Mine Water and the Environment (2024) 43:210–230
https://doi.org/10.1007/s10230-024-00984-4

REVIEW ARTICLE

Mine Water Treatment, Resource Utilization and Prospects in Coal Mining Areas of Western China

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Received: 8 December 2023 / Accepted: 16 May 2024 / Published online: 13 June 2024

Abstract
The scarcity of water resources and environmental pollution in the coal mining areas of western China severely restricts high-quality mine development and construction there. Treating mine water as a valuable unconventional water resource for large-scale processing and efficient utilization is a crucial approach. This paper discusses the current status of mine water treatment technology in this region and provides a systematic comparison and analysis of common and emerging treatment technologies for mine water containing suspended solids, high salinity, and fluoride. The paper extensively elaborates on the fundamental principles, process routes, and technical features of these technologies, citing typical engineering cases. It also outlines the challenges that mine water treatment in the coal mining areas of western China is likely to face in the future. Based on the current status of mine water resource utilization in China, various pathways forward are clarified. Finally, this paper presents a scientific reflection and proposed solutions for mine water treatment technology and resource utilization in the coal mining areas of western China, concluding with a prospective outlook on the future development of this field.

Keywords Mine water · Treatment technology · Water reuse · Zero discharge

Introduction

Coal is an indispensable primary short-term energy resource in China (Wu et al. 2019). The western region of China is rich in coal resources, accounting for 70% of the national total. However, this region is located in an arid to semi-arid zone with sparse surface vegetation and a fragile ecological environment. Water resources are extremely scarce, representing only 4.6% of the total national water resources (Li et al. 2011; Li and Xiong 2016; Wang 1996). As a country with severe water scarcity, where per capita water resources are only a quarter of the world average, mine water in China is now considered an important unconventional water resource. The water quality of mine water mainly depends on the original groundwater quality, but it is often contaminated with suspended solids, salts, special components, and other pollutants due to water–rock interactions and mining activities (Sun et al. 2021). Direct discharge without treatment can lead to various problems, including the waste of valuable water resources, water pollution, and damage to the surface ecology. Therefore, treating mine water resources and reusing them for production, life, and ecology is of paramount importance.

Coal mining generates a tremendous amount of mine water; for every ton of coal mined in China, about two tons of mine water are produced (He et al. 2018). However, the mine water utilization rate remains very low. Survey results indicate that in 2018, the total resource of mine water in Chinese coal mines was ≈ 6.89 billion cubic meters, while the average utilization rate was only 35% (Wu et al. 2017), resulting in a substantial waste of water resources. Faced with this serious situation, the national government has introduced a series of policies and regulations to strengthen the protection and utilization of mine water resources. In 2013, the National Development and Reform Commission issued the "Development Plan for Mine Water Utilization" to ensure the sustainable use of water resources in mining areas (National Development and Reform Commission of China 2013). In 2015, the State Council released the "Action Plan for Water Pollution Prevention," which explicitly stated,

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"Promote the comprehensive utilization of mine water, and prioritize the use of mine water for supplemental water in coal mining areas, production in surrounding areas, and ecological water use (Gu et al. 2021a)." In 2017, the Ministry of Water Resources, the Ministry of Finance, and others issued the "Implementation Measures for Expanding the Pilot Implementation of Water Resource Tax Reform," which included mine water in the collection scope (Wang et al. 2016). In 2021, the State Council issued the "Outline of Ecological Protection and High-Quality Development Plan for the Yellow River Basin," emphasizing the strictest implementation of water resource protection and utilization systems, with a focus on prioritizing the use of mine water (Gu et al. 2021b). In this policy context, it is crucial to enhance mine water treatment technologies and improve the efficiency of mine water utilization.

This paper summarizes the water quality characteristics of mine water in the coal mining areas of western China, provides an overview of the corresponding treatment technologies and the current status of resource utilization, identifies existing issues, seeks improvement solutions, and offers insights into future development trends, thus providing scientific support for the treatment and resource utilization of mine water in China.

Characteristics of Mine Water Quality in Coal Mining Areas of Western China

Understanding the characteristics of mine water quality in coal mining areas is a prerequisite for its treatment and utilization. The main source of mine water is groundwater that enters the mines through water-bearing fractures (Gu et al. 2021a, b; He et al. 2018; Xie 2014). The quality of mine water primarily depends on the original groundwater quality, but it is also influenced by hydrogeological conditions, hydrodynamic conditions, ore body structures, and mining activities (Feng 2014; He et al. 2008).

Researchers typically categorize mine water based on its principal contaminating features into categories such as clean, acidic, high-suspended solids, high salinity, and those containing special components (Liu and Sun 2008; Naidu et al. 2019; Sun et al. 2020). This classification aids in the preliminary understanding and identification of the main issues present in mine water. However, these categories do not fully encompass the complexity and diversity of mine water. In practice, the characteristics of mine water can span these basic categories, displaying a more complex combination of traits. Coal mine water varies tremendously in terms of its level of contamination and pH, and so must be analyzed before any decisions are made regarding water treatment and potential utilization. Contaminants commonly encountered in mine water include: suspended particles such as coal dust and rock fragments; high salinity (often with a total dissolved solids (TDS) content exceeding 1000 mg/L); and special components such as high fluoride, heavy metals, and radioactive elements (Chen 2012; Jin et al. 2022; Tiwari et al. 2016; Yang et al. 2008).

Mine water is less prevalent in China's southern and eastern regions and more common in China's northern and western regions. According to statistics, high-suspended solids mine water Approximately 60% of the total drainage from Chinese coal mines contains high amounts of suspended solids, while ≈ 30% of the water inflow in China's coal mines are very saline. Acidic mine water is mainly found in southern China, accounting for < 10% of China's coal mines. Some coal mines in the western and northern regions of China have high fluoride content in their mine water, often accompanied by high salinity. In western China, coal mine water is mainly characterized by high amounts of suspended solids, high salinity, and fluoride-containing water (Jin et al. 2022; Tiwari et al. 2016; Yang et al. 2008; Zhang et al. 2019). In this paper, we summarize the general characteristics of mine water in western China's coal mining areas based on investigations of 14 key coal mines and analysis of mine water data (Table 1).

Mine Water Treatment Technology

Current State of Mine Water Treatment Technologies in China

Purification and treatment of mine water in China began in the 1970s and over the past two decades, there has been rapid development in mine water treatment and utilization. China currently places a high emphasis on environmental protection, and the government, along with relevant agencies, has

Table 1 General characteristics of the mine water generated in western China's coal mining areas

Parameter	Unit	Value
pH	/	7.04–8.44
Turbidity	NTU	1.0–277
Chemical oxygen demand	mg/L	1.65–300
Total hardness	mg/L	56.1–716
Iron	mg/L	0.003–6.5
Manganese	mg/L	0.05–0.65
Copper	mg/L	< 0.06
Zinc	mg/L	< 0.03
Sulfate	mg/L	111–961
Chloride	mg/L	8.93–630
Fluoride	mg/L	0.23–12.75
Total dissolved solids	mg/L	361–14,600

formulated a "zero discharge" policy for mine water in the coal mining sector. This policy requires comprehensive treatment, recycling, and reuse of mine water by coal and mining enterprises during production. Advanced technological means are used to improve the quality of mine water to meet various reuse standards, thus reducing the discharge of mine water into the environment. This initiative aims to protect water resources, enhance environmental quality, and encourage mining enterprises to operate in an environmentally sustainable manner. Currently, this policy is gradually being implemented in the mining areas of Western China.

Mine water treatment technology has evolved from initial simple precipitation methods to advanced treatment, employing multi-stage processes to meet higher water quality purification standards. Through improvements and optimization of traditional mine water treatment processes, the adoption of multi-stage advanced treatment aims to thoroughly remove various pollutants from mine water and achieve superior water quality purification. China's mine water treatment technology and equipment are gradually catching up with the levels seen in developed countries. Extensive studies have been conducted on aspects such as the mechanism of mine water generation, water quality characteristics, treatment processes, and the development of water treatment materials (He et al. 2018; Jin et al. 2018; Li et al. 2018). Additionally, a series of water treatment engineering demonstration projects have been initiated. Low rate of mine water reuse can be attributed to unclear channels for mine water utilization, high treatment costs, and discrepancies between the treated water quality and the requirements of end-users.

Water Treatment Technologies for Typical Mine Water in the Coal Mining Areas of Western China

Treatment of Mine Water Containing Suspended Solids

The suspended solids in mine water primarily consist of rock fragments, rock dust, coal particles, and coal dust generated during the coal tunneling and mining processes. Their concentration typically ranges from 100 to 400 mg/L. These minute particles exhibit characteristics such as small particle size, low density, and long natural settling times. Therefore, the removal of suspended solids is a crucial challenge that all mine water treatment processes must address. In the coal mining areas of western China, commonly employed technologies for treating mine water containing suspended solids include conventional treatment methods, supermagnetic separation technology, high-density sedimentation technology, and mine water treatment in goaf areas.

