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# Wastewater reuse and recycling of the steel industry in China: history, current situation, and future perspectives

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## ABSTRACT

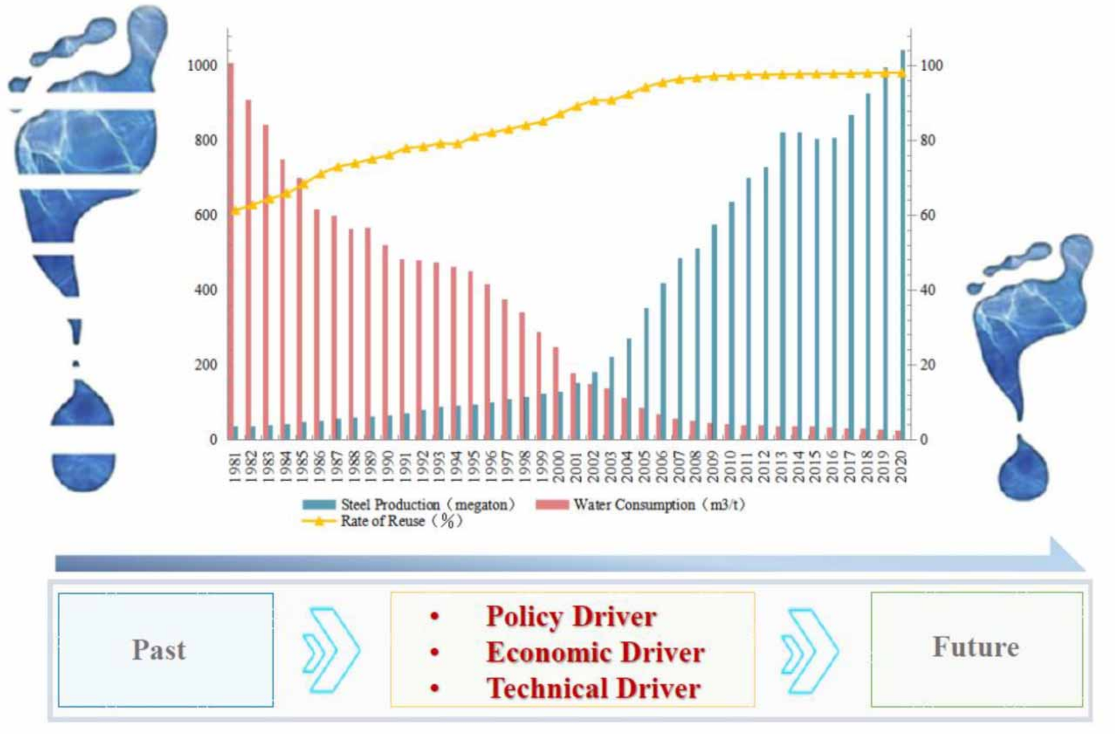
China is the largest steel producer in the world. Effective methods to alleviate the contradiction between water supply and water demand of the iron and steel industry in China are to implement the recycling of wastewater from the iron and steel industry and develop unconventional water resources. This paper reviews the development of wastewater recycling in the iron and steel industry in China in the past 40 years (1980–2020). During this period, steel output has increased from 36 to 1,053 million tons, freshwater consumption per ton of steel has decreased from 35.9 to 2.45 tons, and water resources reuse has soared from 61.2 to 98.02%. Four typical cases, including the Anyang Steel Group, the Tangshan Steel Group, the Tianjin Steel Group, and the Taihang Steel Group, were analyzed. In addition, a water efficiency research project of iron and steel enterprises in China was carried out in 2019. Statistical analyses on wastewater recycling rate, reuse rate, direct cooling water circulation rate, and other indicators were performed. The recycling of wastewater in the iron and steel industry would be continuously improved by policy drivers, economic drivers, and technical drivers.

**Key words:** iron and steel industry, unconventional water resource utilization, wastewater reclamation

## HIGHLIGHTS

- History of steel wastewater reuse and typical projects in China were presented.
- Effective methods to alleviate the contradiction between water supply and demand were introduced.
- Comparisons of the water use efficiency of steel industries in China were conducted.
- Perspectives and challenges of future development of the steel industry were proposed.

## GRAPHICAL ABSTRACT




## 1. INTRODUCTION

China is the largest producer of steel in the world. Crude steel output in China has been higher than that of any other country over the previous 25 years since it reached 100 million tons in 1996. In 2020, China produced 1.065 billion tons of crude steel, accounting for 56.8% of global steel production. China's iron and steel industry has achieved a historic transformation after 70 years of development and its industrial competitiveness has increased constantly (Li *et al.* 2019), making it the most internationally competitive industry in China and providing vital support for global economic development.

China is relatively short of water resources, and the spatiotemporal distribution of its water resources is extremely inconsistent with demand. Consequently, the contradiction between water resource shortages and the sustainable development of the steel industry is becoming increasingly prominent. The steel industry is a major user of water, accounting for approximately 9% of China's total industrial water consumption (Tong *et al.* 2019). The steel industry is also the major discharger of wastewater, accounting for 14% of China's total industrial wastewater emissions (Sun *et al.* 2019). Moreover, the discharge of wastewater (e.g., brine) degrades water quality and thus water cannot be directly used for potable water (via desalination) and industrial applications (Panagopoulos 2022a; Panagopoulos & Giannika 2022a, 2022b). Therefore, effective approaches to alleviate the contradiction between the supply of and demand for water resources in China are to encourage water saving and wastewater emission reduction and enhance the reuse of iron and steel industry wastewater (Alcamisi *et al.* 2014; Gu *et al.* 2015).

The components of the wastewater from iron and steel enterprises are relatively complex and the main components of the wastewater discharged by each production process are presented in Table 1. Most of the wastewater produced by each workshop in an iron and steel enterprise is usually reused after being treated by the workshop water treatment unit to form a workshop-level water circulation system. However, the main problem is that the wastewater must eventually be discharged because of the increased salt content caused by continuous circulation (Huang *et al.* 2011). This part of the recycling of wastewater has become the main component of the comprehensive wastewater discharged by iron and steel enterprises.

The comprehensive wastewater of iron and steel enterprises refers to the total drainage of an entire plant and includes the forced drainage of the direct and indirect circulating cooling water systems of each workshop, drainage of the cold rolling plant wastewater treatment station, and sporadic drainage of the entire system (Wang *et al.* 2020). In China, the comprehensive wastewater produced by an iron and steel enterprise often accounts for more than 40% of its freshwater consumption

**Table 1** | Pollutant composition of wastewater discharged by different processes in iron and steel enterprises

| | Phenol cyanide | Fluoride | Oil | Heavy metal | Suspended solid | Thermo | Acid | Alkali |
|---|---|---|---|---|---|---|---|---|
| Sintering | | | | | √ | √ | | |
| Coking | √ | √ | | | √ | √ | | |
| Iron-making | √ | | | | √ | √ | | |
| Steel-making | | | | | √ | √ | | |
| Steel rolling | | | √ | √ | √ | √ | √ | √ |

(Li *et al.* 2020), which is a proportion that is larger in comparison with that of many similar enterprises in other countries. The development of a Chinese iron and steel enterprise often goes through a process of transformation, expansion, and progression from a small- to large-scale operation. Owing to shortages of water supply and the drainage configuration, together with the level of technology, application, and management, overflows and accidental discharges from the water treatment facilities of each process can often occur in conjunction with the leakage of sewage and rainwater from old drainage systems (Garg & Singh 2022). However, although the total amount of wastewater might be large, the water quality is generally not bad, treatment is not difficult, and wastewater can easily be recycled. Therefore, utilization of the wastewater from the iron and steel industry in China should involve the promotion of plant-wide comprehensive wastewater treatment and reuse. Given the importance of comprehensive wastewater recycling to the sustainable development of the iron and steel industry, the Ministry of Science and Technology of China has incorporated the 'Integration and Demonstration Project of Water Treatment and Sewage Recycling Technology in Iron and Steel Enterprises' and 'Water Saving Technology Development in Large Iron and Steel Joint Enterprises' into the national science and technology research plans of the 10th and 11th 5-year plans, respectively. Additionally, thermal technologies such as multi-stage flash distillation (MSF), multi-effect distillation (MED), and membrane technologies such as reverse osmosis (RO) are used for the treatment of wastewater (Panagopoulos 2022b; Panagopoulos & Giannika 2022b).

