmK1Ttp1ysE4yU-TD3N8d19raZsg==&uniplatform=NZKPT&language=CHS.

Liu, H., Ma, Z., Guo, Y., and Cheng, F. (2019). Distribution characteristics and development and utilization prospects of lithium, gallium aluminum in Shanxi coal system. *Clean. Coal Technol.* 25 (05), 39–46.

Liu, L., Wang, D., Liu, X., Li, J., Dai, H., and Yan, W. (2017). The main types, distribution features and present situation of exploration and development for domestic and foreign lithium. *Mine Geol. China* 44 (02), 263–278. doi:10.12029/gc20170204

Lucyna, L., Monika, J. F., Stanisław, and Kita, A. (2009). Geochemical distribution of trace elements in Kaffioyra and Longyearbyen coals, Spitsbergen, Norway. *Int. J. Coal Geol.* 80 (3), 211–223. doi:10.1016/j.coal.2009.09.007

Lunde Seefeldt, J. (2020). Lessons from the lithium triangle: considering policy explanations for the variation in lithium industry development in the "lithium Triangle"Countries of Chile, Argentina, and Bolivia. *Polit. Policy* 48 (4), 727–765. doi:10.1111/polp.12365

Ma, Z., and Li, J. (2018). Analysis of China's lithium resource supply system: status, issue and suggestions. *China Min. Mag.* 27 (10), 1–7. doi:10.12075/j.issn.1004-4051.2018.10.022

Ning, S., Deng, X., Li, C., Qin, G., Zhang, J., Zhu, S., et al. (2017). Research status and prospects of metal elements mineral resources in China. *J. China Coal Soc.* 42 (09), 2214–2225. doi:10.13225/j.cnki.jccs.2017.0683

Ning, S., Huang, S., Zhu, S., Zhang, J., Zhang, W., et al. (2019). Mineralization zoning of coal-metal deposits in China. *Chin. Sci. Bull.* 64 (24), 2501–2513. doi:10.1360/n972019-00377

Pei, S., Wenfeng, W., Lei, C., Duan, P., Qian, F., and Ma, M. (2018). Distribution, occurrence, and enrichment of gallium in the middle jurass ic coals of the muli coalfield, Qinghai, China. *J. Geochem. Explor.* 185, 116–129. doi:10.1016/j.gexplo.2017.11.010

Pougnet, M. A. B., Orren, M. J., and Haraldsen, L. (1985). Determination of beryllium and lithium in coal ash by inductively coupled plasma atomic emission spectroscopy. *Int. J. Environ. Anal. Chem.* 21 (3), 213–228. doi:10.1080/03067318508078383

Pu, W., sun, B., and Li, Z. (2012). Geochemical of trace and rare element in No.2 coalseam parting in malan coal mine and its geological implication. *J. China Coal Soc.* 37 (10), 1709–1716. doi:10.13225/j.cnki.jccs.2012.10.003

Qi, S., Xiao, K., and Ding, J. (2014). Analysis of lithium resource distribution and potential in China. *Mineral. Depos.* 33 (S1), 809–810. doi:10.16111/j.0258-7106.2014.s1.407

Qin, S., Gao, K., and Lu, Q. (2015). "Research progress of lithium resource in coal seams," in Abstracts of the 15th Annual Academic Meeting of the Chinese Society of Mineral and Rock Geochemistry, Changchun, Jilin, China, 2.

Seredin, V. V., Dai, S. F., Sun, Y. Z., and Chekryzhov, I. Y. (2013). Coal deposits as promising sources of rare metals for alternative power and energy - efficient technologies. *Appl. Geochem.* 31, 1–11. doi:10.1016/j.apgeochem.2013.01.009

Shu, Y., and Wang, J. (2014). Lithium occurrences and enrichment factor law in No.9 coal. *Seam Anjialing Mine Coal Chem. Industry* 37 (09), 7–10.

