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Review

Research Status and Development Trend of Wastewater Treatment Technology and Its Low Carbonization

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Abstract: With the rapid development of the social economy, the demand for water resources is gradually increasing, and the corresponding impact of water pollution is also becoming more severe. Therefore, the technology of sewage treatment is developing rapidly, but corresponding problems also arise. The requirements of energy conservation and emissions reduction under the goal of carbon neutrality and dual carbon pose a challenge to the traditional concept of sewage treatment, and there is an urgent need for low-carbon sewage treatment technology aiming at energy conservation, consumption reduction and resource reuse. This review briefly introduces conventional sewage treatment technology and low-carbon sewage treatment technology, and analyzes the research status and development trend of low-carbon sewage treatment technology in detail. The analysis and comparison of conventional and low-carbon sewage treatment technologies is expected to provide a theoretical basis for the practical engineering application of low-carbon sewage treatment technologyto achieve the goal of carbon neutrality. It is of great significance to promote the sustainable development of society and the economy.

Keywords: sewage treatment; low-carbon technology; research status; sustainable development

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1. Introduction

In recent years, with the rapid development of urbanization and the rapid growth of population, the pressure on our living environment is also increasing day by day [1,2]. The development of industry and people's efforts to meet their quality-of-life requirements have caused a certain degree of impact on the environment. Problems such as the greenhouse effect and water pollution can be seen everywhere in our daily life [3,4]. In addition, the ecological and environmental problems brought by these problems are gradually feeding back into our lives, causing a series of predictable troubles. Global warming caused by greenhouse gases, rising sea level, frequent bad weather, malodorous water and toxic and harmful waste water are causes for alarm, requiring countermeasures [5]. It has become the consensus of all countries in the 21st century to reduce greenhouse gas emissions, reduce carbon emissions and slow down global warming. At the General Debate of the 75th Session of the United Nations General Assembly, China proposed to strive for the grand goal of carbon neutrality before 2060 [6]. This is China's solemn commitment to the world, demonstrating its responsibility as a major country and enhancing its international influence [7]. It also makes clearer the importance of greenhouse gas emissions, low-carbon living and achieving carbon neutrality.

It has become an important trend of social development in the modern era to ensure the quality of our ecological environment, implement energy savings and emissions reductions, improve energy utilization, promote environmental protection and high-efficiency and high quality development, and seek low-carbon technology as the new way forward for the development of energy-consuming industries [8–10]. Sewage treatment accounted for much energy consumption in in our country, and the proportion of energy consumption in society as a whole was increasing year by year [11]. At present, sewage treatment technology in our country consists mainly of conventional pretreatment and conventional advanced treatment, two treatment units, and the treatment methods used differ according to sewage quality and other factors. However, whether physical or biochemical treatment is adopted, a large amount of resources and energy is consumed in the process [12]. In addition, a large number of additional pollutants such as CO_2, CH_4 and N_2O are produced in the treatment process, which is the main contribution of the sewage treatment system to global warming. To some extent, this is a non-green means of changing water quality via energy consumption by energy dissipation and pollution transfer [13]. At the same time, a variety of pollutants contained in sewage are rarely recovered for use, resulting in a great waste of resources [14]. Effective exploitation and utilization of potential resources in sewage or sludge is a means of achieving low carbonization of sewage treatment.

It is very important to vigorously develop energy-saving and low-carbon sewage treatment technology for each treatment process and treatment unit. With the demand for water resource protection and recycling due to economic and social development, sewage treatment in all aspects will increase significantly in the future [15,16]. Therefore, in large sewage treatment systems, low-carbon treatment technology should be promoted in all aspects, and any available resources, whether pollutants themselves or products generated by the treatment process, should be fully utilized to carry out reasonable carbon conversion [17]. In the treatment technology, those processes with high energy consumption and low treatment efficiency should be eliminated, and the treatment process should be improved by means of co-construction or expansion. In addition, accurate assessment of sewage quality and targeted water treatment should be achieved through automated control, to replace tedious and unstable manual control. The operating parameters of each processing unit should be optimized on the basis of accurate assessment, and the best processing effect achieved, while minimizing resource and energy consumption [18,19]. Through the research and development of emerging sewage treatment technologies at home and abroad, new sewage treatment technologies, new materials or microorganisms can be developed to achieve lowcarbon, carbon reuse, carbon sequestration and other clean and green treatment technologies as much as possible.