While gradually achieving the recycling of industrial wastewater, China's iron and steel enterprises have also been active in exploring the use of unconventional water resources such as urban sewage/reclaimed water to alleviate the contradiction between the supply of and demand for water resources. For iron and steel enterprises near cities, urban sewage/reclaimed water has the characteristics of stable quantity and quality, and with proper treatment, it could be used to produce new water, softened water, and desalted water, which is an ideal 'freshwater source'. In 2019, urban sewage discharge in China was approximately 75 billion $m^3$ and the use of renewable water resources was less than 10 billion $m^3$. By adopting urban sewage/reclaimed water as a new water source, China's iron and steel enterprises could not only greatly reduce the demand for new water in the upper reaches of a city, but also transform themselves from being major users and polluters of water, to enterprises that receive sewage and help eliminate pollution, which has obvious environmental and social benefits.

Since 2000, China's iron and steel industry has accelerated the implementation of water saving and wastewater resource utilization, and all related water efficiency indicators have improved markedly. In the process of increasing steel production from 129 million tons in 2000 to 1.053 billion tons in 2020, the freshwater consumption involved in steel production has decreased from 28.96 to 2.45 $m^3$/tons, and the proportion of water reuse has risen from 86.05 to 98.02%. Currently, every index of water use efficiency of China's iron and steel industry ranks among the highest in the world.

To the authors' best knowledge, there has not been a systematic and comprehensive study on wastewater reuse and recycling of the steel industry, which deserves more attention. In order to fill the knowledge gap mentioned above, it is important to make further investigations in this research field. The objectives of this review were (1) to give an overview of the experience of water reuse in China's steel industry, including the history and current situation and (2) to comprehensively evaluate the future perspectives on technologies in water reuse. In brief, this study can promote the development model of the recycling economy and achieve the ecological development of the steel industry.

## 2. HISTORY OF STEEL INDUSTRY WASTEWATER REUSE IN CHINA

The recycling of wastewater by China's iron and steel industry has undergone a process of development. Early in this process, owing to the different levels of production technology, equipment condition, and management of iron and steel enterprises in different regions, the level of wastewater resourceization in China differed greatly (Zhang *et al.* 2011, 2017; Lawal & Anaun 2022). Before 1980, China's iron and steel enterprises mostly used a direct-flow water supply, which involved the consumption of a large volume of water, produced a substantial amount of pollution, and was poorly managed. From 1981 to 2020, after 40 years of development, steel production in China increased from 36 to 1.053 billion tons. During the same period, freshwater consumption involved in steel production decreased from 35.9 to 2.45 $m^3$/tons, the water resources reuse rate increased from 61.2 to 98.02%, and the water efficiency index of China's iron and steel industry improved substantially (Figure 1).

### 2.1. Phase 1: 1980–1990

In October 1978, a Chinese expert group participated in an expert working meeting on environmental protection in the steel industry organized by the Industrial Environment Office of the United Nations Environment Programme in Geneva, Switzerland. Experts from various countries approved the general report of the Secretariat of the Office of Industrial Environment and, on this basis, compiled the 'Environmental Aspects of Iron and Steel Production – Overview', 'Environmental Aspects of Iron and Steel Production – Technical Review', and 'Guidelines for Environmental Management of Iron and Steel Works'. These documents took environmental protection in relation to the iron and steel industry as the main focus, deeply elaborated the main environmental problems such as air pollution control, water pollution prevention and control, solid waste treatment, and proposed technical suggestions such as wastewater treatment and reuse, RO desalination treatment, and indirect cooling with seawater, which have provided important guidance for water resources management by China's iron and steel industry.

During 1981–1990, wastewater treatment by China's metallurgical and iron industry mainly focused on the treatment and recovery of coking wastewater, blast furnace gas washing water, converter flue gas dust removal water, continuous casting and steel rolling wastewater, pickling wastewater, and mine wastewater. Among others, the Ministry of the Metallurgical Industry of China established the following 10 scientific research projects: (1) Research on Improving the Circulation Rate of Blast Furnace Gas Washing Water, (2) Converter Flue Gas Dust Removal Wastewater Recycling Technology, (3) Gas Station Sewage Purification and Reuse Technology, (4) Purification and Utilization Technology of Steel Rolling Wastewater,

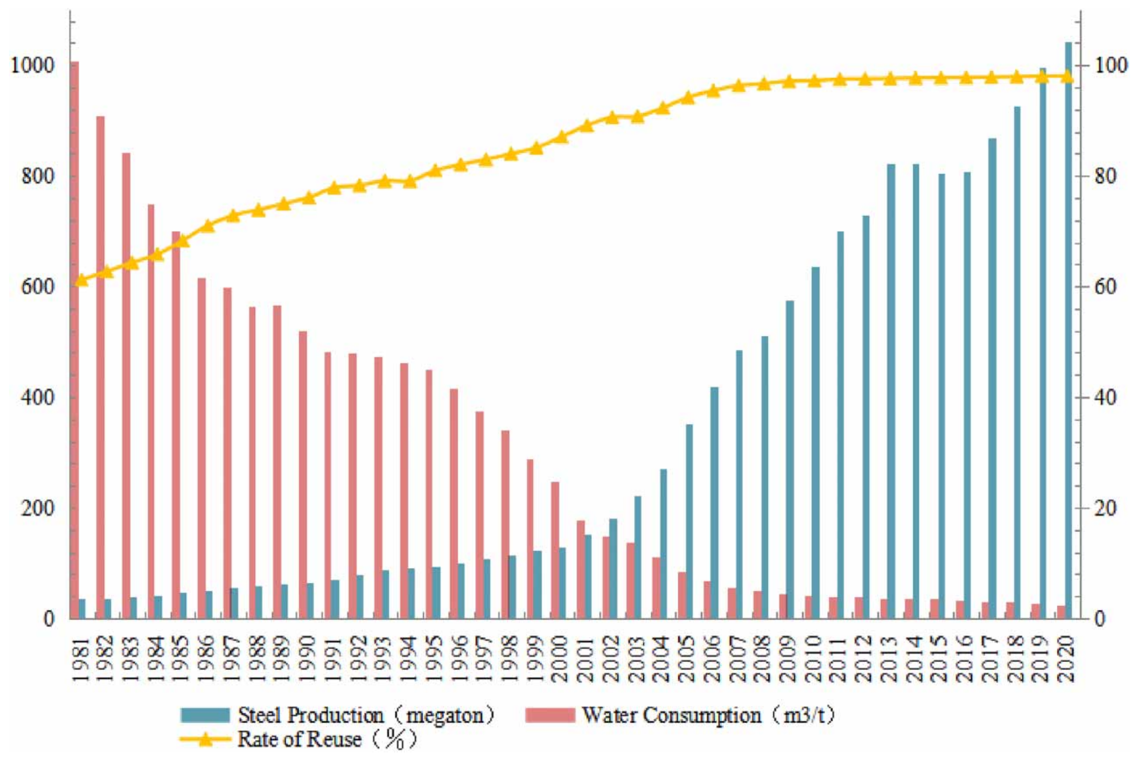



**Figure 1** | Steel production and main water efficiency indexes in China from 1980 to 2020.

(5) Study on Improving the Concentration of Sediment in Concentration Tanks, (6) Sludge Dewatering Technology, (7) Comprehensive Treatment Technology of Coking Wastewater, (8) Treatment Technology of Pickling Waste Liquid, (9) Principles of Diffusion, Migration, and Transformation of Toxic and Harmful Substances in Wastewater, and (10) Research on the Best Approach to Use and Recycle Water Resources in Iron and Steel Enterprises.

During this period, in September 1985, the first phase of Shanghai Baosteel was made available for operation, which was a milestone event in the development of China's steel industry. The first phase of Baosteel, which used the most advanced technologies and equipment available in the 1970s, produced an annual output of 6.71 million tons of molten steel. From the perspective of water efficiency, the consumption of freshwater per ton of steel produced was 9.9 $m^3$, and the average rate of water resources recycling in the circulating water system of the workshop was 95%. In terms of wastewater resource utilization, oil-bearing wastewater from continuous casting, steel rolling, and other processes was centrally processed and reused. Sewage and rainwater discharged from the circulating water systems of each workshop were eventually discharged into the Yangtze River after meeting discharge standards.