Su, T., Guo, M., Liu, Z., and Li, Q. (2019). Comprehensive review of global lithium resources. *J. Salt Lake Res.* 27 (03), 104–111. doi:10.12119/j.yhyj.201903015

Sun, S., Wu, G., Cao, D., Ning, S., Qiao, J., Zhu, H., et al. (2014). Mineral resources in coal measures and development. *Trend Coal Geol. China* 26 (11), 1–11. doi:10.3969/j.issn.1674-1803.2014.11.01

Sun, Y., Li, Y., Zhao, C., Lin, M., Wang, J., and Qin, S. (2010). Concentrations of lithium in Chinese coals. *Energy Explor. exploitation* 28 (2), 97–104. doi:10.1260/0144-5987.28.2.97

Sun, Y., Zhao, C., Qin, S., Xiao, L., Li, Z., and Lin, M. (2016). Occurrence of some valuable elements in the unique "high-aluminium coals" from the Jungar Coalfield, China. *OreGeol Rev.* 72, 659–668. doi:10.1016/j.oregeorev.2015.09.015

Sun, Y. Z., Zhao, C. L., Li, Y. H., et al. (2013a). Further information of the associated Li deposits in the No 6 coal seam at jungar Coalfield,Inner Mongolia,northern China. *Acta Geol. Sin. Engl. Ed.* 87, 801–812. doi:10.1111/1755-6724.12112

Sun, Y. Z., Zhao, C. L., Li, Y. H., Wang, J., and Liu, S. (2012). Li distribution and mode of occurrences in Li-bearing coal seam # 6 from the Guanbanwusu mine, inner Mongolia, northern China. *Energy Explor. &Exploitation* 30, 109–130. doi:10.1260/0144-5987.30.1.109

Sun, Y. Z., Zhao, C. L., Zhang, J. Y., Yang, J., Zhang, Y., Yuan, Y., et al. (2013b). Concentrations of valuable elements of the coals from the Pingshuo mining District,Ningwu Coalfield,northern China. *Energy Explor. Exploitation* 31, 727–744. doi:10.1260/0144-5987.31.5.727

Swaine, D. J. (1990). *Trace elements in coals*. London: Butterworth, 278.

U.S. Geological Survey (2023). Lithium mineral commodity summaries 2023. Available at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-lithium.pdf (Accessed May 30, 2023).

Wang, C. (2018). Comparative study of coal seams in the north of Ningwu coalfield. *Min. Equip.* (03), 62–63.

Wang, L., and Chao, L. (2017). Research progress of Lithium extraction from fly ash. *Chem. Enterp. Manag.* (21), 223.

Wang, T., and Zhang, X. (2019). Summary of occurrence and extraction method of associated minerals in coal. *Multipurp. Util. Mineral Resour.* 04, 21–25. doi:10.3969/j.issn.1000-6532.2019.04.004

Wang, X., Chai, X., and Cui, W. (2014). Exploitation and utilization of global lithium resources: trend and our responses. *China Min. Mag.* 23 (06), 10–13.

Xu, F., Qin, S., and Li, S. (2021). Research progress on geochemistry and extraction of lithium from coal and coal ash. *Coal Sci. Technol.* 49 (9), 220–229. doi:10.13199/j.cnki.cst.2021.09.030

Yang, H., Liu, L., and Ding, G. (2019). Present situation and development trend of lithium resources in the world. *Conservation Util. Mineral Resour.* 39 (05), 26–40. doi:10.13779/j.cnki.issn1001-0076.2019.05.004

Zheng, M., and Liu, X. (2007). Lithium Resources in China. *Adv. Mater. Industry* (08), 13–16.

Zhong, C., Liu, J., and Lv, B. (2018). Lithium resource demand analysis and policy suggestions of China's new energy vehicle industry. *China Energy* 40 (10), 12–15. doi:10.3969/j.issn.1003-2355.2018.10.002

Zhou, P., Tang, J., and Zhang, T. (2014). Supply and demand prospects of global lithium resources and some suggestions. *Geol. Bull. China* 33 (10), 1532–1538.

Zhu, H., Chen, H., and Zhang, W. (2016). Metal mineral types and distribution characteristics in coal in northern China. *J. China Coal Soc.* 41 (02), 303–309. doi:10.13225/j.cnki.jccs.2015.6102

Zhuang, X., Zeng, R., and Xu, W. (1998). Trace elements in 9 coal from Antaibao open pit mine, Pingshuo, Shanxi Province. *Earth Sci.* 23, 583–587. doi:10.1016/s0140-6701(00)96193-9