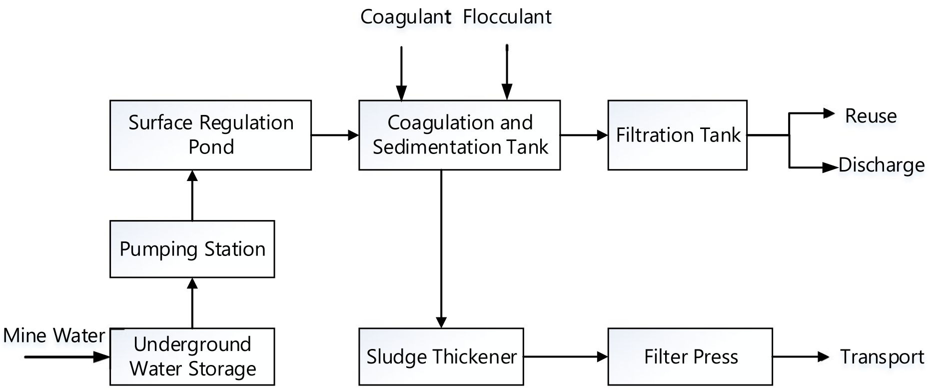
Conventional treatment technology primarily focuses on the removal of fine suspended solid particles and colloidal contaminants in mine water using processes such as coagulation, sedimentation, and filtration (Fig. 1) to achieve environmental discharge standards and industrial production needs (Ministry of Ecology and Environment of the People's Republic of China 2015; Wang et al. 2023).

In comparison to conventional treatment methods, in addition to conventional coagulants and flocculants, supermagnetic separation technology introduces a magnetic seed primarily composed of iron into the water stream to achieve efficient water purification. This technology is characterized by high efficiency, stable equipment operation, and simple management (Cai et al. 2017; Lv et al. 2018; Zheng et al. 2016). The process of mine water treatment using supermagnetic separation technology is illustrated in Fig. 2.

High-density sedimentation technology is an emerging method for mine water treatment, which involves adding heavy medium particles to the mine water to form large flocs for solid–liquid separation. It markedly reduces the design volume of sedimentation tanks and enhances sedimentation efficiency (Guo 2018; Shi et al. 2007; Wang et al. 2011). Common process routes for high-density sedimentation technology are shown in Fig. 3.

Mine water treatment in goaf areas involves having the water flow through collapsed rock masses and a small amount of residual coal in goaf areas. The suspended solids are removed as the water permeates through the rubble by

Fig. 1 Conventional mine water treatment process



sedimentation, filtration, adsorption, etc. This technology does not require specialized water treatment equipment and chemicals, and the treated water quality usually meets underground reuse and recycled water standards, greatly alleviating the water supply–demand shortage problem in coal mining areas of western China (Chen and Ju 2011; Feng et al. 2004; Gu 2015; Yang et al. 2013). The main technical parameters of these high suspended solids mine water treatment technologies are compared in Table 2.

Treatment of Highly Saline Mine Water

Highly saline mine water generally refers to mine water with a salt content > 1000 mg/L. Such mine water is predominantly found in the western and northern regions of China, such as Shaanxi, Shanxi, Inner Mongolia, Ningxia, and Xinjiang (Fan et al. 2016). In the northern mining areas of China, the salt content in mine water typically ranges from 1000 to 3000 mg/L, reaching 7000 to 10,000 mg/L in the Ningdong region and up to 12,000 mg/L in Xinjiang. The salt content mainly comes from ions such as Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and most of this type of mine water is alkaline or weakly alkaline (Sun et al. 2022). Desalination is relatively complex and expensive, making it a research hotspot in mine water treatment. Especially in recent years, numerous coal mines have been constrained by environmental policies, requiring the use of crystallization and evaporation technology to achieve "zero discharge" of highly saline mine water. Commonly employed techniques in the coal mining areas of western China include chemical, membrane separation, electrochemical, and thermal methods, all of which require substantial engineering investments.

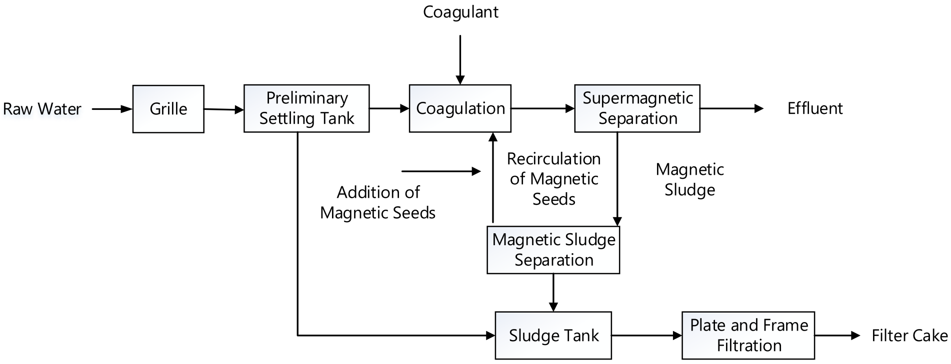


Fig. 2 Supermagnetic separation process

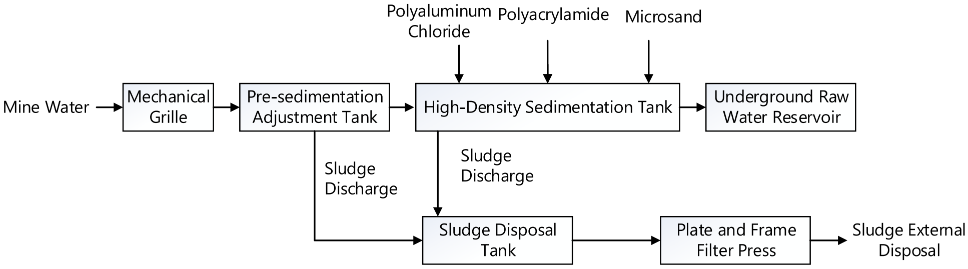


Fig. 3 High-density sedimentation technology process

Table 2 Comparison of main treatment technologies for high suspended solids mine water

Item	Conventional treatment technology	Supermagnetic separation technology	High-density sedimentation technology	Mine water treatment in goaf areas
Investment and operating costs	Low investment, high chemical and labor costs	High investment, moderate chemical and labor costs	High investment, low chemical and labor costs	Low investment, no chemicals required
Land area	Large footprint, not suitable for underground treatment	Medium footprint, suitable for underground treatment	Small footprint, ideal for underground treatment	Utilizing underground goaf
Influent requirements	ρ(ss) ≤ 600 mg/L, low resistance to water quality fluctuations	ρ(ss) ≤ 1000 mg/L, moderate resistance to water quality fluctuations	ρ(ss) ≤ 1500 mg/L, strong resistance to water quality fluctuations	No limitations
Effluent SS (mg/L)	≤ 80	≤ 20	≤ 20	≤ 20

Chemical methods primarily remove salts from mine water through chemical reactions or ion exchange. Chemical reagent methods require a large amount of reagent input, which may lead to secondary pollution, while ion exchange require long separation cycles, extended processing times, and the need for multiple exchange resins. Chemical desalination is typically used as a pretreatment method for desalination processes (Chen et al. 2018; Guo 2014; Hu et al. 2015; Vanoppen et al. 2015).

The membrane separation technology that is commonly used to treat highly saline mine water includes microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) (Hou and Liu 2010; Van Der Bruggen 2003; Skuse et al. 2021). The main characteristics of the four pressure-driven membranes are shown in Fig. 4. Among them, RO technology is efficient, but issues such as lack of selectivity in ion retention, high operating pressure, low water production rate, and high energy consumption exist (Henthorne and Boysen 2019; Salvador et al. 2014; Zhou 2015). Nanofiltration technology has selective salt separation capabilities, but also faces problems such as membrane fouling and high membrane replacement frequency (Abdel-Fatah 2018; Antony et al. 2011; Du et al. 2020; Zhao et al. 2011). Membrane desalination has been widely applied to treat highly saline mine water in the coal mining areas of western China. A typical membrane desalination process is illustrated in Fig. 5.