### 2.2. Phase 2: 1991–2000

In June 1992, the United Nations Conference on Environment and Development, held in Rio de Janeiro (Brazil), adopted the 'Rio Declaration on Environment and Development, Agenda 21', together with other documents that focused on sustainable development. In July 1994, the Chinese government prepared a white paper on China's population, environment, and development in the 21st century, which for the first time incorporated the sustainable development strategy into the long-term plan of China's socio-economic development. This document clearly stated China's ambition for 'promoting cleaner production technology, achieving minimum quantitative and recycling waste output, saving resources and energy, and improving efficiency'.

In this period, to meet environmental requirements, China's iron and steel industry continued to focus on ammonia nitrogen and chemical oxygen demand (COD) degradation technology for the treatment of coking wastewater, the treatment of steel rolling oily wastewater, and the comprehensive wastewater treatment and reuse of the plant-scale. For example, Anshan Iron and Steel, Capital Iron and Steel, and other enterprises completed comprehensive wastewater treatment and reuse projects for entire plants such that their industrial water reuse rate reached approximately 95%, thereby laying the foundation for subsequent development of the plant-scale use of comprehensive wastewater resources.

During 1991–2000, China's iron and steel industry experienced huge investment, considerable transformation, and substantial development, undergoing an average annual growth rate of 9.8%. At this time, China's iron and steel enterprises were trying to promote cleaner production, narrow the gap in terms of global technology level, promote the reuse of wastewater resources, and overcome the bottleneck of resource shortages restricting the development of the industry.

The completion of the Tianjin Seamless Steel Pipe Project in 1993 was another important event in the development of China's steel industry. The annual production was 600,000 tons of steel and 500,000 tons of seamless steel pipe, of which 350,000 tons was oil casing. In this project, the water system adopted a series of energy- and water-saving measures, such as series water use, closed circuit and open circuit circulation, high concentration ratios, and plant-scale production wastewater treatment and reuse facilities. The water resource recycling rate of the entire plant was 94.08%, the average water resource recycling rate of the workshop circulating water system was 97.10%, and the wastewater recycling rate was 72.5%, which not only reduced the freshwater replenishment and wastewater discharge, but also contributed to environmental protection.

### 2.3. Phase 3: 2001–2010

To encourage cleaner production, improve the efficiency of resource utilization, and promote sustainable socio-economic development, China officially implemented the 'Cleaner Production Promotion Law of the People's Republic of China' on 1 January 2003. Thus, the requirement for sustainable socio-economic development was written into law for the first time, marking a milestone with regard to the promotion of the recycling of wastewater in China's iron and steel industry. In July 2005, China issued the 'Iron and Steel Industry Development Policy', which proposed clear objectives for the iron and steel industry to develop a circular economy, save resources and energy, and proceed on the path of sustainable development. Furthermore, it specified clear requirements for water efficiency indicators such as water consumption per ton of steel produced by the iron and steel industry.

During this phase of development, the preparation of steel industry technical specifications received increasing attention. In 2006, the 'Cleaner Production Standard for the Iron and Steel Industry (HJ/T189-2006)' was released, the 'Design Specification for Comprehensive Utilization of Resources in the Iron and Steel Industry (GB 50405-2007)' was released in 2007, and the 'Specification for Water Saving Design of Iron and Steel Enterprises (GB 50506-2009)' was released in 2009.

Concurrently, an increasing number of researchers in China undertook in-depth studies on iron and steel wastewater recycling technology. In 2007, some researchers suggested that water recycling could be considered an economy that integrates cleaner production with wastewater utilization, water conservation, and emission reduction, establishes an economic development model based on continuous recycling of water resources, and forms the process of a repeated circular flow of water resources–products–renewable resources according to a natural ecosystem model that minimizes wastewater and maximizes the recycling of wastewater. On this basis, it was proposed that the iron and steel industry should actively promote a multipurpose mode of 'water supply by quality–water cascade use', a reuse mode of 'wastewater–harmless–resource', and a recycling mode of 'comprehensive wastewater–purification–reuse' (Lei 2007).

In 2008, some scholars believed that China's iron and steel industry should learn from the successful experiences and approaches of developed countries with regard to wastewater treatment and resource utilization technology. Generally, it was considered that such approaches should be in accord with international management methods and ideas on clean production, and implement comprehensive process management for reducing, recycling, and detoxifying the wastewater from the iron and steel industry. The objectives of such methods were to minimize wastewater and discharge as little wastewater as possible in the production process, and comprehensively utilize, recycle, and reuse the generated wastewater to make it as resourceful as possible. On this basis, wastewater that was generated but could not be recycled would be disposed of harmlessly (Wang *et al.* 2009).

During this period, many Chinese iron and steel enterprises undertook a wide range of comprehensive wastewater reuse projects, and many advanced water treatment technologies developed internationally, such as high-density sedimentation tanks and V-type filter technology of Delyman, and high-density sedimentation tanks and filter technology of Veolia, were adopted for use by the Anyang Steel Group, the Chengde Steel Group, the Tangshan Steel Group, and other enterprises. Concurrently, the potential of comprehensive wastewater advanced treatment processes incorporating ultrafiltration and RO as the core technologies was increasingly recognized. In December 2002, Taiyuan Iron and Steel completed China's first double-membrane comprehensive wastewater advanced treatment project (72,000 tons/day). Subsequently, iron and steel enterprises in water-deficient areas such as Beijing, Tianjin, and Hebei successively put into operation urban sewage/reclaimed water projects that were used for generating production water after treatment and achieved satisfactory results.

### 2.4. Phase 4: 2011–2020

Since 2011, China's iron and steel industry has gradually transformed from extensive management to green, informatization, and diversification, and from rapid incremental development to green transformation and progressive development (Li 2020). In 2012, China implemented eight stricter emission standards for pollutants emitted by the steel industry. In 2014, the National Development and Reform Commission, Ministry of Environmental Protection, and Ministry of Industry and Information Technology jointly issued the 'Evaluation Index System for Cleaner Production in the Iron and Steel Industry' to guide and promote iron and steel enterprises in implementing cleaner production and improving resource utilization efficiency, in which the index of wastewater resource recovery is highly valued. In 2015, China issued the 'Action Plan on Water Pollution Prevention and Control', which specified the need for 'encouraging the in-depth treatment and reuse of wastewater from steel and other water-consuming enterprises, and improving the water consumption quota standard for industries with high water consumption'. It was expected that the steel industry and other industries with high water consumption would meet the advanced quota standard by 2020.

In April 2019, the National Development and Reform Commission and the Ministry of Water Resources jointly issued the 'National Action Plan for Water Saving', which proposed that enterprises with high wastewater consumption should strengthen the in-depth treatment and standard reuse of wastewater by differentiating water prices and sorting water saving benchmarks. This would build a batch of water saving benchmark enterprises in high water consumption industries such as steel by 2022. In September 2019, targeting the Beijing–Tianjin–Hebei region (the largest steel production region in China), the Ministry of Industry and Information Technology issued the 'Action Plan for Industrial Water Saving in the Beijing–Tianjin–Hebei Region', which specified that by 2022, 'the water efficiency of key high water consumption industries (such as steel) in the Beijing–Tianjin–Hebei region should reach the international advanced level'. Furthermore, it also identified certain fundamental actions, i.e., the promotion of 'enterprises to carry out recycling of circulating water, water cascade utilization, wastewater treatment and reuse', the improvement of 'water efficiency and repeat utilization rate of all links of enterprises', encouragement of 'enterprises to use seawater, rainwater, and mine water', and the exploration of 'approaches to integrate industrial and urban water use and increase the use of reclaimed water'.

During this phase of development, the standards of the water reuse system of the steel industry gradually improved. In 2011, the 'Iron and Steel Enterprises Sewage Treatment Plant Process Design Specification (GB50672-2011)' was released. In 2012, the 'Engineering Technical Specification for Wastewater Treatment and Reuse of the Iron and Steel Industry (HJ2019-2102)' was issued. In 2017, the revised 'Design Criterion for Comprehensive Utilization of Resources in the Iron and Steel Industry (GB 50405-2017)' was released. In 2018, a document specifying the 'General Rules for Green Factory Evaluation (GB/T36132-2018)' was released. In 2019, the 'Guidelines for Green Plant Evaluation in the Steel Industry (YB/T4771-2019)' was released. In 2020, the 'General Specification for Comprehensive Wastewater Treatment of Iron and Steel Enterprises' was prepared and will be released soon.