This review briefly introduces conventional sewage treatment technology and low-carbon sewage treatment technology, and then analyzes the research status and development trend of low-carbon sewage treatment technology in detail. Through the analysis and comparison of conventional and low-carbon sewage treatment technologies, it is expected to provide a theoretical basis for the practical engineering application of low-carbon sewage treatment technologies and continue towards achieving the goal of carbon neutrality, which is of great significance to promoting the sustainable development of the social economy.

2. Conventional Wastewater Treatment Technology

This section examines conventional urban sewage treatment technology, and takes the activated sludge removal process as an example to discuss and analyze.

The traditional activated sludge removal process is to supply oxygen to activated sludge in sewage through external aeration equipment, and convert organic matter in sewage (40–50%) into CO_2 through activated sludge, and the remaining organic matter (50–60%) into residual sludge, which is difficult to be degraded by microorganisms [20]. From long-term engineering practice and various studies, it has been found that, depending on the change of water quality, the characteristics of microbial metabolic activity, operation management, technical economics, discharge requirements, etc., a variety of operation modes and pool types have been developed. The main types are as follows: pushed-flow activated sludge method, completely mixed activated sludge method, adsorption-regeneration activated sludge method, delayed aerated activated sludge method, pure-oxygen-aerated activated sludge method, sequential-batch-reactor activated sludge method (SBR), etc. Their removal rates of biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and other pollution indicators in municipal sewage, as well as their advantages and disadvantages, are shown in Table 1 below:

Table 1. Removal rate of BOD, COD, TSS and other pollution indicators in municipal sewage by activated sludge methods and their advantages and disadvantages.

Operation Mode of Activated Sludge Method	BOD	COD	TSS	Advantages	Disadvantages	References
	Removal Rate (%)					
Pushed-flow activated sludge process	90–95	90–95	90–95	① The degradation efficiency of sewage is higher. ② The treatment of wastewater is more flexible.	The phenomenon of insufficient aeration at the head of the tank and excessive gas supply at the tail of the tank increases the power cost.	[21,22]
Completely mixed activated sludge process	85–90	85–90	90–95	① Strong ability to bear the impact load, to weaken the peak load. ② It can save power and facilitate operation management.	①Continuous water inflow and outflow may cause short circuits. ②Prone to sludge swelling.	[23,24]
Adsorption-regeneration activated sludge process	80–90	80–85	85–90	① The contact time is shorter and the adsorption pool volume is smaller. ② Bearing a certain impact load, the sludge in the regeneration tank is convenient to use.	①The treatment effect of wastewater is lower than that of the traditional activated sludge process. ②The treatment effect of wastewater with high dissolved organic matter is poor.	[21,25]
Delayed aerated activated sludge process	75–95	85–95	90–95	① The organic load is low, the residual sludge is less, and the sludge is stable and does not need to be digested. ② It has high stability of treatment water quality, strong adaptability to the impact load of wastewater and does not require a primary sedimentation tank.	The tank capacity is large, the aeration time is long, the construction cost and the operation cost are high, and it occupies a large area.	[26,27]
Pure-oxygen-aerated activated sludge process	90–95	85–90	90–95	① Greatly improves oxygen diffusion ability in the mixture ② The volume of gas required can be greatly reduced, the volume load can be greatly increased, it is not prone to sludge swelling, it has high treatment efficiency, the required aeration time is short, the amount of residual sludge generated is less.	The device is complex, management is troublesome, and the structure of the closed container is demanding.	[28–32]
Sequential-batch reactor activated sludge process (SBR)	85–95	85–90	90–99	The operation management is simple, the cost is reduced, the impact load is resistant, the effluent quality is good, the activated sludge filamentous bacteria can be inhibited, the nitrogen and phosphorus removal.	Automation control requirements are high. Operation, management and maintenance require high quality of operation and management personnel. High requirements for drainage equipment.	[33–37]