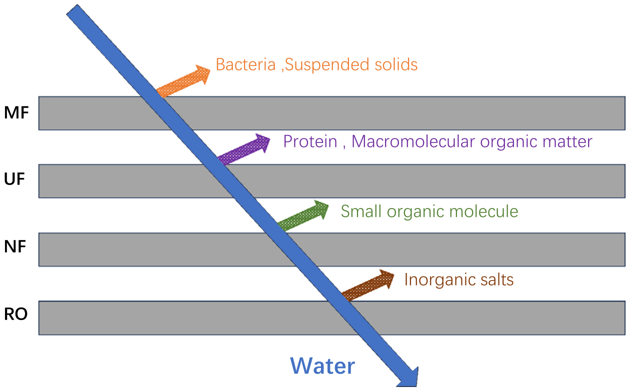
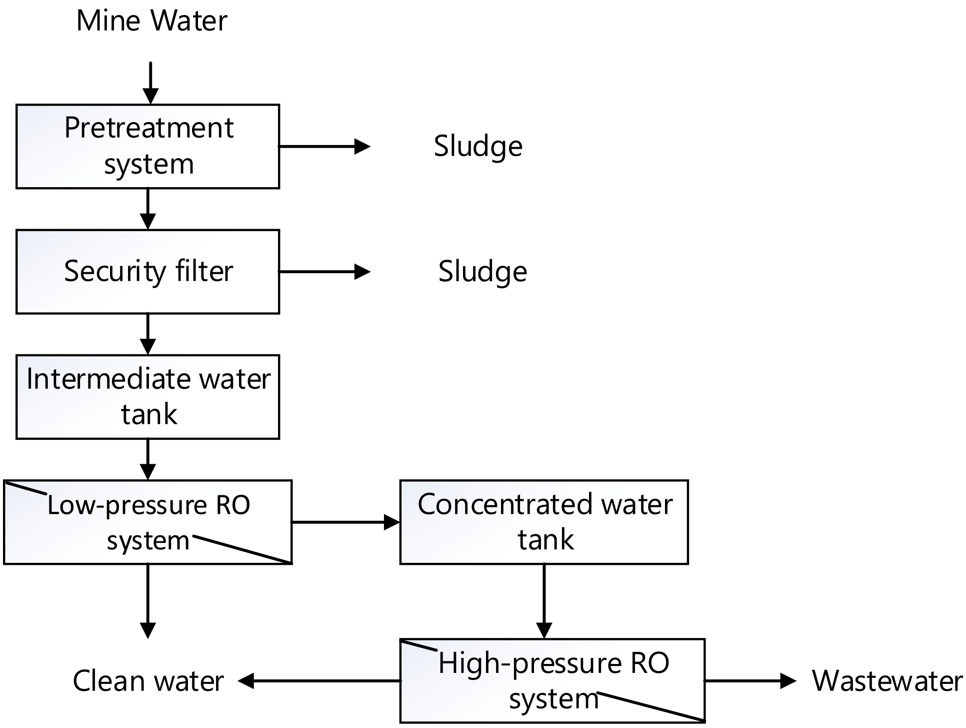


Fig. 4 Characteristics of pressure-driven membrane processes

Electrochemical desalination methods, such as electrodialysis and electroadsorption, offer environmentally friendly options for treating highly saline mine water. Electrodialysis uses ion exchange membranes to separate ions, while electroadsorption removes ions through electrochemical processes on electrode surfaces. Challenges include lower desalination efficiency and limited industrial applications (Banasiak et al. 2007; Cui 2010; Generous 2020; Guan and Hu 2021; Yuan 2015). Figure 6 illustrates the working principle of electrodialysis.

As evaporative desalination technology continues to advance, thermal desalination is also gradually being used to treat highly saline mine water (Li et al. 2015), particularly showing advantages when dealing with mine water containing more than 3000 mg/L of salt (Tang and Ma 2014). Multi-effect evaporation has simple pretreatment requirements and

Fig. 5 Mine water membrane separation technology process



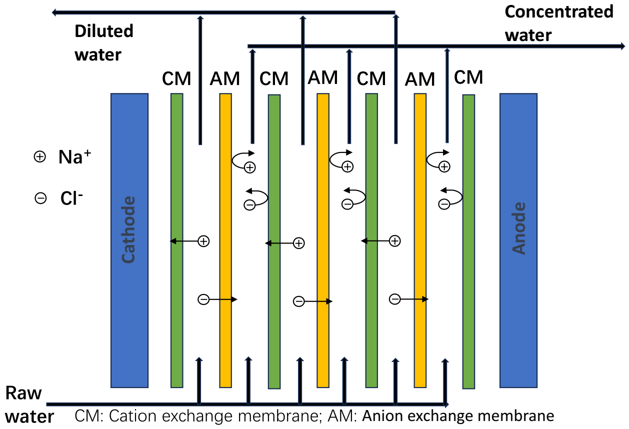


Fig. 6 Electrodialysis principle diagram

high reliability. Compared to other thermal desalination technologies, it exhibits relatively lower energy consumption. However, a notable drawback is its susceptibility to scaling (Ran 2017; Zhu 2019). Mechanical vapor recompression (MVR) evaporation can save energy (Zhu 2018). Humidification-dehumidification (HD) treatment technology is cost-effective, efficient, and greatly reduces equipment corrosion and scaling (Al-Hallaj et al. 2006; Ettouney 2005). Freezing desalination is a relatively environmentally friendly desalination method but has high energy consumption and operating costs (Kalista et al. 2018; Luo 2016; Williams et al. 2015). Since thermal desalination is an energy-intensive process, energy conservation is crucial, and some processes face challenges such as high costs, mechanical complexity, and inability to operate on a large scale.

Through extensive on-site investigations and data analysis, a comparison of key technical parameters for several common highly saline mine water treatment technologies can be found in Table 3.

Treatment of Mine Water Containing Fluoride

Coal mining disrupts the structure of underground aquifers, causing groundwater to seep into tunnels through mining-induced fractures. As groundwater flows through fluorine-rich rocks, solid-phase fluorides transform into soluble fluoride. Fluoride in groundwater commonly exists in forms such as F^-, MgF^+, and CaF^+. Ideally, fluoride concentrations in groundwater should be < 1 mg/L. However, some coal mine waters in China exceed this standard, with levels even surpassing 10.0 mg/L (Sun et al. 2020; Xie et al. 2019; Wu et al. 2010). High fluoride mine water is widespread, especially in northwestern mining areas such as Shendong and Ningmei (Cai 2009; Xie 2015; Yang et al. 2007; Zhu 2012). Treatment of mine water containing fluoride is crucial due to potential risks to the environment and human health. Various

Table 3 Comparison of highly saline mine water desalination technology

Desalination method	Advantages	Disadvantages	Cost	Application range
Chemical desalination	Simple process, strong operability	Large chemical input, potential secondary pollution	High chemical cost, ion exchange resin regeneration	Suitable for low to moderate salinity mine water treatment
Membrane desalination	Efficient desalination, high water quality	High energy consumption, requires regular maintenance and membrane replacement	Relatively high initial investment and operating costs	Suitable for high salinity and high-quality requirements mine water treatment
Electrochemical desalination	Environmentally friendly, suitable for high salinity water, small footprint	Single process, high energy consumption, unstable operation, lower desalination rate compared to reverse osmosis	High electricity costs, high equipment cleaning costs	Suitable for deep processing projects with low desalination accuracy requirements
Thermal desalination	Effective desalination, no need for chemical addition, avoids secondary pollution	High energy consumption, complex machinery, limited heat source, limited industrial applications	High energy costs, using industrial waste heat can to some extent reduce costs	Suitable for mine water with a salinity greater than 3000 mg/L, limited application range, not widely adopted in industry

methods are employed, including precipitation, electrochemical, membrane separation, ion exchange, and adsorption.

Chemical and coagulation precipitation are commonly used to remove fluoride ions from mine water. Chemical precipitation involves adding specific chemicals to mine water containing fluoride to form fluoride precipitates or adsorb fluoride ions onto existing precipitates, which are then removed through solid–liquid separation (Lei and Guo 2012; Li et al. 2000). Coagulation precipitation involves adding coagulants and flocculants to mine water, followed by rapid mixing and slow coagulation and settling to promote fluoride removal (Liu 2019; Wang et al. 2004). These methods are simple and cost-effective, but may generate sludge that is difficult to dewater, and achieving water quality compliance with higher standards can be challenging (Aldaco et al. 2005; Jiao 2012; Wang et al. 2017; Zhao et al. 2009).

Electrochemical methods for fluoride removal commonly include electrocoagulation and electrodialysis. Electrocoagulation involves the dissolution of anodic metals to form metal hydroxides, which then undergo coagulation, flocculation, adsorption, and coprecipitation with fluoride ions. Its removal mechanism is essentially similar to chemical coagulation (Gomes et al. 2007). Compared to traditional coagulation, it offers advantages such as on-site generation of coagulants and no need for post-treatment neutralization (Apshankar and Goel 2017; Hu et al. 2005). The working principle is illustrated in Fig. 7. Electrodialysis, on the other hand, offers environmental benefits but faces challenges such as expensive equipment costs and more energy consumption (Jiao 1985).

Though membrane separation technology has been widely applied to treat highly saline mine water, its application in fluoride removal is limited (Mao et al. 2017). Nanofiltration membranes can partially remove fluoride ions, while reverse osmosis membranes exhibit higher retention rates. In addition, nanofiltration membranes are more susceptible to contamination by F^- (Liu 2019; Wang and Li 2009).