In the field of technological research and development, in 2014, Jiangyin Xingcheng Iron and Steel and other enterprises completed research on 'Advanced Treatment and Recycling Technology and Application of Comprehensive Wastewater in Iron and Steel Complexes', which focused on the development of scale inhibitors, concentrated crystallization, and intelligent management and control of concentrated salt wastewater in the process of advanced treatment of comprehensive wastewater in iron and steel enterprises. In 2017, the Handan Steel Group and other enterprises completed the 'Demonstration of System Integration and Comprehensive Application of the Whole Process Control Technology for Water Pollution in the Iron and Steel Industry' project, which addressed the difficult problem of deep removal of low-concentration cyanide and refractory organic matter in iron and steel comprehensive wastewater. Ozonation technology and a process package for coagulation, decolorization, and decyanization of comprehensive wastewater were developed and applied in a demonstration of the comprehensive wastewater advanced treatment project by the Hegang Handan Iron and Steel (24,000 $m^3$/day).

By the end of 2016, the proportion of comprehensive wastewater supporting production by iron and steel enterprises had reached more than 75%, according to statistics from the China Iron and Steel Association. At this time, the advanced treatment process represented by the double-membrane method was widely popularized, and the proportion of high-quality recycled water had increased substantially. For some enterprises, the discharge of production-related wastewater was effectively zero. Additionally, the technology for recycling concentrated brine and unconventional water resources has also developed rapidly. Taking the Baosteel Zhanjiang Iron and Steel company as an example, it achieved zero discharge of production wastewater in 2019, and actively developed seawater and rainwater as new water sources. Thus, its consumption of unconventional water resources accounted for approximately 75% of its total water consumption.

## 3. TYPICAL WASTEWATER REUSE PROJECTS OF THE STEEL INDUSTRY IN CHINA

### 3.1. Wastewater reuse project of the Anyang Iron and Steel Group Company Ltd

In 2005, Henan Anyang Steel Group began construction of a large-scale wastewater recycling project (120,000 $m^3$/day), which was intended to mainly treat the general discharge of industrial wastewater by the plant and some urban domestic sewage derived mainly from the Anyang Steel Group. In this system, after being treated by the pretreatment system, part of the sewage is used as supplementary water for the production water and circulating water systems, and part of the water is supplied to the soft water pipe network of the entire plant as high-quality reclaimed water after in-depth treatment. RO-concentrated water and RO-cleaning wastewater are mixed and used for steel-making slag stewing and blast furnace slag washing.

As shown in Supplementary Figure S1, the pretreatment process of this project comprises grid + aeration + oil removal + coagulation + precipitation + filtration. A Densadeg high-density sedimentation tank and an Aquazur-V filter represent the core technologies. The advanced processing process of this project involves a multimedia filter and RO. The project required a total investment of 90 million RMB, and the total area is 360 m (length) × 110 m (width).

Since the project was put into operation in 2006, it has recovered 600 million $m^3$ of wastewater with a number of remarkable benefits. (1) In this project, there are three parallel treatment sequences in the single pool and high-density pool, but the sequential treatment water volume is 1,800 tons/h. A common coagulation tank unit is designed at the total inlet end. In actual operation, the high-density tank system is prone to severe sludge accumulation. Therefore, it is recommended that the treatment water volume of a single tank under similar conditions should not exceed 1,000 tons/h and that each sequence should be designed separately for each coagulation unit. (2) During 2006–2012, no sewage such as coking wastewater treatment station drainage was discharged into the total inflow, and the RO system ran smoothly with an average cleaning cycle of 3 months. After 2012, the performance of the RO system fluctuated greatly when raw water was mixed into part of the coking wastewater and it was prone to become fouled; consequently, the average cleaning cycle was shortened to 1 month. Wastewater with high organic concentration such as coking wastewater has considerable influence on the RO unit of the integrated wastewater treatment and it should not be allowed to enter the integrated wastewater treatment system. (3) The advanced treatment system of this project adopts a multimedia filter and RO. Since the system was put into operation, the SDI value of the RO influent has been 4–5, although the SDI value has exceeded 5 since 2008. Nevertheless, the RO system runs stably with a normal water yield and desalination rate, and the service life of the RO film is longer than 6 years. The question of whether it might be necessary to set the ultrafiltration system before the RO and the selection of the SDI value are topics worthy of further study.

### 3.2. Wastewater reuse project of the HBIS Group Tangsteel Company

In October 2009, the Wastewater Reuse Project of the HBIS Group Tangsteel Company was put into operation following a total investment of 326 million RMB. It is the largest comprehensive wastewater treatment center for steel and urban reclaimed water in North China. The two sequences of integrated steel wastewater treatment and urban reclaimed water treatment both have a treatment capacity of 3,000 $m^3$/h. After the water treatment center project was put into operation, the Tangsteel Company shut down all extraction of deep well water and took urban reclaimed water as the only production water source. The project supplies 4,200 $m^3$/h of fresh production water, 1,000 $m^3$/h of softened water, and 300 $m^3$/h of demineralized water. In terms of design, the project was planned and constructed according to the highest standards of the landscaping of industrial projects. Each process facility is a unique natural landscape that complements the surrounding 120,000 $m^2$ of green space to form an ecological park. It has become an important part of the Tanggang Garden Factory of Hegang and it won the 'Luban Award for Construction Engineering', which is the highest honor for engineering quality in China's construction industry.

As shown in Supplementary Figure S2, the pretreatment process of this project comprises grid + regulating pool + coagulation + precipitation + filtration. The core process involves a Densadeg high-density sedimentation tank and an Aquazur-V filter tank from Degremont, France. The advanced processing process of this project involves a horizontal multimedia filter + microfiltration + RO + mixed bed. The RO water is used as softened water and the mixed bed water is used as demineralized water, and both are supplied to the production users of the plant.

Since the project was put into operation in 2009, approximately 300 million $m^3$ of industrial wastewater and 300 million $m^3$ of urban reclaimed water have been recycled and utilized, bringing a number of remarkable environmental and socio-economic benefits. (1) The total inflow of the project comprises not only the comprehensive wastewater from the iron and steel industry, but also the wastewater from the city. Therefore, microbial fouling in the RO system is relatively serious. Measures such as ultralow differential pressure membrane elements and regular flushing are used to slow the process of microbial contamination, thereby increasing the chemical cleaning cycle of the RO system and reducing the required frequency of cleaning. The engineering operation example for 12 consecutive months shows that when the two measures are used alone, the cleaning cycle can be extended under the condition of high microbial contamination, and when the two measures are used simultaneously, the average chemical cleaning cycle can be increased from 15 to 30 days. (2) To minimize land occupation, the project adopts eight horizontal multimedia filters with a double-layer layout. In actual operation, it was found that the horizontal multimedia filter has a large water distribution section and that the uniformity of the water distribution section and backwash cloth water is relatively poor, which can have adverse effects on subsequent ultrafiltration; consequently, horizontal multimedia filters were not used in subsequent projects. (3) RO-concentrated brine in this project is supplied to users of blast furnace slag in the factory area. Salt is easily enriched in the water circulation system, and the chloride ions and electrical conductivity of the RO influent increase continuously, thereby reducing the RO water production rate. Given such problems, the enterprise increased the proportion of soft water supplements in the circulating water system of some workshops, reduced the salt content of wastewater recycling, and alleviated the trend of increasing salt content in water replenishment. At the same time, a decentralized desalting device was introduced in systems with a high volume of circulating water, such as power generation, to reduce the concentration of calcium ions in the system and to effectively control the concentration ratio of the circulating water.

### 3.3. Wastewater reuse project of the Tianjin Iron and Steel Group Company, Ltd

In 2011, the Tianjin Iron and Steel Group invested 200 million RMB to build a comprehensive wastewater treatment center for the factory. The comprehensive wastewater of the entire plant, discharged up to the standards, is reused as new water in the production system after treatment, thereby saving water resources, improving the rate of water reuse, and reducing the new water consumption per ton of steel produced. At the same time, an unconventional water resource utilization system was established, and municipal reclaimed water was also used to further improve the water efficiency of the enterprise. Commissioning of the project at the end of 2012 has saved on the purchase of 15 million $m^3$ of tap water annually and realized zero consumption of tap water for production. The process flow is shown in Supplementary Figure S3. It is worth noting that the project adopted 3D digital design, which greatly improved the design accuracy and shortened the construction period, marking a leap forward in terms of the development of design in the field of China's iron and steel industry.