2.1. *Pushed-Flow Activated Sludge Process*

The pushed-flow activated sludge process is also known as the traditional activated sludge process. The surface of the push-flow aeration tank is rectangular. Under the push of aeration and hydraulic conditions, the water in the aeration tank is evenly pushed to flow. The wastewater enters from the head end of the tank and flows out from the tail end of the tank, and the liquid flow in the front section and the liquid flow in the back section do not mix. The process flow chart is shown in Figure 1. In the process of aeration, with the change in environment from the head of the tank to the end of the tank, , the biological reaction rate, the F/M value, the quantity and quality of microbial community, the adsorption, flocculation and stabilization of activated sludge, and the settlement-concentration performance are all constantly changing [21,22].

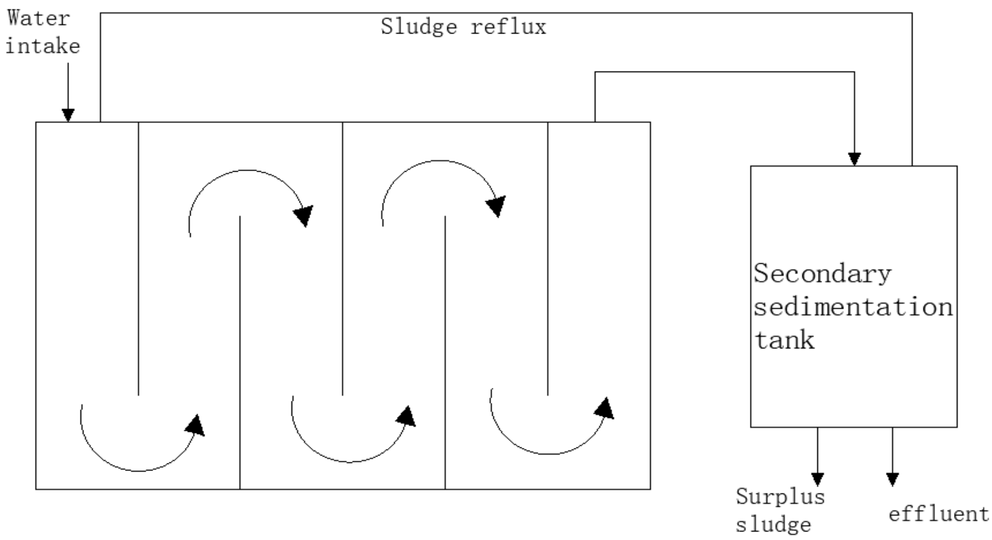


Figure 1. Process flow chart of pushed-flow activated sludge process.

The traditional activated sludge aeration tank is rectangular, the water flow is longitudinal mixed push flow, the aeration time of the mixed liquid in the aeration tank is usually 4–8 h, the sludge concentration is generally controlled within 2–3 g/ L, the amount of returned sludge requires 25–50% of the water intake, and the removal rate of BOD, COD and suspended matter can reach 90–95% [38]. The pushed-flow activated sludge method has the advantages of high treatment efficiency and flexible treatment modes, but it also leads to an energy surplus. The activated sludge at the head of the tank always absorbs gas from the head of the tank to the end of the tank, which increases the power cost to a certain extent and has the problem of energy waste, which is not conducive to the low-carbon emissions advocated by the present concept of carbon-neutral and sustainable development.