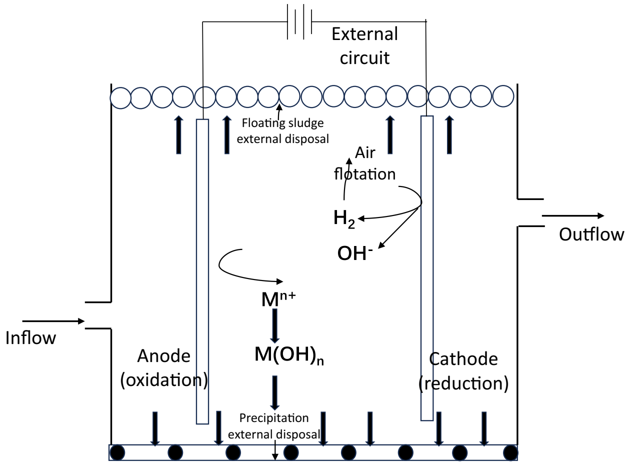


Fig. 7 Principle of electrocoagulation process

Ion exchange methods utilize certain ions on ion exchange resins or ion exchange fibers to exchange with fluoride ions in water, thereby achieving defluorination (Liu 2011). Different resins or conditions can affect the removal efficiency, and high costs limit their large-scale application (Millar et al. 2017).

The adsorption method utilizes the physical and chemical properties of adsorbents, as well as ion exchange, to remove fluoride ions from mine water. This method is effective, easy to operate, and cost-effective, making it widely applied in the field of fluoride-containing mine water treatment (Loganathan et al. 2013; Medellin-Castillo et al. 2014; Rajkumar et al. 2019). The core of fluoride removal through adsorption lies in the choice of adsorptive materials (Liu et al. 2017). While traditional adsorption materials are widely used, they suffer from stability issues (Ayinde et al. 2018; Fernando et al. 2019; Mtavangu et al. 2022; Sani et al. 2016). Exploring novel modified materials to increase adsorption capacity and reduce adsorption costs is a trend for future research and development (Li et al. 2021b).

A comparison of the main technical parameters for several common techniques used to treat mine water containing fluoride can be found in Table 4. The relationship between the typical types of mine water and effective treatment technologies in the coal mining areas of western China is summarized in Fig. 8.

Examples of Mine Water Treatment Projects in the Coal Mining Areas of Western China

Treatment Project for High Suspended Solids Mine Water

This mine is located in northern Shaanxi, an area with scarce water resources and a fragile ecological environment. The mine water is characterized by a large volume, high turbidity, and a high content of emulsified oil. Environmental regulations require mine water discharge to meet Class III standards of the Surface Water Environmental Quality Standards (GB3838-2002). Exceedances of chemical oxygen demand and ammonia nitrogen (NH_3-N) are mainly caused by coal dust, which can be treated by coagulation, sedimentation, and filtration, but dissolved organic compounds, ammonia nitrogen, and oil residues require further treatment such as ozone oxidation, activated carbon adsorption, and decomposition. The process flow for mine water treatment is shown in Fig. 9, and the water quality parameters for system inflow and outflow are presented in Table 5.

Table 4 Comparison of fluoride-containing mine water treatment technologies

Treatment method	Advantages	Disadvantages	Treatment effect	Current application
Precipitation	Simple process, easy operation	High sludge moisture content, poor settling, relatively lower water quality	Challenging to meet standards	Widely used in industry, typically as a pre-treatment process
Electrochemical	No need for additional chemicals, comprehensive water quality improvement	Expensive equipment, complex management, high energy consumption	Meets standards	Less commonly used in mine water defluoridation
Membrane separation	Low energy consumption, no need for chemical additives, high fluoride ion removal rate	High influent water quality requirements, membrane flux gradually decreases over time	Meets standards	Widely used in high salinity mine water treatment, less used in mine water defluoridation projects
Ion exchange	Effective fluoride removal, high resin reusability, regenerable	Expensive resin, high regeneration costs	Meets standards	High resin costs limit large-scale application of this method
Adsorption	Simple operation, high defluoridation efficiency, reusable adsorbents	Low water treatment capacity, requires suitable adsorbents, ion competition exists	Meets standards	Currently more suitable for removal of fluoride in low-concentration ranges

Advanced Treatment Project for Fluoride-Containing Mine Water

This coal mine is located in the Binchang mining area of Shaanxi. The mine water is characterized by high suspended solids, high salinity, and fluorides. The treatment system adopts a mine water purification process mainly based on two stage pre-settling and clarification. The performance of the mechanical clarification unit of this process has been improved to achieve the synergistic removal of suspended solids and fluorides. The water treatment process is shown in Fig. 10. For detailed design parameters, refer to Table 6.

The operational results of the project show that when the average concentration of suspended solids in the influent mine water is < 5000 mg·L^{-1}, the average removal efficiency of suspended solids can reach 99.73%. The fluoride concentrations in the influent and effluent are 1.26 mg·L^{-1} and 0.87 mg·L^{-1}, respectively, with a removal rate of 31.0%. The effluent water quality meets the requirements set for reuse and discharge standards, and the operational cost of mine water purification is only 0.34 yuan/ton of water. Table 7 provides water quality measurement results before and after treatment.

Advanced Treatment and Resource Utilization Project for Highly Saline Mine Water

This mine is located in the southwestern part of Shenmu County, Yulin City, Shaanxi Province. The original mine water treatment station no longer met the current water quality standards, so the treatment station was renovated, and a new advanced mine water treatment system was added. The underground drainage advanced treatment system is divided into four sections: (1) Medium-pressure RO concentration and pretreatment system; (2) Nanofiltration desalination and pretreatment system; (3) High-pressure RO re-concentration and pretreatment system; (4) Evaporation crystallization system. The process flowchart is shown in Fig. 11, the water quality of the system's influent and effluent is shown in Table 8, and the salt product indicators is provided in Table 9.

Challenges Facing Mine Water Treatment in the Coal Mining Areas of Western China

Substantial Improvement in Mine Water Discharge Standards

At the policy level, the enhancement of water quality standards imposes more stringent requirements on mine water treatment in coal mines. Historically, most coal mine water treatment plants have primarily referred to GB 20426-2006

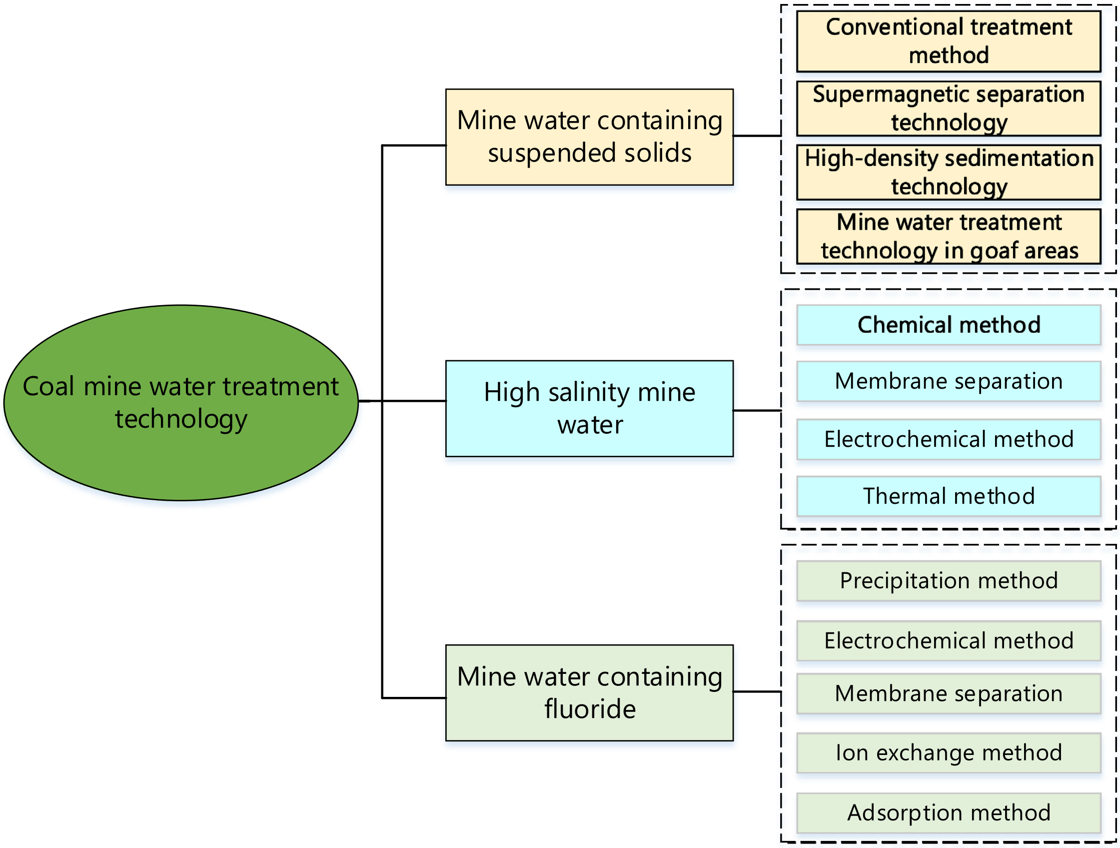


Fig. 8 Water treatment technologies for typical mine water in coal mining areas of Western China

"Emission Standards for Pollutants from the Coal Industry" for design and construction. This standard sets the maximum allowable concentrations for six pollutants in mine water, including pH, total suspended solids, chemical oxygen demand, petroleum substances, total iron, and total manganese. With the implementation of a series of policies and regulations such as the "Water Pollution Prevention and Control Action Plan" and the coal mine environmental impact assessment system, the salt concentration in discharged mine water is strictly required to be maintained at < 1000 mg/L. Additionally, in recent years, major coal-producing regions such as Shaanxi, Shanxi, and Inner Mongolia have begun to demand that the discharge standards for mine water be raised to the Class III standard or higher, as per GB 3838-2002 "Environmental Quality Standards for Surface Water." A comparison between the mine water discharge standards specified in "Environmental Quality Standards for Surface Water" and "Emission Standards for Pollutants from the Coal Industry" (Table 10) reveals that the former covers four times as many basic water quality parameters. Moreover, within the shared water quality parameters, the limits of Class III standards in the "Environmental Quality Standards for Surface Water" are much more stringent (Li 2018).