In 2016, the Tianjin Steel Group Concentrated Brine Comprehensive Utilization Project was put into operation. This project was the first RO-concentrated brine wastewater resource recovery project in China. The designed water treatment capacity is 235 $m^3$/h. Most of the produced water is used as new industrial production water, and the remaining concentrated liquid (25 $m^3$/h) is used for low-quality water consumption in the steel slag treatment workshop and the electric furnace slag yard. After the project was put into operation, 1.8 million $m^3$ of tap water was saved annually. The process flow is shown in Supplementary Figure S4. This project won the highest design award of China's metallurgical industry in 2017.

The Tianjin Steel Group Concentrated Brine Comprehensive Utilization Project has a number of important features. (1) A nanofiltration membrane device is used to realize the initial reduction of the concentrated brine. The nanofiltration system adopts the collective concept of staged circulation to effectively control the concentration polarization on the surface of the organic matter membrane. The nanofiltration device is designed with a recovery rate of 85% and its initial reduction effect is obvious, which is a feature that can lead to reductions in the physical scale and the project investment of similar facilities built subsequently. Through reasonable calculation of the overall water quality, the design of the nanofiltration system separates $CaF_2$, which has a serious scaling tendency in the water body, thereby realizing stable operation of the membrane treatment system. (2) The self-crystallizing fluidized bed is used for dehardening of the concentrated brine, and the cross-sectional flow rate of the fluidized bed is as high as 80–100 m/h, which effectively overcomes the disadvantages of insufficient reaction and easy scaling inside a traditional dehardening reactor. The calcium carbonate crystals in the reactor grow well, and spherical particles of calcium carbonate crystals with a diameter of 0.5–1.0 mm can be formed, which have good fluidity, no obvious wall-hanging characteristic, and reasonable dehydration. Component analysis shows that it can be used in the production of sintering ingredients in the iron and steel industry to realize resource utilization. (3) The improved moving bed biofilm reactor (MBBR) biological treatment technology is used to control the organic matter in the concentrated brine, and the COD removal rate is approximately 30%. In the MBBR reactor, a suspended filler with a density close to that of water is added to the aeration tank as the active carrier of microorganisms. It is introduced in a fluidized state and relies on the aeration in the aeration tank and the lifting effect of the water flow. In comparison with the traditional biofilm method, the MBBR not only has the characteristics of impact load resistance, long sludge age, and less excess sludge, but also has the efficiency and operational flexibility of the activated sludge method. Thus, the MBBR has unique advantages in treating low-concentration wastewater.

Through a series of wastewater recycling projects implemented during 2011–2016, the Tianjin Steel Group has effectively improved its water efficiency index and water supply safety, bringing about substantial socio-economic benefits and considerable environmental benefits for the Tianjin region, which is extremely short of water.

### 3.4. Wastewater reuse project of the Hebei Taihang Iron and Steel Group Company, Ltd

In 2020, the Hebei Taihang Steel Group built a central water plant project, which is considered the representative project of wastewater reclamation in China's iron and steel industry. Following its completion, the central water plant has served as the water resource preparation and control center of the plant, responsible for both the preparation and supply of fresh water, desalinized water, fire water, domestic water, the treatment and reuse of comprehensive wastewater, rainwater, and other unconventional water resources (Supplementary Figure S5).

The project has a number of notable features. (1) The concept of water system resource utilization is obviously enhanced. The project established a plant-wide water supply system by quality, implemented cascade utilization and centralized treatment of water resources, formed a plant-wide scientific water resource allocation system, and built a comprehensive utilization system for unconventional water resources such as rainwater. (2) For concentrated salt wastewater, the process of 'deep concentration by membrane + evaporation crystallization by MVR' is adopted, realizing the complete separation of brine and the utilization rate of 100% of the comprehensive wastewater resource. Once the project was put into operation, it produced approximately 9.8 million $m^3$ of freshwater annually, and realized zero discharge of wastewater in the factory, thereby substantially reducing the intake of external freshwater.

## 4. WATER USE EFFICIENCY OF THE STEEL INDUSTRY IN CHINA (2017–2018)

This study selected 46 large- and medium-sized iron and steel enterprises as the research object. The total output of the surveyed enterprises in 2018 was 294.51 million tons of crude steel, accounting for 53.8% of the total output of 547.64 million tons of the key statistical enterprises of the China Iron and Steel Association, as shown in Figure 2. The 46 large- and medium-sized steel enterprises selected comprised 40 general steel enterprises and 6 special steel enterprises, 41 of which are long-process iron and steel complex enterprises that perform sintering (pelletizing), coking, iron-making, steel-making, and steel rolling processes. The survey covered a wide range of enterprises, including major administrative regions and different river basins within China. The iron and steel enterprises have some common characteristics and certain differences in terms of water resources conditions, water supply and drainage policies, water efficiency, and the application of water saving technology. Analysis of the survey data reflects the overall level of water consumption efficiency of China's steel industry, especially that of large- and medium-sized steel enterprises.

According to the feedback from the survey, China's iron and steel enterprises have gradually adopted advanced production technology, strengthened the management of water conservation in each process, and emphasized the use of sewage treatment as supplementary water for the circulating cooling water system, which are measures that have increased the water recycling rate and improved the water efficiency indicators. In this special survey of the water efficiency of 46 large- and medium-sized steel companies, the average water saving indicators in 2018 were as follows: water intake per ton of steel produced = 2.78 $m^3$/ton, direct cooling water circulation rate = 97.38%, wastewater reuse rate = 84.86%, water reuse rate = 97.87%, and comprehensive water leakage rate = 4.9%. The percentage of the surveyed steel companies that met all five indicators specified in the 'Water saving Enterprise Steel Industry (GB/T26924-2011)' standards for enterprises was 48.57%, as shown in Figure 3.

The wastewater reuse rate is a key indicator of the degree of wastewater recycling. It means the percentage of treated and reused water volume compared to the total drainage volume of industrial wastewater generated in an enterprise within a certain period. This index directly reflects the resource utilization degree of the wastewater of the entire plant. Among the 46 iron and steel enterprises surveyed, the total number of enterprises that provided clear wastewater reuse rate data was 31, as

