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REVIEW ARTICLE

Municipal wastewater treatment in China: Development history and future perspectives

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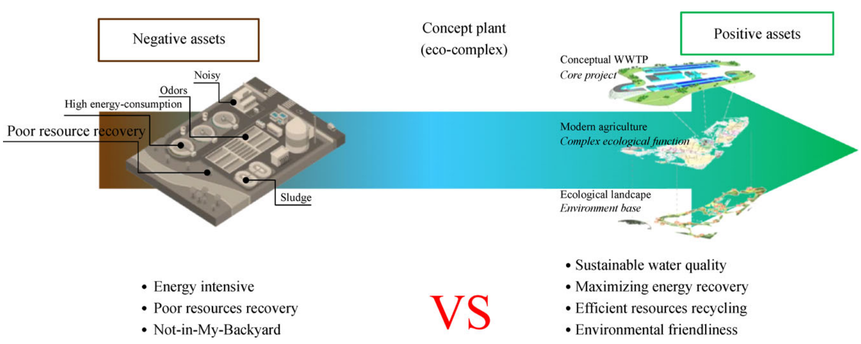
HIGHLIGHTS

- The history of China's municipal wastewater management is revisited.
- The remaining challenges in wastewater sector in China are identified.
- New concept municipal wastewater treatment plants are highlighted.
- An integrated plant of energy, water and fertilizer recovery is envisaged.

GRAPHIC ABSTRACT



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ABSTRACT

China has the world's largest and still growing wastewater sector and water market, thus its future development will have profound influence on the world. The high-speed development of China's wastewater sector over the past 40 years has forged its global leading treatment capacity and innovation ability. However, many problems were left behind, including underdeveloped sewers and sludge disposal facilities, low sustainability of the treatment processes, questionable wastewater treatment plant (WWTP) effluent discharge standards, and lacking global thinking on harmonious development between wastewater management, human society and the nature. Addressing these challenges calls for fundamental changes in target design, policy and technologies. In this mini-review, we revisit the development history of China's municipal wastewater management and identify the remaining challenges. Also, we highlight the future needs of sustainable development and exploring China's own wastewater management path, and outlook the future from several aspects including targets of wastewater management, policies and technologies, especially the new concept WWTP. Furthermore, we envisage the establishment of new-generation WWTPs with the vision of turning WWTP from a site of pollutant removal into a plant of energy, water and fertilizer recovery and an integrated part urban ecology in China.

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1 The past of municipal wastewater treatment practice in China

1.1 Late development

Water pollution control is now one of the most pressing challenges faced by China (Lu et al., 2015; Yu et al., 2019). In the battle against environmental pollution, wastewater treatment plays a pivotal role. Although China has the largest wastewater treatment capacity and market of the world, its development history is actually very short. Compared with the industrialized countries that have already widely implemented wastewater management a century ago, wastewater management in China was almost in blank until 40 years ago. Back to 1949, the foundation year of the People's Republic of China, only four municipal wastewater treatment plants (WWTPs) were documented with a total treatment capacity of 40000 m^3/d. Even worse, only one of these WWTPs (located in Shanghai) was operated normally, thus the actual wastewater treatment capacity was 16000 m^3/d only in China in 1950s. During the subsequent 20 years, only 10 small-scale WWTPs were newly constructed in several big cities. During this period, many drainage facilities had been constructed to facilitate wastewater collection and discharge in cities, and no specific wastewater treatment was applied due to the lack of environmental protection consciousness and the financial difficulty for the newly-born country.

Entering the 1970s, the situation started to change, due to the occurrence of several famous environmental pollution issues that arose global health concerns. For precaution, Chinese government started to strengthen wastewater management and treatment. In 1980s, the National Environmental Protection Bureau was set up, and the first large-scale WWTP with a treatment capacity of 260000 m^3/d was constructed in Tianjin. Also in this period, environmental engineering became an important major in many universities in China.

1.2 High-speed development over the past 40 years

China entered into rapid development period since the initiation of Reform and Development in 1979. Accompanied with the rapid economic development and urbanization, the amount of municipal wastewater increased drastically and the wastewater composition became increasingly complicated because more industrial wastewater entered into the sewers. With increased discharge of wastewater into the environment, severe water and soil pollution started to occur, especially in some water-deficient large cities like Tianjin, Beijing, and Xi'an. The aggravating environmental pollution directly endangered urban water and food security, giving rise to an urgent demand on water pollution control. To address this challenge, China started to build more centralized WWTPs and supplementary facilities. The construction speed and WWTPs scale have been increasing continuously over the years till the end of the "Twelfth Five-Year Plan" period (Fig. 1).