"Zero Discharge" Policy for Mine Water

After desalination and concentration treatment of mine water, a portion of high-salinity wastewater is generated. With increasingly stringent environmental requirements, a "zero discharge" policy for mine water has gradually been implemented in major coal-producing regions such as Inner Mongolia and Ningxia. Currently, the "zero discharge" technology for high-salinity wastewater typically adopts the process of evaporation and crystallization. However, challenges exist, including high energy consumption and difficulty in handling mixed salts. In recent years, some studies have proposed storing high-salinity mine wastewater in sealed goaf areas to create an "underground reservoir" within the coal mine. This concept has been implemented in the Shendong mining area, confirming the reliability of sealed goaf areas for storing mine water (Gu 2014). The "zero discharge" policy for mine water is expected to be a primary direction for future mine water resource utilization.

Fig. 9 Shaanbei high suspended solids mine water treatment project process

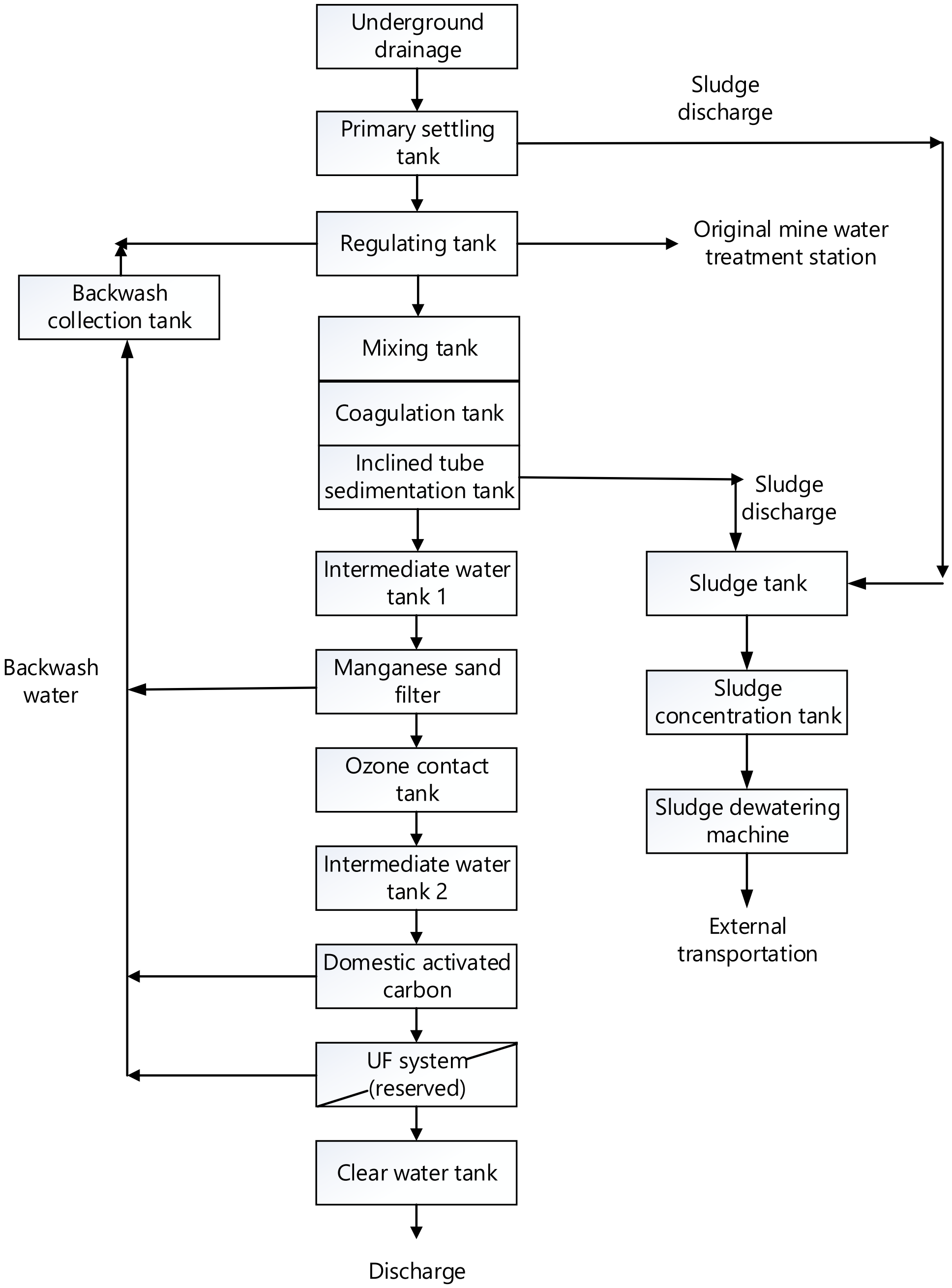


Table 5 Water quality parameters for system inflow and outflow

Water quality indicators	Influent water quality	Effluent water quality
ρ(SS)/mg·L^{-1}	8500 ~ 9700	0.3 ~ 0.8
ρ(NH3-N)/mg·L^{-1}	0.9 ~ 1.6	0.2 ~ 0.35
ρ(TP)/mg·L^{-1}	0.11 ~ 0.17	ND
COD/mg·L-1	360 ~ 650	13.4 ~ 17.3

Increase in Highly Saline Mine Water and Fluoride-containing Mine Water in Western Coal Mining Areas

In recent years, the coal mining areas of western China are facing new challenges, namely the increasing occurrence of highly saline mine water and mine water with special components (especially fluoride). This issue arises from the arid climate, water scarcity, high evaporation rates, and complex geological conditions. As the coal production in western regions continues to increase, the technical requirements for treating these mine waters become

Fig. 10 Process for the advanced treatment project of fluoride-containing mine water

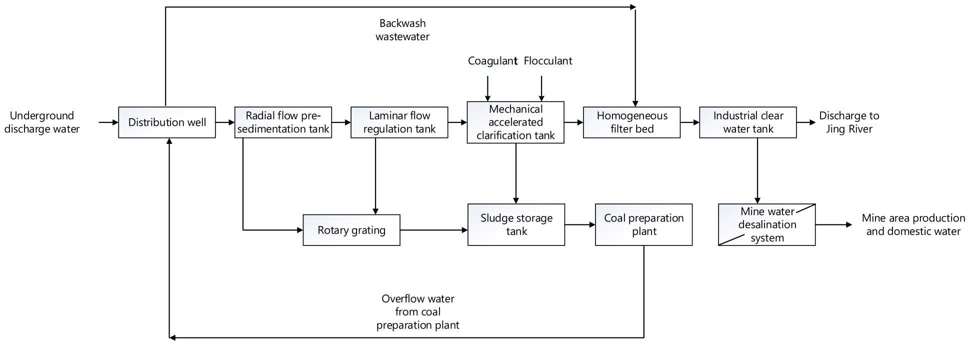


Table 6 Main process design parameters

Item	Design parameters
Radial flow pre-sedimentation tank	Surface load: 3.9 m^3 /(m^2·h) Hydraulic retention time: 0.8 h
Laminar flow regulation tank	Horizontal flow velocity: 4.9 mm/s Hydraulic retention time: 2.20 h
Mechanical accelerated clarification tank	Surface load: 3.3 m^3 /(m^2·h) Flocculation time: 32 min Sludge recirculation ratio: 8:1 Hydraulic retention time: 2.1 h Sludge concentration: 3%
Homogeneous filter bed	Normal filtration rate: 8.0 m/h Forced filtration rate: 8.7 m/h Filter thickness: 1.25 m Air wash intensity: 55 m^3/(m^2·h) Air–water combined wash intensity: 10 m^3/(m^2·h) Water wash intensity: 17 m^3/ (m^2·h) Surface sweep intensity: 4 m^3/(m^2·h)

Table 7 Design of influent and effluent water quality parameters

Item	Influent	Effluent
pH	6 ~ 9	7 ~ 9
CODCr/(mg·L^{-1})	≤ 600	≤ 20
SS/(mg·L^{-1})	≤ 5000	≤ 10
Fluoride/(mg·L^{-1})	≤ 1.3	≤ 1.0

more urgent. According to surveys, the TDS of mine water in the Ningdong mining area is generally greater than 3000 mg/L, with some coal mines reaching 12,000 mg/L. In the Shendong mining area, over 50% of mine water has a TDS exceeding 1000 mg/L, and fluoride ion concentrations also exceed the Class III standard limit of 1 mg/L in the "Environmental Quality Standards for Surface Water." This renders the existing conventional mine water treatment processes inadequate, necessitating increased financial investment for upgrading and transforming water treatment technologies and facilities at coal mines.