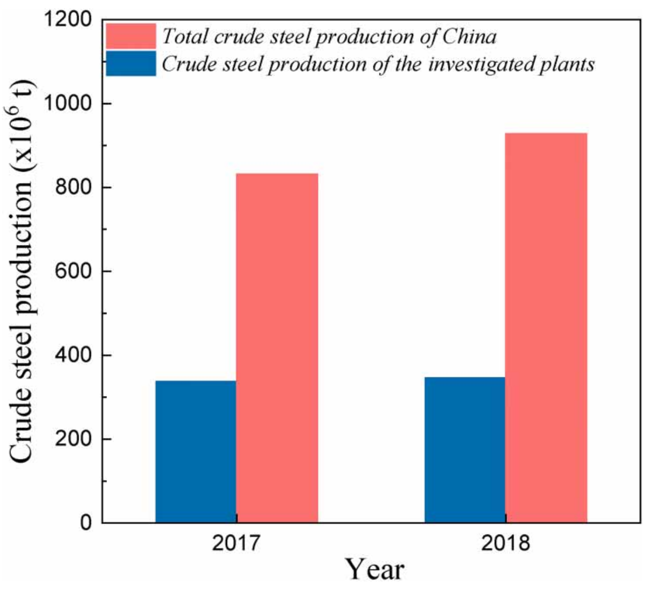



**Figure 2** | Proportion of output of steel enterprises participating in the survey.

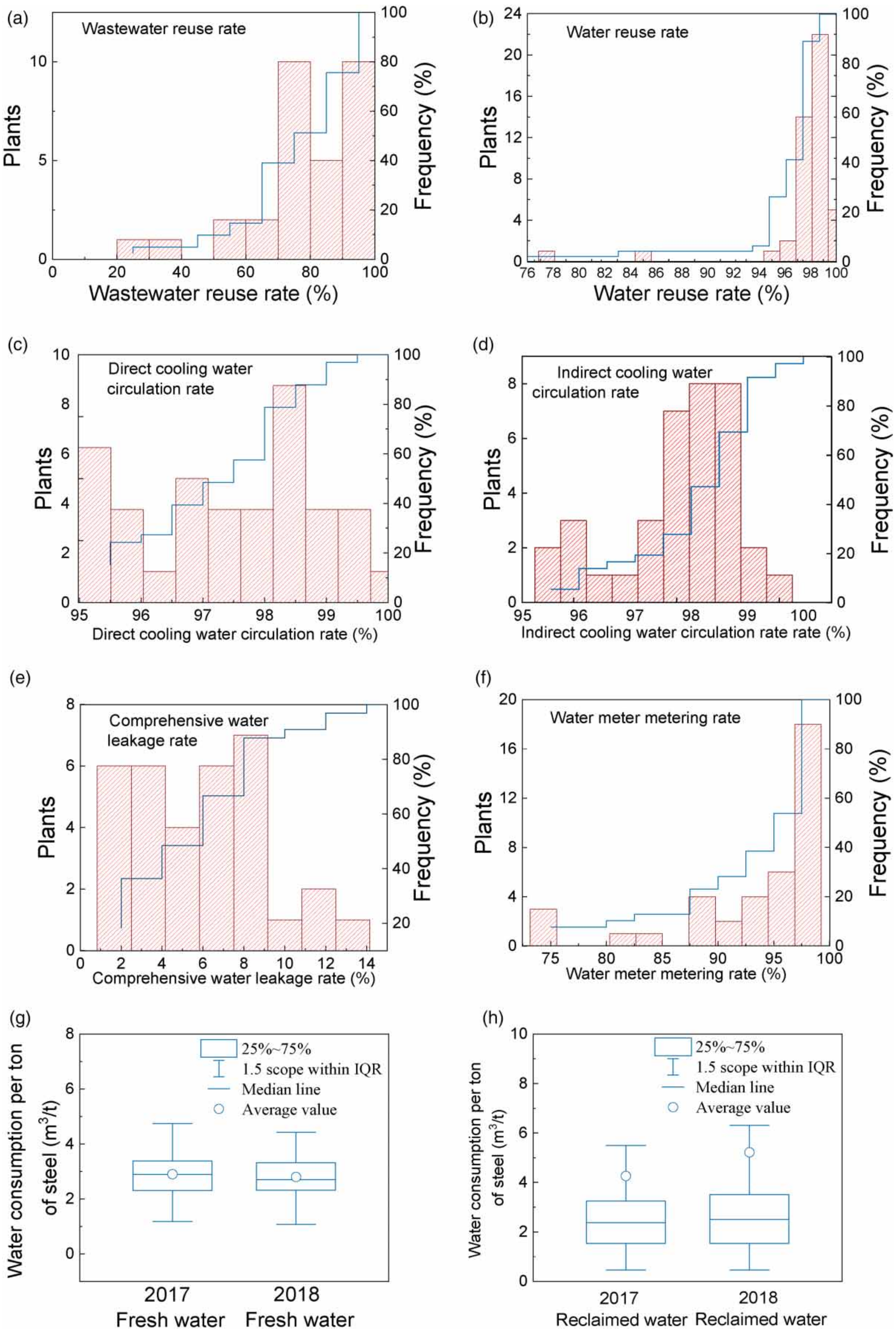



**Figure 3** | Survey results of the 46 iron and steel enterprises: (a) wastewater reuse rate; (b) water reuse rate; (c) direct cooling water circulation rate; (d) indirect cooling water circulation rate; (e) comprehensive water leakage rate; (f) water metering rate; (g) fresh water consumption per ton of steel; and (h) wastewater consumption per ton of steel.

shown in Figure 3(a). Overall, 25 of the 31 steel companies (80.65%) had a wastewater reuse rate exceeding 70%, and of those 25 companies, the wastewater reuse rate of 10 (32.26%) exceeded 90%.

Most steel companies in China are actively exploring the development of unconventional water sources, and municipal reclaimed water, seawater, and rainwater are all currently widely used (Figure 4). Municipal reclaimed water has the characteristics of stable water quantity, controllable water quality, and local availability. After proper treatment, it can produce new water, softened water, and demineralized water, thereby representing an ideal unconventional water resource for iron and steel enterprises. Currently, municipal reclaimed water accounts for the highest proportion (approximately 40%) of unconventional water sources used by iron and steel enterprises.

The continual efforts of iron and steel enterprises to conserve water have changed the extensive development model of the past and established a new framework for water saving development. Through analysis of the survey data, the overall water efficiency improvements in the steel industry are mainly attributable to the following:

(1) Restriction and guidance of national and local water conservation and environmental protection laws and policies, and strict supervision and management by the government of enterprise water intake and wastewater discharge.
(2) Progress in the management of water use and water conservation by iron and steel enterprises. Based on the survey, it appears that water management by iron and steel enterprises has become more standardized and systematic. A relatively complete water management system has generally been established, and water system measurement management has been improved. Moreover, improvement in the overall level of water management in China's iron and steel industry is also consistent with the overall trend of development of China's iron and steel enterprises from producing medium- and low-end products to producing high-quality/high value-added products, and the development of enterprise management from extensive to fine operation.
(3) Adoption of high-efficiency water saving technology. Most of the surveyed large- and medium-sized enterprises have adopted water saving technologies such as 'Integrated Technology for Steel Comprehensive Wastewater Reclamation

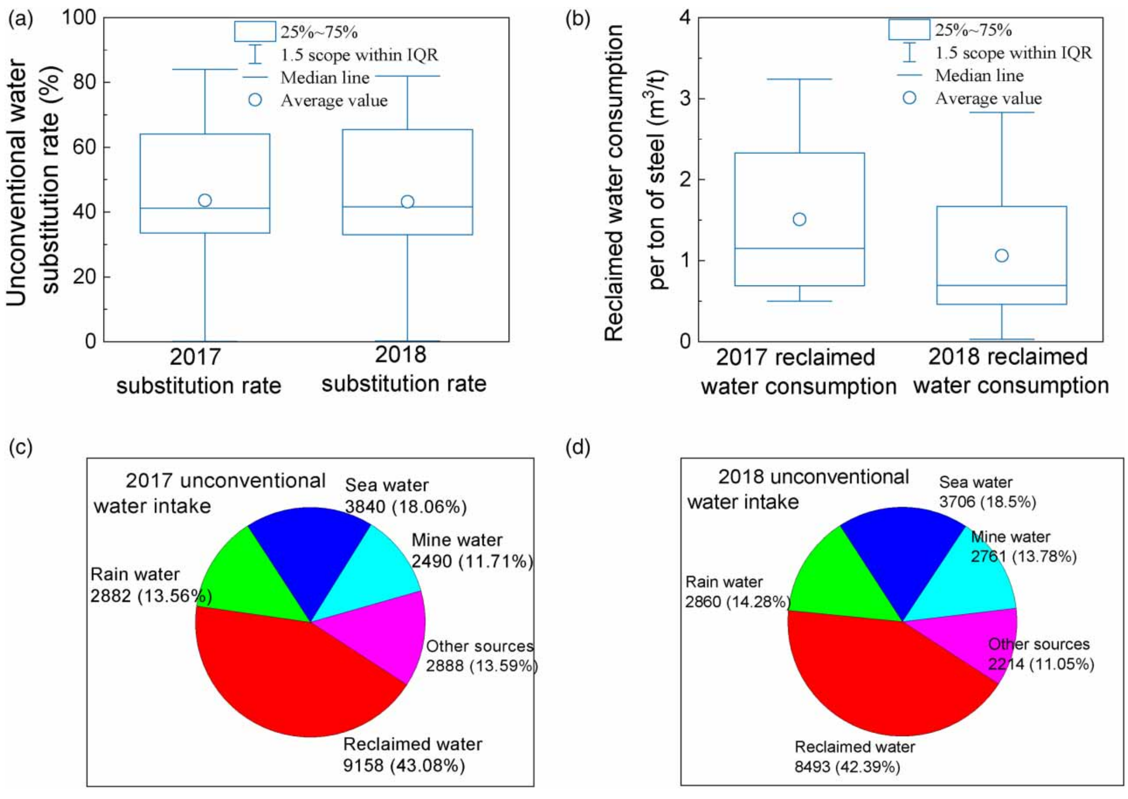



**Figure 4** | Distribution of water reuse rate of the iron and steel enterprises investigated in 2017 and 2018: (a) unconventional water substitution rate; (b) reclaimed water consumption per ton of steel; (c) proportion of unconventional water intake in 2017; and (d) proportion of unconventional water intake in 2018.

and Reuse', 'Water Quality Classification, Cascade Use Technology', 'Water Resource Monitoring and Management Technology', 'Reheating Furnace Vaporization and Cooling Technology', 'Closed Circulation Cooling Water Technology for Large Blast Furnaces', and 'Dry Dust Removal Technology' as recommended in the 'Catalog of Industrial Water saving Processes, Technologies, and Equipment Encouraged by the State', issued by China. Some enterprises with advanced water saving technology have actively introduced unconventional water sources such as seawater, rainwater, and urban reclaimed water to reduce the amount of surface water and groundwater taken. Some enterprises have adopted advanced treatment technologies such as wastewater desalination and advanced oxidation to increase the wastewater reuse rate and reduce the quantity of wastewater discharge. Technological innovation and progress are important guarantees for improving the water efficiency of industrial enterprises. However, at present, most enterprises are encountering problems such as the high cost of concentrated brine disposal, the advanced treatment and reuse of special wastewater such as coking and cold rolling, and leakage of pipe networks in long-term operation. Additionally, there are certain differences in water efficiency among different iron and steel enterprises.