Table 1 shows the information of some milestone WWTPs in the development history of China's municipal wastewater sector. The construction and operation of Tianjin Jizhuangzi WWTP, which implemented standard activated sludge process, opened the prelude of large-scale centralized wastewater treatment in China. Nevertheless, the WWTPs construction speed was still very slow in 1980s due to the financial restriction in China at this stage. The situation started to change with the introduction of international loans and social capitals in 1990s. One representative plant is the East Handan WWTP built in 1991, for which not only foreign capital but also advanced technologies (i.e., oxidation ditch process) was introduced from Denmark. Since then, WWTP construction in China

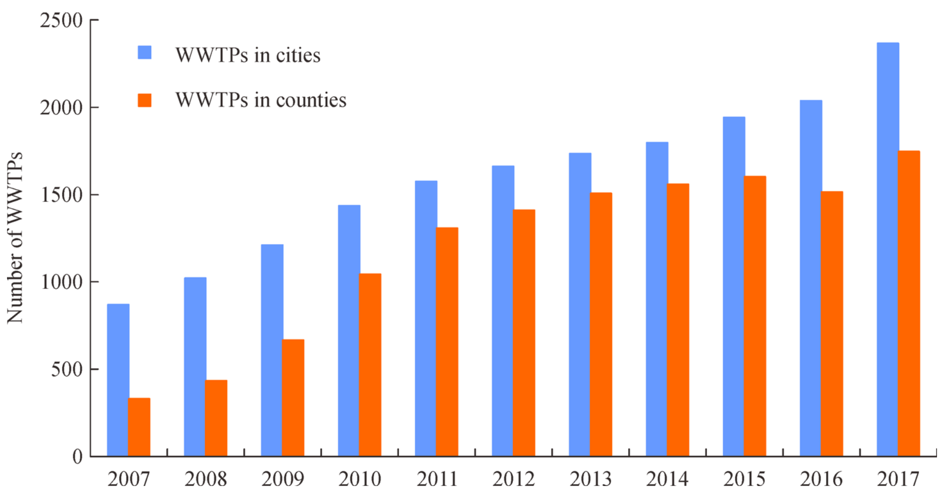

Fig. 1 Growth of municipal WWTPs number in China during 2007–2017.

Table 1 The milestone WWTPs in the development history of China's municipal wastewater sector

Year of operation	Name of Municipal WWTP	Treatment capacity (m^3/d)	Milestone
1984	Tianjin Jizhuangzi WWTP	260000	The first large-scale WWTP implementing activated sludge process in China
1993	Phase One of Beijing Gaobeidian WWTP	500000	The first 500000-scale WWTP in China
1991	East Handan WWTP	100000	The first plant with three-groove oxidation ditch process (built by using the Danish government grant)
2000	Dalian Malan River WWTP	120000	The first plant applying BIOSTYR biological aerated filter
2001	Shanghai Taopu WWTP	60000	The first plant applying SBR process
2002	Shanghai Shidongkou WWTP	400000	The first Unitank Municipal WWTP
2008	Wuxi Lucun Village WWTP	200000	The first plant implementing Grade 1-A standard; the first plant adopting large-scale IFAS/MBBR system
2016	Beijing Water Reclaimation Plant	1000000	The largest reclaimed water plant in China

has entered the period of leap-forward development. Nevertheless, the development speed and treatment capacity of the WWTPs and supplementary facilities (especially sewers and sludge disposal systems) still lagged behind the economic growth and industrial development in China. The overall water environmental quality kept decline, forcing Chinese government to implement more strict pollution control strategies.

In 2007, the large-scale algae bloom occurred in Taihu Lake due to severe water eutrophication, severely threatening the drinking water security in nearby cities. Learning from this lesson, the local government started to enforce more stringent WWTP effluent discharge standards. One year later, the first WWTP that implemented Class 1A effluent discharge standards (GB 18918-2002) was put into use in Wuxi, which was realized by upgrading the conventional activated sludge process into anaerobic/anoxic/oxic (A^2/O) process in combination with integrated fixed-film activated sludge (IFAS)/ moving bed biofilm reactor (MBBR) system. This plant has been operated efficiently and stably for over 10 years.