2.2. Completely Mixed Activated Sludge Process

A completely mixed aeration tank means that the waste water is fully mixed with the original mixture after entering the aeration tank. Therefore, the composition, F/M value and quantity and quality of microbial community of the mixture in the tank are completely uniform. The position of the whole process on the sludge growth curve is only one point. This means that the biological reaction is the same in all parts of the aeration tank, and the oxygen absorption rate is also the same. This process is characterized by a strong ability to withstand impact load, and the ability of the mixed liquid in the tank to dilute the wastewater and weaken the peak load. And because the aerobic requirement of the whole tank is the same, it can save power. The aeration tank and sedimentation tank can be built together for easy operation and management. However, the continuous inflow and outflow of water may cause short circuits, and the process is prone to sludge swelling and other problems [23]. The technological process is shown in Figure 2. For the treatment of municipal wastewater, the BOD load (Ns) is 0.2–0.6 kg BOD5 / (kg MLSS·d), the volume load (Nv) is 0.8–2.0 kg BOD5 / (m^3·d), the sludge age (mean residence time of biosolids) (θr) is 5–15 days, the concentration of suspended solids (MLSS) is 3000–6000 mg/L, the concentration of volatile suspended solids (MLVSS) is 2400–4800 mg/L, the sludge reflux ratio (R) is 25–100%, and the aeration time (t) is 3–5 h. The removal rate of BOD, COD and TSS reaches more than 85% [24]. Since the completely mixed aeration tank requires continuous water inflow and outflow, and the tank is fully and evenly mixed, there is the problem that the sludge resources cannot be better treated, and it is easy to cause sludge expansion. At the same time, it is not easy to adjust the treatment method after certain changes in sewage quality making the recycling of sludge resources is especially difficult. Compared with the traditional activated sludge process, it may be more efficient in energy utilization. However, the poor utilization of sludge is a shortcoming.

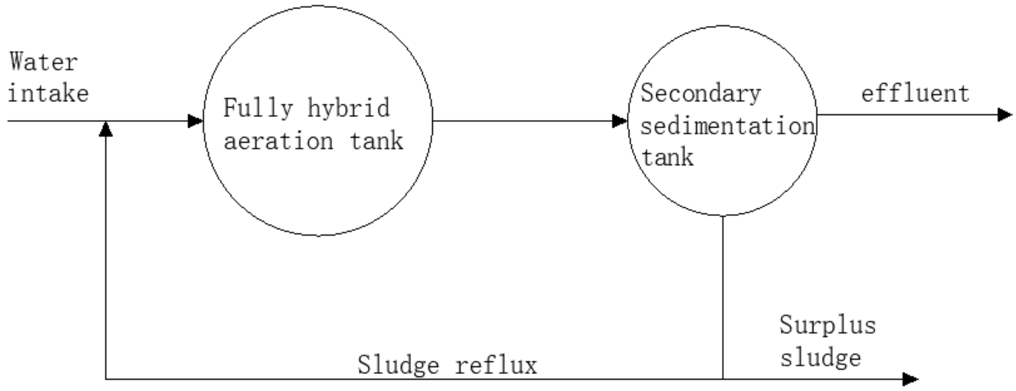


Figure 2. Process flow chart of completely mixed aeration tank.