## 5. FUTURE PERSPECTIVES ON TECHNOLOGIES FOR WATER REUSE

During the period of the 14th 5-year plan, China's iron and steel industry will continue to follow the path of sustainable development. The recycling of wastewater from the iron and steel industry will also herald new development opportunities, and further refinement and diversification will become important features. From the perspective of technology, the following wastewater recycling technologies are considered to have sound development prospects.

### 5.1. RO membrane fouling control technology based on water feature analysis

The RO system is the core process in the recycling of wastewater in the iron and steel industry. RO technology is used in the desalination and concentration of comprehensive wastewater from iron and steel enterprises. As the high-quality reuse rate of wastewater from the iron and steel industry increases, the use of RO technology will become increasingly widespread. The current understanding of the mechanism of RO membrane fouling is not sufficiently comprehensive, and the RO membrane fouling control index system must be improved, especially the index system for organic fouling and biological fouling. Recently, the 'water feature' was proposed by Hu *et al.* (2019), in reference to the concentration level, component characteristics, safety, stability, and spatiotemporal changes of pollutants in sewage, which can support water quality safety evaluation, treatment characteristic prediction, treatment process design, and information integration for optimized diagnosis. Through expansion and deepening of research on water quality in relation to the water feature, the theory and method of complex water quality systems could be developed further, existing sewage treatment processes and water quality standards could be improved, and existing technology could be optimized in terms of process combination and operation, which could provide strong support for building a scientific and effective risk management system (Hu *et al.* 2016).

Taking RO membrane fouling prevention and the control of organic matter as an example, the method of water feature analysis should be used to scientifically and comprehensively analyze the influent organic matter in iron and steel industry wastewater. In addition to the total amount of organic compounds, methods such as resin separation, gel exclusion chromatography, and ultrafiltration membrane filtration should be used to comprehensively understand the molecular weight, acid–base composition, hydrophobicity, and solubility of the relevant organic compounds. The combination of resin separation technology and gel exclusion chromatography could further analyze the 'fingerprint' of organic components. From the perspective of RO membrane fouling by organic matter in the process of wastewater recycling in the iron and steel industry, the multidimensional fingerprint of organic matter should be established to determine the characteristics of refractory organic matter, clarify the relationship between the characteristics of organic matter components and their treatability, and obtain the optimal solution of RO organic pollution prevention and control.

### 5.2. RO brine utilization technology in iron and steel enterprises

According to our investigation, most steel companies still have the problem of disposing of concentrated brine in a way that is not detrimental to the water system. Therefore, technology for green recycling of concentrated brine wastewater suitable for the particular characteristics of steel production remains the primary focus of future development (Xu *et al.* 2021; Yu *et al.* 2021), and the following modes have demonstrated strong application potential.

### 5.2.1. Mode A: concentrated brine treatment technology aiming at cleaner production

Mode A (Supplementary Figure S6) can reuse the concentrated brine produced by the iron and steel industry as production water after treatment, such that all water resources can be recycled. Additionally, if the solid waste generated by the chemical hard waste removal unit and the COD adsorption unit is used as raw material for production in the steel industry, full resource utilization of the solid waste generated by water treatment could be realized.

Mode A makes full use of the residual pressure of the concentrated water of the RO unit, and the nanofiltration unit adopts a circulating backflow operation mode to increase the cross-flow velocity on the membrane surface, which alleviates the concentration polarization caused by the enrichment of organic matter on the membrane surface. The chemical hardening unit adopts a two-stage, two-phase, self-crystallization fluidized bed system. By adding sodium hydroxide and sodium carbonate to the influent water, the calcium and magnesium ions in the concentrated brine are discharged from the system in the form of spherical particles with a diameter of 5–8 mm. These spherical calcium and magnesium carbonate particles can be used as raw materials in the blast furnace sintering process. The COD adsorption unit uses coke powder with a particle size of less than 8 mm as the adsorbent and it adopts a fluidized bed tower structure. The coke powder is discharged from the fluidized bed after being saturated via adsorption. The saturated coke powder can be used as raw material in the pellet sintering process in the iron and steel industry, thereby realizing full resource utilization of the solid waste in this unit.

Mode A co-disposes the RO concentrate and steel slag, which are solid wastes inevitably generated by the iron and steel industry. Silicate is the main component of steel slag, and the silicon–oxygen tetrahedron is one of the basic structural units of silicate minerals. Silicon elements in the silicon–oxygen tetrahedron are connected by oxygen elements, which can connect to metal elements such as potassium and sodium in addition to connecting directly with silicon atoms. Potassium feldspar and albite, which are widely present in nature, are the products of this effect. Using steel slag and concentrated salt wastewater as raw materials, making full use of its double salt effect and silicon–oxygen tetrahedral coordination effect, it is feasible to prepare cementitious materials to solidify concentrated salt wastewater. A technical roadmap of this process, shown in Supplementary Figure S7, highlights the principal ways that the co-resource utilization of concentrated brine and metallurgical slag could be realized, which are described in the following.

(1) Mine filling materials with full tailings. Preparing cementing materials by grinding slag, steel slag, and desulphurization gypsum with subsequent mixing. The resultant product is then introduced into a mining cavity with an aggregate, which is prepared with dressing tailings.
(2) Precast concrete parts. Utilizing magnetite quartzite iron ore tailings and waste stone to manufacture high-end products, e.g., C60–C80 railway sleepers and pipe piles.
(3) Artificial reefs. Research on C40 artificial reef concrete with extremely low clinker has successfully prepared reef concrete with aggregate constructed of 100% tailings and waste stone (Liu *et al.* 2021).

### 5.2.2. Mode B: concentrated brine treatment technology aiming at safe ecological water replenishment

In China, many iron and steel enterprises are built near rivers that provide convenient water intake and drainage conditions. According to China's emission standards, some areas with high environmental sensitivity are subject to requirements regarding drainage salt content. However, in most areas, owing to abundant surface runoff around iron and steel enterprises and low environmental sensitivity, there is no need for requirements regarding drainage salt content, which creates conditions for the concentrated brine of the iron and steel industry to be used as part of the ecological make-up of the water system after effective treatment. From a technical perspective, the effective removal of COD, nitrogen, and phosphorus from high-salinity wastewater is fundamental to concentrated brine ecological water replenishment.

As shown in Supplementary Figure S8, concentrated brine can be treated using catalytic ozonation to effectively remove antibacterial agents, scale inhibitors, and other RO process additives, with the improvement of biodegradability. COD, ammonia, and nitrate can be removed through biological treatment. A flocculation unit is installed in the front of the filter device, which mainly removes suspended solids and phosphorus in the water. Finally, microalgae/constructed wetland coupling technology is also used for the comprehensive removal of COD, phosphorus, and ammonia nitrogen to ensure that the effluent meets the ecological water replenishment standards. Microalgae can grow in high-salinity water and absorb nitrogen and phosphorus from the water depending on the characteristics of the microalgae and the coupled constructed wetland technology, which can realize high-efficiency nitrogen and phosphorus removal from concentrated brine of the iron and steel industry. Furthermore, microalgae can fix carbon dioxide in the process of growth, and can produce microalgae biomass and biodiesel while realizing water purification. To achieve this goal, it is necessary to screen the most appropriate algae species.