The water environmental pollution in China has also aggravated the shortage of water resources, especially in North China, which gives rise to an urgent demand for wastewater reclamation and reuse. Beijing pioneered in this direction and has achieved great progress in constructing water reclamation infrastructures. In 2016, the Beijing Gaobeidian WWTP was upgraded into a reclaimed water plant (Fig. 2), with an extraordinary treatment capacity of 1 million m^3/d, announcing a transition wastewater management in China from simply treatment to reclamation. However, the overall water reclamation in China is still very low compared with many developed countries, and the reclaimed water was mainly reused as landscape water due to relatively low quality. At current stage, the price of reclaimed wastewater still lacks competitivity with conventional water supply, and establishment of water reuse infrastructures and program is at slow pace.

Fig. 2 Beijing Gaobeidian reclaimed water plant.

2 The achievement and challenges today

2.1 Remarkable achievements of wastewater sector in China

After near 40 years of remarkable development, China now possesses the world's largest municipal wastewater infrastructure. By the end of 2018, more than 5000 municipal WWTPs have been built in China, with a daily treatment capacity of nearly 200 million m^3/d (Fig. 1). Accordingly, the wastewater treatment ratio has reached over 90% by 2018. These WWTPs play key roles in environmental pollution control by reducing the release of pollutants.

The WWTP construction is only one part of the rapid wastewater sector growth in China. Benefited from its powerful national administration system and the valuable experiences from developed countries, China has achieved leap-forward progress in its wastewater infrastructure construction and management over the past 40 years, reaching a similar level to the developed countries that have taken three decades of efforts. To date, a full-chain, huge-scale wastewater sector has come into being in

China, with the total market value and operating capacity of its water enterprises all at global leading level. The wastewater management mode has also changed from the unitary government-dominated construction and operation into a multiple system that involving both the government and enterprises. Such a transition not only to certain extent lessened the financial burden of the government but also improved the construction and operation efficiencies of wastewater facilities.

Importantly, China now also possesses the world's largest research team in the water management field, benefited from the continuously-growing financial support that far exceeds the rest of the world. The innovation ability and international competitiveness of China can be seen from the publications to some extent, where China's total numbers of SCI papers in the water research field was only next to USA (Fig. 3). Such a remarkable innovation ability lay a strong basis for the future revolution of wastewater management mode and treatment technologies in China.

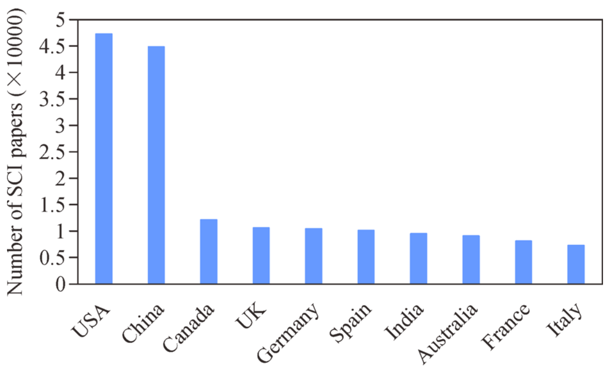

Fig. 3 Publications in the water research field by several major countries in 2018.

2.2 The remaining gaps and challenges

Despite of these remarkable progresses achieved by the wastewater sector in China, the government-dominated, pursuant-type development also left behind many problems. In particular, there are still considerable gap in the design principles and operation performances of the treatment facilities compared to those in the developed countries.

The first issue is that the plant design and operation did not agree with the demand of sustainability development. Currently, improving pollutants removal is still the core target of WWTPs operation, and the Class 1A effluent standards is increasingly applied in the WWTPs nationwide (Fig. 4). To this end, most of the plants canceled the primary sedimentation tank, implement delayed aeration processes and some added biofilters for enhanced nitrogen removal. This significantly increased the energy/chemical consumption (Fig. 4) and consequently made WWTPs a non-negligible source of indirect greenhouse gases emission.