Engineering Practices of Underground Mine Water Treatment

The traditional approach to treating mine water in coal mines involves pumping the mine water to the surface and employing processes such as coagulation, sedimentation, clarification, and filtration to remove suspended solids. Subsequently, technologies like electrodialysis or membrane separation are used for concentration and desalination. This process incurs high energy consumption for pumping the mine water to the surface, requires a large footprint for the treatment system, has a long processing cycle, and generates solid waste and concentrated brine that can cause secondary pollution to the environment. As a result, some researchers have proposed and implemented underground mine water treatment schemes (He and Li 2010; Liu et al. 2003; Li et al. 2014; Zhou et al. 2013). In comparison to traditional surface treatment of mine water, underground treatment faces limitations imposed by the unique underground environment. Key technical challenges include the rational use of underground space, equipment safety (explosion-proof and corrosion-resistant), pollution triggered by the diffusion of

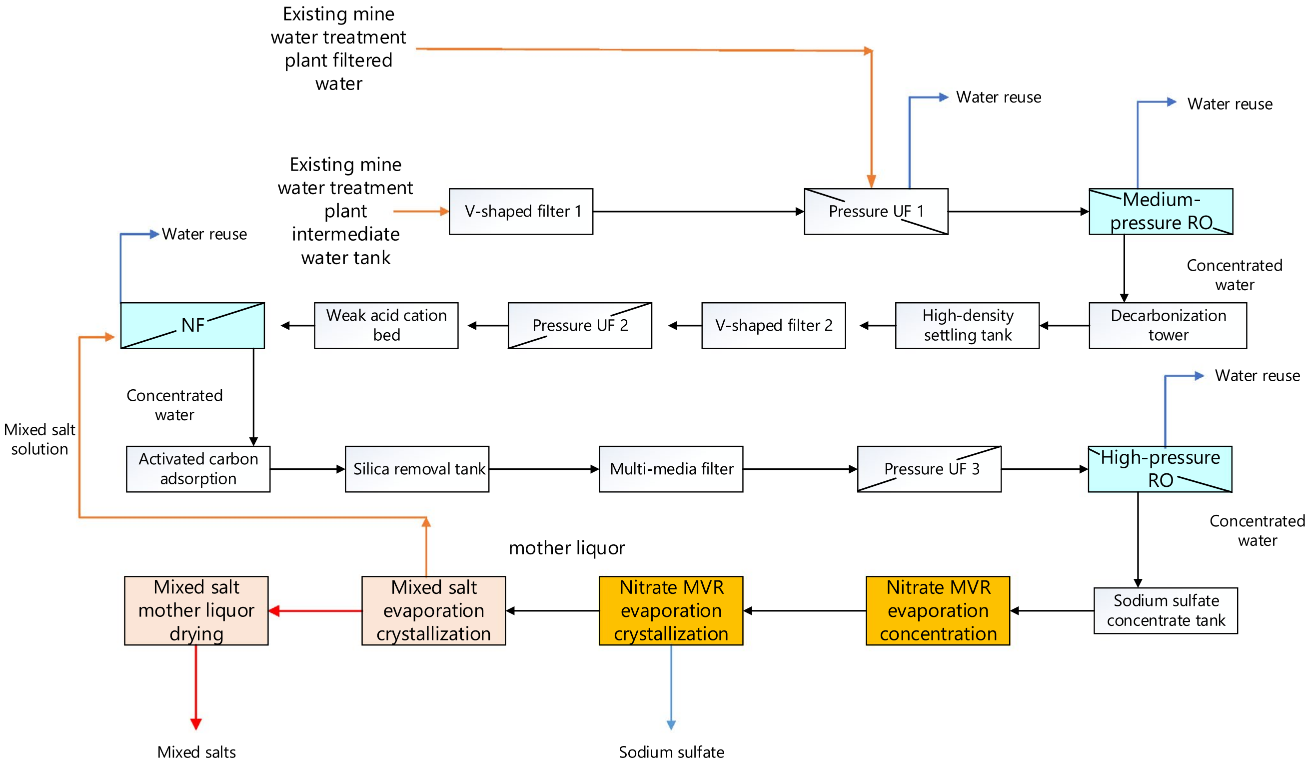


Fig. 11 The process for the advanced treatment project of high-salinity mine water

Table 8 Influent and effluent water quality parameters of the system (mg/L)

Testing parameters	Influent water quality	Designed effluent water quality	Surface water Class III	Industrial park requirements
Total dissolved solids	1643	≤ 1000	/	≤ 1000
Chemical oxygen demand	25	≤ 20	≤ 20	≤ 20
Fluoride	2	≤ 1	≤ 1	≤ 1
NH_3-N	2.17	≤ 1	≤ 1	≤ 1
Total phosphorus	0.2	≤ 0.2	≤ 0.2	≤ 0.2
Petroleum compounds	0.2	≤ 0.05	≤ 0.05	≤ 0.05

Table 9 Quality of the product salt

Testing parameters	Meets the requirements of "Industrial Anhydrous Sodium Sulfate" (GB/T6009-2014) Class II, First-grade specifications
Na_2SO_4 (w/%)	≥ 98.0
Insoluble (w/%)	≤ 0.10
Ca and Mg (w/%)	≤ 0.30
Chlorides (w/%)	≤ 0.70
Fe(w/%)	≤ 0.010
Moisture (w/%)	≤ 0.5
Whiteness (/%)	82

Table 10 The main emission limits for pollutants in coal mine water (mg/L)

Item	Emission Standards for Pollutants from the Coal Industry	Environmental Quality Standards for Surface Water
pH	6 ~ 9	6 ~ 9
Total suspended solids	50	/
Chemical oxygen demand	50	20
Petroleum substances	5	0.05
Total iron	6	0.3
Total manganese	4	0.1
Fluoride, ammonia nitrogen, total phosphorus, arsenic, mercury, and other indicators	No specified limits	Specified limits

chemicals, and the implementation of an automatic control system (Ackman 2000; Li et al. 2014).

Mine Water Resource Utilization

Development Process and Current Status of Mine Water Resource Utilization in China

In recent years, China has placed increasing emphasis on the utilization of mine water resources. The government has formulated a series of policy documents, such as "Several Opinions of the State Council on Promoting the Healthy Development of the Coal Industry" (State Council of the People's Republic of China 2005), "Special Planning for Mine Water Utilization" (National Development and Reform Commission of the People's Republic of China 2006), and "Development Plan for Mine Water Utilization" (National Development and Reform Commission of the People's Republic of China 2013), emphasizing the principles of efficiency, environmental protection, and comprehensive utilization in the integrated development and effective utilization of discharged mine water. The National Development and Reform Commission and the National Energy Administration have set corresponding development goals, explicitly stating the need to establish a sound legal and regulatory framework, macro-management policies, policy and technological systems, and innovative technologies and mechanisms to promote the rational utilization of mine water resources. Additionally, the State Council has explicitly called for promoting the use of mine water for production, living, and ecological water in mining areas and surrounding areas in the "Strategic Development and Recent Action Plan for Circular Economy" (State Council of the People's Republic of China 2013). The Ministry of Environmental Protection has issued relevant documents encouraging the use of mine water, restricting the use of groundwater, and, in some areas, prohibiting the use of groundwater for production to reduce the waste of fresh water. In recent years, some local governments, such as Shanxi Province, Yulin City, Jincheng City, Ordos City, and the Ningxia Hui Autonomous Region, have also formulated plans specifically for the utilization of mine water resources.

Mining and water scarcity in the coal mining areas of western China have long been regarded as a contradiction. Some coal mines established water treatment stations as early as the 1980s, increasing the comprehensive utilization rate of water resources. After 2010, provinces and cities gradually attached more importance to the utilization of mine water. In general, China is actively taking measures to fully utilize mine water resources, especially in water-scarce regions, and this trend is strengthening year by year (Gu et al. 2016; Sun 1996; Zhang and Jiang 2006). According to investigations conducted at 11 coal mines in western China, the utilization rate of mine water resources steadily increased from 59% in 2013 to 73% in 2018. The introduction and use of concepts such as underground water reservoirs have greatly enhanced on-site mine water utilization. Currently, the main methods of mine water resource utilization, both domestically and internationally, include industrial water use, agricultural water use, ecological water use, and domestic water use (Fig. 12).