Hu *et al.* (2009) proposed a strategy of a coupling process for deep denitrification and phosphorus removal from sewage and microalgal biomass energy production. They also separated algae species with a high growth rate, a strong ability for denitrification and phosphorus removal, and high oil content when cultured in sewage. The removal rates of nitrogen and phosphorus could be higher than 90%, and the oil content could be more than 30% (Hu *et al.* 2009). As photosynthetic organisms, microalgae can utilize various inorganic or organic carbon wastes as growth nutrients and convert them into potentially valuable compounds (e.g., biofuels, polysaccharides, pigments, vitamins, and unsaturated fatty acids). Although microalgal carbon sequestration technology has been extensively studied in recent decades, further targeted research work is required with regard to its large-scale application.

The flue gas of iron and steel enterprises is rich in $CO_2$, and steel slag contains many nutrients. If a suitable microalgae reactor were developed, it would represent a promising technology for combining water treatment and carbon reduction using the concentrated brine from the iron and steel industry as the culture medium. Yoshimura *et al.* (2021) isolated unicellular microalgae (NS001C strain) from wastewater treatment equipment in a steel works, which showed a high growth rate with a high tolerance of ammonia. In their experiments, in which the NS001C strain was applied to a small-scale substrate surface culture, the maximum biomass productivity was 15.4 $g/m^2$/day. Through effective utilization of sunlight in the system, a biomass productivity of 20–30 $g/m^2$/day could be realized, which is theoretically more than five times higher than that of current pond systems (Yoshimura *et al.* 2021).

### 5.3. Intelligent control technology of water system

With the rapid development of refined management in the iron and steel industry, there is an urgent need to develop intelligent management and control technology to mine data value from a deeper level and to further improve water efficiency. The intelligent management and control technology of the iron and steel industry's water system should meet the following requirements.

(1) The basic principle is to control the risk of industrial water operation in steel plants, prevent external risks of excessive sewage and rain discharge, and prevent internal production-related risks (e.g., supply risks and fire safety risks).
(2) Enterprises should reduce water intake, improve water efficiency, and reduce wastewater discharge. Considering the cost reduction, the water consumption index per ton of steel produced should be reduced to improve the overall water efficiency. Water resources should be taken as the core carrier to establish the relationship between the form and energy changes of water resources in the process of circulation of the entire plant. Relying on water resources and energy management and control, the integrated management and control of regional water resources production, consumption, and discharge could be realized through various links of multilevel cycles of water resources.
(3) Water production processes and the water resource utilization rate of water treatment facilities should be optimized, and intelligent production and allocation of water resources within the entire plant should be realized.
(4) From the perspective of low carbon emissions and environmental protection, energy consumption in the processes of water transportation and water treatment should be minimized and carbon emissions reduced.
(5) The 'information island' effect in the production and use of water resources throughout the entire plant should be overcome. Thus, an industrial water platform for the entire plant should be established that extends consideration of the underlying production equipment (e.g., process, electrical, and instrumentation) to each production unit, connects the water resources system equipment of the entire plant, and achieves full coverage of the industrial water production information, thereby providing data mining and process optimization opportunities.

## 6. DISCUSSION OF POLICY, ECONOMIC, AND TECHNICAL DRIVERS

### 6.1. Policy drivers

On 11 January 2021, China issued the 'Guiding Opinions on Promoting the Utilization of Wastewater Resources', which stated that by 2025, the utilization rate of reclaimed water in prefecture-level water-deficient cities in China should be more than 25%, and that in the Beijing–Tianjin–Hebei region, it should be more than 35%. By 2035, a systematic, safe, environmentally friendly, and economical wastewater resource utilization pattern should be constructed. Industrial utilization is one of the main ways via which to use urban sewage as a resource. For projects involving industries with high water consumption, such as the iron and steel industry, which meet the conditions for using reclaimed water but do not yet fully use reclaimed water effectively, new water abstraction permits will be strictly controlled. Moreover, the 'Guiding Opinions on Promoting the Utilization of Wastewater Resources' requires the promotion of resource utilization of industrial wastewater and the improvement in the reuse rate. The iron and steel industry and other industries should perform internal wastewater utilization, create a number of industrial wastewater recycling demonstration enterprises, and promote the improvement of enterprise water efficiency through typical demonstrations. This document has encouraged the promotion of the recycling of industrial wastewater by iron and steel enterprises and the recycling of urban sewage, and it has created a new situation for the recycling of wastewater by the iron and steel industry.

### 6.2. Economic drivers

During the period of the 14th 5-year plan, China will undoubtedly increase the investment of central government funds in the utilization of sewage resources, to support local governments to pack bonds for qualified sewage resource utilization construction projects. It is estimated that local governments will devise a diversified financial capital investment guarantee mechanism. Moreover, China will encourage companies to adopt green bonds, asset securitization, and other means to broaden finance channels to support compliance with laws and regulations, promote pilot projects of real estate investment trust funds in the field of infrastructure, explore the development of pledged financing guarantees such as project income rights and franchise rights, and implement relevant tax preferential policies. The price mechanism of urban reclaimed water will also be gradually improved. The government will gradually release the pricing of reclaimed water, and the reclaimed water supply enterprises and users will then negotiate and price independently according to the principles of high-quality and high-price, thereby increasing the enthusiasm of enterprises to participate in the utilization of industrial wastewater and urban regenerated water resources. Furthermore, the government will propose preferential tax policies to support research and development in the reuse of wastewater.

### 6.3. Technical drivers

Integration of fundamental technologies for sewage recycling will be promoted in China's medium- and long-term scientific and technological development plans, e.g., the 14th 5-year plan Special Plan for Scientific and Technological Innovation of Production Environment. Furthermore, relevant key special projects will be conducted to trail technological innovation for sewage recycling. China's scientific research institutes, colleges, and universities will form an innovative strategic alliance with sewage treatment companies to develop the utilization of sewage resources by focusing on breakthroughs in key technical equipment such as advanced sewage treatment, compiling advanced practical technologies and practical cases of wastewater resource utilization, promoting mature technologies and equipment, and publishing a catalog of industrial wastewater resource utilization technologies and equipment encouraged by the state (Gao *et al.* 2020).

It will also be important to improve the innovation capability of industrial wastewater resource utilization, select a group of industrial wastewater resource utilization technologies, equipment, and system solution suppliers, and cultivate a group of industrial wastewater resource utilization third-party service agencies (Wang *et al.* 2017). By organizing and implementing industrial wastewater resource utilization services into the activities of enterprises, suppliers and third-party service agencies will be encouraged to provide wastewater resource utilization services for industrial enterprises in parks and agglomeration areas, and provide water saving diagnosis, water balance testing, and industrial wastewater resources for the iron and steel industry. The utilization of integrated comprehensive services such as plan preparation, technological transformation, facility construction, operation, and maintenance will be of great importance, which will help create an industrial alliance for the utilization of industrial wastewater resources, and strengthen the promotion and application of related technology.

## 7. CONCLUSIONS AND THE WAY FORWARD

This study is the first review of wastewater reuse and recycling of the steel industry in China. The recycling of wastewater in China's iron and steel industry has experienced a qualitative leap forward from 1980 to 2020. Generally, the level of wastewater resourceization of iron and steel enterprises varied greatly. Before 1980, most of China's iron and steel enterprises adopted direct-flow water supply, which had large water consumption, much pollution, and rough management. After 40 years of development, the water efficiency index of China's iron and steel industry has improved significantly. Specifically, steel production in China increased notably, while freshwater consumption per ton of steel decreased by 93.2%. The above-mentioned results could be attributed to the following causes:

Firstly, some restrictions and guidance of the national and local water conservation and environmental protection laws and policies were introduced. Besides, the enterprise water intake and wastewater discharge were strictly regulated by the governments.

Secondly, the water management of iron and steel enterprises tended to be more standardized and systematic. A relatively complete water management system was generally established for each enterprise.

Thirdly, a number of efficient water saving technologies (water resource monitoring and management technology, dry dust removal technology, wastewater desalination, advanced oxidation process, etc.) were widely adopted in actual production processes.

In order to better follow the path of sustainable development, challenges and perspectives for the future development of China's iron and steel industry were proposed. On the one hand, the recycling of wastewater from the iron and steel industry will usher in new development opportunities. On the other hand, refinement and diversification will become important features. Moreover, several technologies in water reuse were suggested in the near future. For example, RO membrane fouling control technology based on water feature analysis should be used to scientifically and comprehensively analyze water qualities. The green recycling technology of concentrated brine wastewater suitable for the characteristics of steel production showed stronger application prospects. In addition, the intelligent management and control technology of the iron and steel industry's water system was the focus of future development.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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