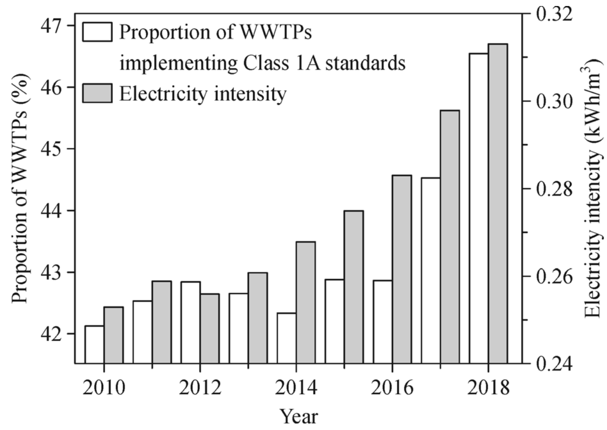

Fig. 4 Proportion of WWTPs implementing Class 1A effluent standards and the energy consumption intensity of WWTPs in China.

The situation is further aggravated by the lagged development of sewer system, especially at county level. This has resulted in insufficient wastewater collection (the sewer access ratio of about 90% in 2018) on one hand and a lower operating ratio (86%) of the WWTPs on the other hand. Such insufficient municipal wastewater collection plus the dilution by storm water (due to still widespread adoption of separated sewers, accounting for about 55% of the total sewers) significantly lowers the organic strength, while increases the pollutants complexity in WWTP influent (Fig. 5). As a consequence, the organic matters in wastewater are insufficient to support denitrification and anaerobic sludge digestion. The low organic content and high sand composition of wastewater sludge prohibit their anaerobic digestion treatment, a widely adopted strategy in the developed countries to recover resource from wastewater. It is estimated that less than 3% of WWTPs in China

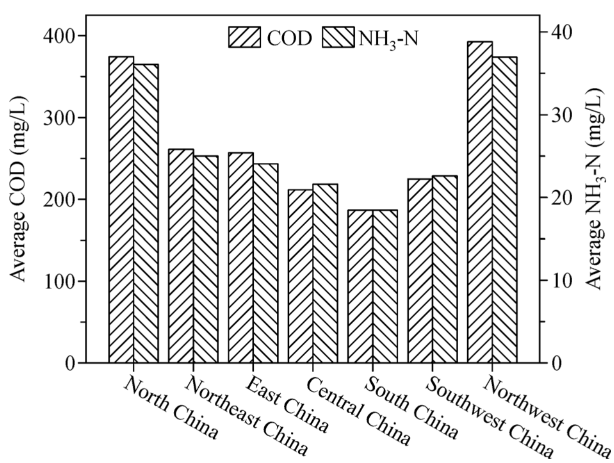

Fig. 5 The geographic distribution of influent COD and NH_3-N concentrations of WWTPs in China.

have been equipped with anaerobic digestion facilities, and a considerable fraction of which are in poor operation (Jin et al., 2014; Zhang et al., 2016). Therefore, basically there is no energy recovery in China's WWTPs, not to mention the recovery of the nutrient resources. How to improve the sustainability of wastewater treatment in China remains a critical issue to be addressed.

Another issue is the poor linkage between the WWTPs effluent discharge standards and the local conditions and environmental protection demands. The geographical diversity in wastewater properties, environmental conditions and economic development levels in China implies a high necessity for different WWTPs to implement customized, flexible technologies and effluent discharge standards in, instead of the currently prevailing uniform mode. This will be of particular importance for the environmental-sensitive and water-deficient regions where inappropriate wastewater management may result in severe ecological, environmental and social consequences. Currently, a new round of WWTPs discharge standards upgrading that takes into account regional differences is underway. However, there is considerable debate about the upcoming new standards (draft), which set special pollutants limits approaching the Class 4 surface water quality standards. One core controversy is whether implementing such strict discharge standards nationwide is necessary and economically feasible, and what criteria should apply for setting the discharge limits. Nevertheless, it is unanimously agreed that more strict WWTPs effluent standards need to be applied in China, which will affect the development of future WWTPs.

Lastly, China's wastewater management practice lacks global thinking of harmonious development between human and the nature. On one hand, the importance of appropriate sludge disposal has long been overlooked. In general, disposal (i.e., stabilization, decontamination or even valorization) of sludge from WWTPs has been paid little attention. As a consequence, the large amount of pollutant-enriched sludge from WWTPs ultimately returns back to the environment without appropriate disposal, becoming another pollution source (Fig. 6). On the other hand, WWTP operation usually disturbs the living of nearby residents due to generated odor and noise. This problem has become increasingly prominent with the urbanization development, where many existing WWTPs are gradually surrounded by urban communities. Thus, establishing a harmonious relationship between WWTPs, environment and human society presents another challenge for wastewater management in China.