2.3. Adsorption-Regeneration Activated Sludge Process

The adsorption-regeneration activated sludge method is also known as the biological adsorption method or contact stabilization method. The main feature of this operation mode is that the adsorption and metabolism of activated sludge for the degradation of organic pollutants are each carried out in their own reactors. The wastewater is fully recycled in the regeneration pool, and the activated sludge with strong activity enters the adsorption pool at the same time. The two contact fully in the adsorption pool, and most of the organic matter in the wastewater is absorbed by the activated sludge, and purified. The sludge separated from the secondary sedimentation tank enters the regeneration tank, where the activated sludge metabolizes and degrades the organic matter, and microorganisms proliferate. When the microorganisms enter the endogenous metabolic stage, the activity and adsorption function of the sludge are fully recovered, and it then enters the adsorption tank together with the wastewater [25,39]. The technological process is shown in Figure 3. For the treatment of municipal wastewater, the BOD load (Ns) is 0.2–0.6 kg BOD5/(kg MLSS· d), the volume load (Nv) is 1.0–1.2 kg BOD5/(m^3·d), the sludge age (mean residence time of biosolids) (θr) is 5–15 d, the mixed liquid suspended solids concentration (MLSS) is 1000–3000 mg/L, the mixed liquid volatile suspended solids concentration (MLVSS) is 3200–5200 mg/L, the adsorption pool concentration is 600–1200 mg/L, the regeneration pool concentration is 2400–7000 mg/L, and the adsorption pool reaction time is 0.5–1.0 h. The removal rates of BOD, COD and TSS can reach 80–90% under the conditions of 3–6 h of regeneration tank, 25–100% sludge reflux ratio (R) and 3–5 h aeration time (t). Its treatment effect on sewage is lower than that of the traditional activated sludge process, and it also has the disadvantage of poor treatment effect on wastewater with high dissolved organic matter [40]. Its advantages are that its energy consumption and sludge utilization are considerable, and it can more fully use the sludge, combined with the regeneration pool to carry out sludge conversion operation, reduce the discharge and disposal of sludge, and to a certain extent achieve the purpose of energy saving.

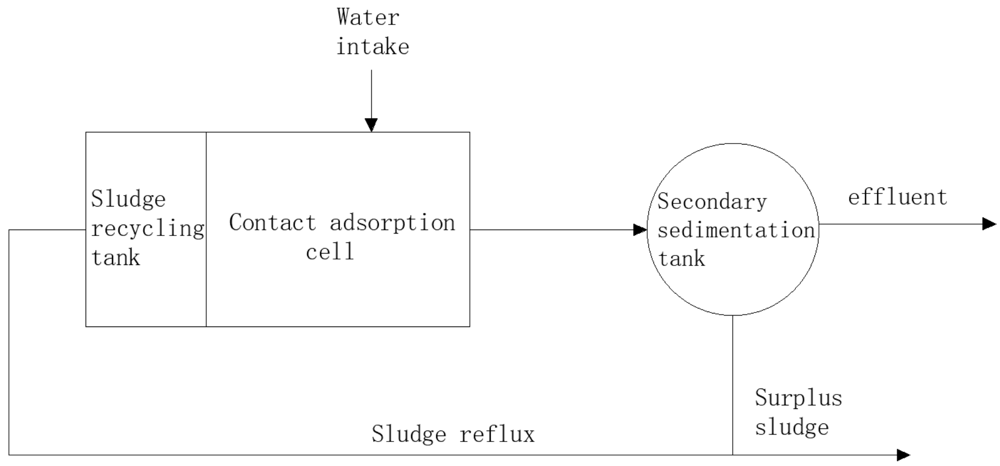


Figure 3. Process flow chart of adsorption-regeneration activated sludge method.

2.4. Delayed Aerated Activated Sludge Process

The delayed aerated activated sludge process is also called the completely oxidized activated sludge process. The main characteristics of the process are low organic load, continuous internal metabolism of sludge, less residual sludge, and stable sludge with no need for further digestion treatment. This process can be called the comprehensive wastewater and sludge treatment process. The process has the advantages of high stability of water quality treatment, strong adaptability to the impact load of wastewater, and no need to set up a primary sedimentation tank. The main disadvantages are large pool capacity, long aeration time, high construction and operation costs, and large size. This process is suitable for the sewage and industrial wastewater needs of a small town, which requires high water quality, and therefore should not be treated by sludge alone. The aeration tanks used in the process are completely mixed or push-flow. The technological process is as shown in Figure 2. When the reference values of the various design parameters used in the treatment of urban sewage are the same as 2.2, the removal rate of BOD, COD and TSS can only reach 85–90%. The removal rate is also lower than that of the previous activated sludge treatment processes [26,27].