Industrial Water Use

The use of mine water by the industrial sector mainly includes coal production, coal washing and processing, utilization in surrounding power plants, and coal chemical projects. Some coal mining enterprises generate a large amount of mine water, and after treatment, supply the remaining mine water to surrounding enterprises as industrial process water, after meeting their own water needs. In Inner Mongolia, some coal mines not only recycle the mine water they produce but also transport the surplus mine water, after thorough treatment, to nearby industrial parks to support the activities of coal chemical projects. This practice not only alleviates the pressure of mine water discharge but also addresses the industry’s needs in water-scarce areas (Sun et al. 2020). In addition, a coal mine in northern Shaanxi uses a centrally planned mine water comprehensive utilization network to collect

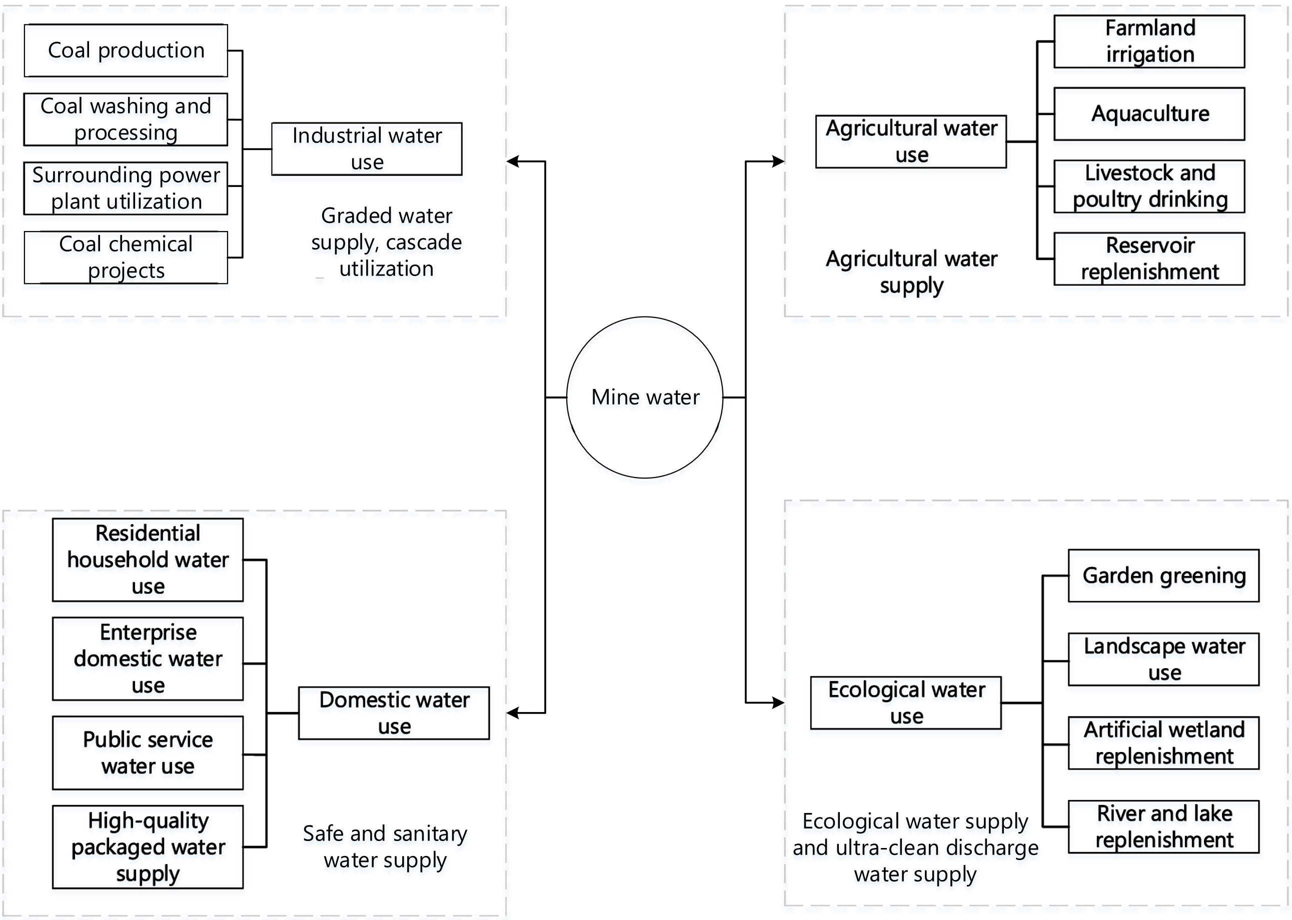


Fig. 12 The main methods of mine water resource utilization

a large amount of generated mine water and supplies it to surrounding industrial parks as industrial water (such as water for cooling systems, boiler feedwater, etc.). This approach not only avoids environmental pollution but also mitigates water scarcity there (Miao and Wang 2017).

Agricultural Water Use

Mine water is primarily utilized in agriculture for purposes such as farmland irrigation, aquaculture, livestock and poultry watering, and reservoir replenishment. In the coal mining areas of western China, the main application of mine water resources in agriculture is for farmland irrigation. According to surveys, several coal mines in Shaanxi use the surplus treated mine water treated for irrigating wheat fields for nearby residents and supplemental water for agricultural landscapes. This practice alleviates the local shortage of agricultural water supply.

Ecological Water Use

Ecological utilization of mine water resources primarily includes aspects such as landscaping, landscape water use, artificial wetland supplementation, and river and lake replenishment. In recent years, China has gradually emphasized the role of mine water for ecological conservation. In an ecological park in Ordos City, a man-made waterfall was constructed using treated mine water. The water for the landscaping comes from the underground drainage water of surrounding coal mines, successfully alleviating water scarcity issues. In the Shendong mining area, located in the Mu Us Desert, a considerable amount of mine water is supplied annually for local ecological governance. This measure has supported the sustainable utilization of water resources and ecological governance in the mining area, greatly improving the ecological environment. Specifically, the availability of water resources has promoted the establishment of diverse ecological communities, including habitats suitable for various amphibians, birds, and other species. The treated mine water further enhances the biodiversity and ecosystem services of the region's natural water bodies.

Domestic Water Use

After undergoing advanced purification treatment and meeting the requirements of the "Hygienic Standard for Drinking Water" (GB 5749-2022), mine water can be used as domestic water. Typically, after meeting the domestic water needs of the mining enterprises themselves, the remaining water can be provided for domestic use by surrounding enterprises or residents (Li et al. 2021a). According to surveys, several coal mining enterprises in Shaanxi province employ advanced mine water treatment technology to have the mine water comply with the standards for domestic drinking water. Mine water that meets quality standards is directly used in staff canteens and the daily lives of employees. Some enterprises even package mine water rich in trace elements as bottled mineral water, such as strontium-enriched and selenium-enriched water, improving the urban domestic water supply. These measures signify continuous exploration of comprehensive utilization methods for mine water and contribute to diversifying the use of mine water in mining areas.

Challenges to the Utilization of Mine Water Resources in China

Ambiguity in Relevant Policies and Lack of National Incentives Guidance

Despite the government's recent efforts to formulate a series of policy documents to promote the comprehensive development and resource utilization of mine water, these policies exhibit ambiguity and uncertainty in practical implementation. For instance, issues such as the clear definition of mine water resources, water quality standards for the categorized use of mine water, the jurisdictional scope of supervisory authorities, tax incentives, and detailed specifications lack unified and detailed policies. This lack of operational policy guidance hampers related enterprises from effectively utilizing mine water resources. The complexity of mine water quality, combined with the absence of relevant standards and coordinated planning for the utilization of different types of mine water, often results in irrational process selection. Substantial investments of manpower and financial resources may yield lower-than-expected cost–benefit ratios. These circumstances greatly affect the enthusiasm around reutilization. In comparison, in the United States, there are clear regulations regarding the allocation and permits of mine water rights for mining companies. Certain water rights permits specify that coal mining enterprises can receive financial incentives if they can prove that mine water is being beneficially used as an alternative water source. The cost of using mine water is limited to transportation and treatment expenses, with no volumetric payment required. Conversely, there is a risk of losing water rights allocation if these conditions are not met. These policies greatly contribute to the protection and promotion of mine water reuse (Thomashausen et al. 2018).

Insufficient Recognition of Mine Water Resources

Mine water, as a byproduct of coal mining, does not receive enough recognition. Despite the government's gradual emphasis on the utilization of mine water resources in recent years, incorporating mine water into various aspects of production and daily life, the general public still lacks a proper understanding of mine water. Perception of mine water among the public tends to focus on incidents related to mine safety accidents and environmental pollution, without recognizing it as a potentially valuable water resource. There is insufficient information dissemination about the resource potential of mine water, with a lack of social organizations and platforms for promotion. Furthermore, some mining enterprises prioritize coal production benefits over the ancillary benefits of mine water, leading to issues in mine water management. These enterprises commonly perceive mine water as difficult to treat due to its turbidity, failing to recognize it as a genuinely valuable resource for development and beneficial reuse. To create an environmentally friendly mining area and fulfill social responsibilities, some international mining companies often utilize mine water to supply residents in the mining area with water. For instance, PT Adaro, the second-largest coal company in Indonesia, treats mine water to meet drinking water standards and provides it to nearby villages, benefitting thousands of villagers. In addition, the water treatment facilities are entirely managed and operated by the villagers themselves, with the company offering expert technical training. This initiative has transformed the issue of insufficient recognition among local villagers regarding mine water resources (Adaro Energy 2011).