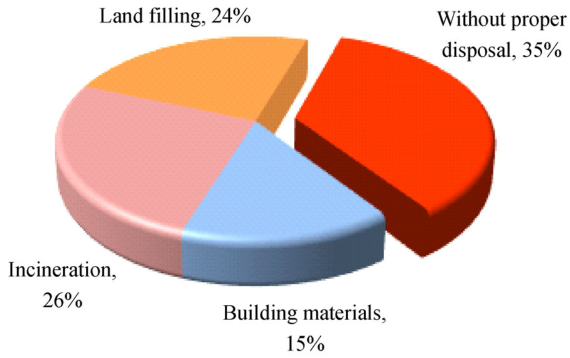

Fig. 6 Disposal situation of wastewater sludge from China's WWTPs in 2018.

3 Outlook

Over the past 40 years, China's wastewater sector has gone through a high-speed growth and achieved remarkable progress in infrastructure construction, technology innovation, and talents cultivation, which lay a solid foundation for its future sustainable development. However, the future is still full of uncertainty and challenges. It is anticipated that, with the continuing population growth and urbanization, the water shortage will become more severe and urban ecology may become more vulnerable (Yu et al., 2019), whereas the wastewater quantity will further increase. These unprecedented challenges call for fundamental changes in wastewater management target, policies and technologies.

3.1 Targets of future wastewater management

Despite of the controversy in specific discharge standards, it is for sure that more strict and global-scale water pollution control will be implemented by the China's wastewater sector in the future. Actually, many provinces and cities such as Beijing, Tianjin, Jiangsu, Zhejiang and Hunan have already started to implement more stringent local WWTPs effluent standards. Based on the international development trend, the next step will be enhancing the control of emerging pollutants and water reclamation, which are still at the very beginning in China (Wang and Gong, 2018a). Thus, there is a fundamental shift in the target of wastewater management from pollutant abatement to water reuse, resource recovery and water ecology restoration. Such target transition is reflected by the recent policy revolutions in China.

3.2 Policies

For many years, China has followed the end-of-pipe pollution control strategy, i.e., emphasizing wastewater treatment and water environmental remediation. However, the overall environmental quality has shown no obvious improvement. In 2015, the Chinese government issued the Action Plan on Water Pollution Control (The State Council, 2016), opening a new age of water environmental protection aiming at improving the quality of the overall water ecological environment instead of simple water quality control (Brundtland, 1987; Hansen et al., 2018). This means that the frontier of pollution control will extend from WWTPs to the upstream sewer networks and the downstream rivers and wetlands. Therefore, instead of simply and uniformly improving the WWTPs effluent standards, it is encouraged to pay more attention to improving the capacity in wastewater collection and sludge disposal (Verstraete et al., 2009). The urgency for overcoming the bottleneck of insufficient wastewater collection and poor treatment facilities has been stressed in a recent issued guideline by the Chinese government.

3.3 Technologies

A realization of the above targets of wastewater management will depend on the advances of more efficient and sustainable pollution control strategies. In terms of wastewater treatment, the treatment technologies are advancing mainly in three directions: 1) Efforts in modification of activated sludge process has never ceased. A typical example is aerobic granular sludge. Due to advantages of good effluent quality, energy saving and small footprint, this process has been intensively studied in the past decade and has now been successfully demonstrated in several WWTPs in Europe and Africa. 2) Implementation of innovative technologies is on the horizon (Li et al., 2014, Li and Yu, 2016). A representative new technology is Anammox (van Loosdrecht and Brdjanovic, 2014), which effectively circumvents the conventional nitrification/denitrification route to substantially lower the energy consumption and enables an efficient implementation of energy-producing carbon bioconversion processes such as anaerobic membrane bioreactors. 3) Development of more efficient facilities and materials as well as better process control techniques allows optimized operation of WWTPs. Advances in this respect include development of efficient carrier materials for biofilm growth, better aeration devices for efficient oxygen supply, advanced membrane technologies for raising effluent quality (Shannon et al., 2008), and online monitoring/intelligent control techniques for improving process stability. In particular, the recent development of low-fouling ultrafiltration and reverse osmosis technologies is making a scaled-up, stable wastewater reclamation possible (Schnoor, 2009).

While resource-oriented wastewater treatment is gradually becoming the theme of the time for the global wastewater sector (Lu et al., 2018), China is also actively exploring its own suitable path (Hao et al., 2015). With the vision of turning WWTP from a site of pollutant removal into a plant of energy, water and fertilizer and an integrated part urban ecology, in 2014 several experts from top institutes, universities and authority in China jointly proposed the construction of a brand-new plant for valorization of wastewater (Qu et al., 2014). Due to its foresight and exploration nature, this plant was expected to be built in next few years and serve as a trail plant for guiding large-scale, sustainable treatment of wastewater in the near future. Thus, it was named the "New Concept Wastewater Treatment Plant" (Fig. 7). This plant aims to realize the quadruple goal of sustainable water supply, energy self-sufficient operation, resource recovery and environmental harmony by integrating various innovative design and leading-edge technologies (McCarty et al., 2011; Wang and Gong, 2018b), which is different from the global prevailing mode of seeking for breakthrough in individual fields or technologies (Li et al., 2015). In 2018, the first ground-breaking concept WWTP has been built in Wuxi, Jiangsu Province (Fig. 8), opening a new chapter for sustainable wastewater management and harmonious urban water ecology in China.

4 Conclusions

Looking back to the 40-years rapid development history of

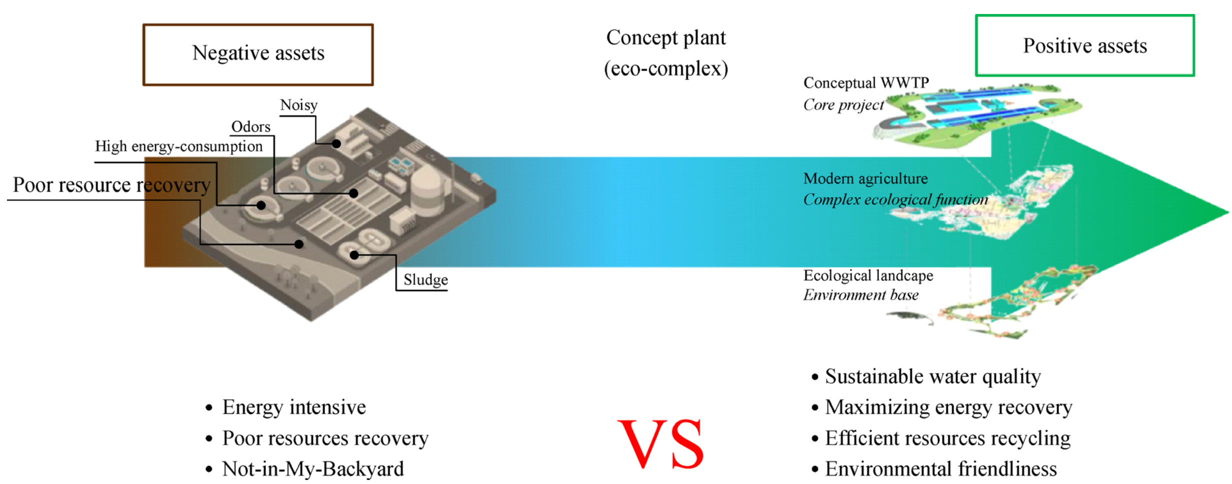

Fig. 7 The principles of Concept Plant to be established in China.

Fig. 8 The first New Concept WWTP to be constructed in Wuxi, Jiangsu Province.

China's wastewater sector, there are both remarkable achievements and numerous failures. Although China has almost accomplished the wastewater infrastructure construction at a speed far exceeding the western countries, many problems are left behind, including the under-developed sewers and sludge disposal facilities, remaining high energy consumption and insufficient operating performance, poor linkage between the WWTP effluent discharge standards and the local conditions and environmental protection demand, and lacking global thinking of harmonious development between human and the nature. Looking forward, there will be more challenges and uncertainties, due to the multiple pressures of environment protection, economic development, and water shortage, especially in the near future that China is in the transition from developing to developed countries. Addressing these challenges requires China's wastewater sector to explore its unique path of sustainable development according to its own characteristics and needs, including the development of new concept plants that highlight resource recovery and build an integrated and harmonious water ecology.

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