Uneven Development in the Utilization of Mine Water

There is uneven development in the mine water utilization in China, primarily due to regional disparities and differences in water resource conditions. In water-scarce regions such as the western coal mining areas, there is a strong emphasis on the utilization of mine water, resulting in a relatively high overall utilization rate. In regions with relatively abundant water resources, such as the southwestern and southeastern coal mining areas, the utilization of mine water is lower than the national average due to unclear economic benefits. Currently, mine water is mainly used in the industrial sector, with a high treatment cost averaging 5 yuan per ton. The treatment cost alone exceeds the average cost of industrial water in the area, which is 4.1 yuan per ton. Additionally, the substantial upfront investment in mine water resource utilization projects poses a notable challenge, especially for the southwestern coal mines with generally smaller production scales and lower mine water inflow. The high initial investment and ongoing operation and maintenance costs severely hinder the development of mine water resource protection and utilization in this region. Some international coal mining companies are encouraged to sell or donate excess mine water resources to nearby industrial, agricultural, or municipal consumers. This helps offset some water treatment costs, and the potential assessment of trading excess water between mines further promotes the resolution of uneven development issues in mine water utilization (Cote et al. 2007; Northey et al. 2019; Rimawi et al. 2007).

Lack of Detailed Water Resource Allocation Plans and Monitoring Systems

Currently, the mine water resource allocation model employed by Chinese coal mining enterprises is relatively rudimentary. The simplistic categorization of mine water utilization into “production,” “daily life,” and “ecological” purposes cannot meet the current urgent needs and does not allow for creative reuses. Various water demands exist within coal mining areas, including surface greening water, underground fire prevention, mud grouting water for strata consolidation, dust suppression, wash water for coal preparation plants, and domestic water use. However, the lack of detailed water quality grading and quantitative allocation during the entire process from mine water generation, phased treatment, to final utilization results in the inefficient use of mine water. This seriously impedes the coordinated development of coal and water resources in mining areas. Additionally, Chinese coal mining enterprises lack a comprehensive water quantity-water quality dynamic monitoring system for mine water from generation to final utilization. Some western coal mines have established basic online monitoring of individual indicators such as water level, water pressure, and water temperature, but this falls short of meeting the requirements for detailed mine water resource grading, quality allocation, and utilization. In this regard, the U.S. Environmental Protection Agency regularly monitors the mine water quality and records it. The evaluation encompasses various mining and milling techniques, as well as the raw water quality of various facilities, processes, and minerals. The parameters involved are extensive, including pH, total suspended solids, total dissolved solids, alkalinity, hardness, and sulfate concentrations, among others. This comprehensive assessment lays the foundation for subsequent steps in graded and quality-based utilization of mine water (Dou et al. 2015; Ni et al. 2020; U.S. EPA 1982; Wen 2023; Zhang et al. 2009).

Development Prospect of Mine Water Treatment and Resource Utilization In Coal Mine

Mine Water Treatment

Improvement and Perfection of Underground Mine Water Treatment Systems

Underground treatment is increasingly being recognized as a vital component of mine water treatment strategies. Compared to traditional surface treatment, underground treatment permits direct utilization without the need for pumping, reducing costs associated with raising the mine water and surface land acquisition. However, the constraints of underground space requires efficient, compact, modular mine water treatment equipment. Simultaneously, it needs to meet the special safety requirements of underground coal mines, including being explosion-proof, moisture-proof, dust-proof, and anti-static electricity. However, this is destined to become a future trend. To prevent groundwater pollution, underground mine water treatment systems will require additive-free direct filtration systems, such as goaf filtration and ceramic membrane filtration. Additionally, underground treatment systems should have automatic control functions, with monitored mine water inflow and water quality, and automatic dosing. Technological innovation will be the key to achieving this development.

Large-Scale, Low-Cost, Efficient Treatment Technologies for Highly Saline and Fluoride-Containing Mine Water

The western mining areas have abundant solar and geothermal resources. In large coal bases, there are usually associated projects such as large-scale thermal power and coal chemical projects, leading to a great amount of steam waste heat. Utilizing these heat sources in conjunction with corresponding technologies, such as low-temperature multiple-effect evaporation and membrane distillation, can greatly reduce the energy consumption costs of treating highly saline mine water. However, achieving this goal requires overcoming challenges in technological innovation, engineering design, and equipment development. Pre-treating highly saline mine water and then sealing it in the safe deep layers can also reduce costs and energy consumption, considering geological, environmental, and safety factors. However, this method of disposal is proposed as a potentially viable approach for managing highly saline mine water in regions where conventional treatment methods are either impractical or not cost-effective. Additionally, developing high-capacity, renewable adsorptive materials for high-fluoride mine water will be necessary, along with the collaborative treatment of high-salt and high-fluoride mine water.

Graded Treatment and Quality-Based Utilization of Mine Water

Graded treatment and quality-based utilization of mine water involve selecting treatment technologies based on water quality and final usage to avoid substandard water quality or excessive treatment costs. Currently, there is a lack of uniformity in national mine water treatment standards, with some regions still using outdated GB 20426–2006 "Coal Industry Pollutant Emission Standards," resulting in insufficient water quality and lax standard limits. Some regions enforce strict standards, such as Class III standards in the "Surface Water Environmental Quality Standards," even requiring zero discharge, leading to high treatment costs and increased corporate burdens. Future standards should be more scientifically systematic, aligning with water quality requirements and reuse goals, utilizing multiple technologies, optimizing processes and parameters to achieve the ultimate goals of mine water graded treatment and quality-based utilization. Advancing the scientific and systematic nature of standards requires coordinating various interests, ensuring the formulation of reasonable plans, and promoting the synergy of multiple technological treatments. Additionally, a thorough understanding of water quality requirements in different regions is crucial.

Utilization of Mine Water Resources

Enact Executable Policies for the Utilization of Mine Water Resources

To achieve the utilization of mine water resources, it is essential to establish sound policies and regulations. National and local authorities should coordinate efforts, collaboratively address water quality and environmental protection issues in the development and utilization of mine water resources. Detailed plans for mine water utilization should be formulated at the national level with clear utilization goals and assessments. At the local level, standards and regulations should be refined, and rational tax subsidies policies established, ensuring the participation of frontline workers to guarantee policy stability and feasibility. This requires strong regulatory and enforcement mechanisms, as well as a great deal of financial investment. Conflicts of interest and priorities between local governments and enterprises may exist, and these conflicts need to be fully considered when formulating relevant policies.

Intensify Publicity on the Utilization of Mine Water Resources and Expand Financing Channels

We recommend establishing a dedicated association for the utilization of mine water resources to organize industry conferences, facilitate collaboration between research institutions and enterprises, coordinate needs and conflicts between enterprises and the government, and strengthen public awareness of the utilization of mine water. Additional objectives include broadening financing channels, attracting social capital, extending the downstream industrial chain of comprehensive mine water utilization, and reducing water treatment costs. Promoting mine water utilization requires overcoming the public's cognitive gaps, necessitating expenditures for widespread promotion and education. In addition, introducing social capital and expanding financing channels requires addressing investors' risk concerns, formulating incentive policies, and reducing investment risks.

Refined Mine Water Resource Allocation Plan and Full-Cycle Monitoring System

Establishing a refined mine water resource allocation plan involves precisely allocating graded treated mine water to meet the water needs at various levels, including production, ecology, and daily life, for individual coal mines and even entire mining areas. Implementing a full-cycle monitoring system for mine water resources, from generation to utilization, would enable precise monitoring of water quantity and quality. This system would provide data support for the refined graded and quality allocation and utilization of mine water resources, greatly enhancing overall utilization efficiency. The key lies in coordinating collaboration among coal mines and mining regions to ensure the accuracy and timeliness of data. Additionally, sufficient investment and technical support are required to ensure the smooth implementation of the full-cycle monitoring throughout the entire lifecycle.

Exploring New Approaches for Mine Water Resource Utilization

Mine water inherently contains stable geothermal energy, nearly unaffected by external influences, making it suitable for heating and cooling in mining areas. The utilization of waste heat from mine water has a major impact on energy conservation and emission reduction, with high economic value and environmental benefits (Alvarado et al. 2022; Ebel et al. 2023; Kwon et al. 2023; Mandemvo et al. 2024). Additionally, clean mine water, primarily sourced from unpolluted underground water, can be treated easily to become high-quality drinking water, rich in various trace elements. The development and utilization of such water can generate substantial income for coal mining enterprises. Faced with national capacity reduction policies and declining coal mine profits, the development of high-quality mine water is expected to become a future trend. However, obstacles to overcome include the development and widespread adoption of adaptive technologies, potential environmental impacts during the treatment process, and regulatory measures to ensure water quality safety.

Acknowledgements The authors gratefully acknowledge the valuable feedback provided by the editors and reviewers. This work was supported by Tiandi Science and Technology Co., Ltd. Science and Technology Innovation Venture Capital Special Project (Grant 2022-2-TD-ZD005), and the Natural Science Basic Research Plan of China's Shaanxi Province (Grant 2023-JC-ZD-27).

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

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