This process has a very strong advantage in the operation and management of sludge, and can make full use of sludge resources, so as not to need much sludge disposal, and save part of the energy in the whole treatment system. However, its long aeration time, high operating cost and large area are great shortcomings of the process, and these shortcomings are difficult to make up objectively. Therefore, the process can only be applied if the site conditions are sufficient, and the water quality conditions are more suitable to better use the advantages of sludge treatment to better realize the purpose of energy saving, emissions reduction and low carbonization of sewage treatment.

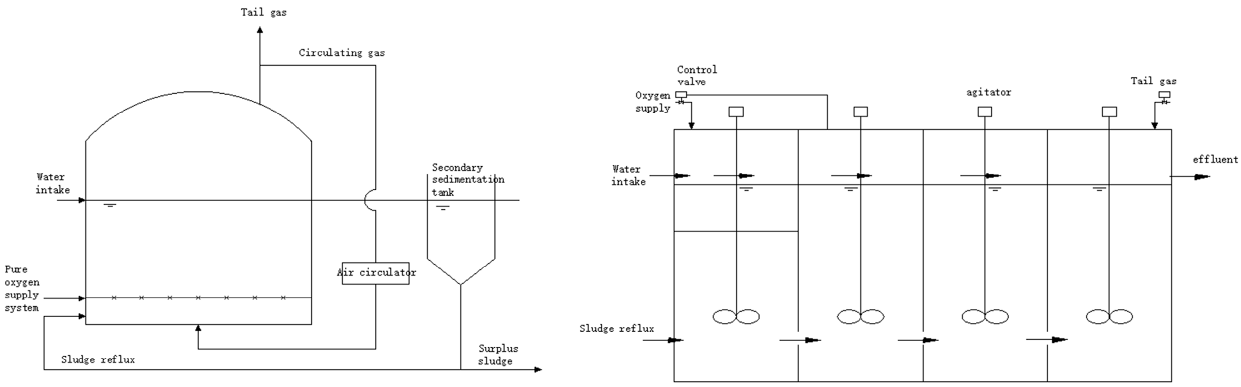
2.5. Pure-Oxygen Activated Sludge Process

Compared with air aeration, pure-oxygen aeration, also known as enriched-oxygen aeration, has the following characteristics:

(1). The oxygen content of air is generally 21%; the oxygen content of pure oxygen is 90–95%, and the partial pressure of oxygen is 4.4–4.7 times higher than that of air, so pure oxygen aeration can greatly improve the diffusion capacity of oxygen in the mixed liquid.
(2). The oxygen utilization rate can be as high as 80–90%, while the air-aerated activated sludge method is only about 10%, so the volume of gas required to achieve the same oxygen concentration can be greatly reduced.
(3). Activated sludge concentration (MLSS) can reach 4000–7000 mg/L, so the volume load can be greatly increased at the same organic load.
(4). The sludge index is low, only about 100, which is not prone to sludge swelling;

(5). High treatment efficiency and short aeration time.
(6). The amount of residual sludge produced is small.

There are three types of pure oxygen aeration pool: (1) multistage- sealed, in which oxygen is introduced into the pool from the closed top cover, the sewage from the first stage is pushed forward step-by-step, oxygen flows from a centrifugal compressor through a hollow shaft into a rotary impeller, which mixes the sludge and oxygen in the pool to keep full contact, so that the sludge can greatly absorb unused oxygen and biochemical reaction metabolites from the previous level of discharge. (2) The old aeration tank is reformed, and a curtain is set on the pool. Not only pure oxygen enters, but also compressed air. Some tail gas is discharged, and can also be recycled. (3) Open pure oxygen aeration tank. The technological process is shown in Figure 4. When the reference values of the various design parameters used in the treatment of urban sewage are the same as 2.2, the removal rate of BOD, COD and TSS can reach 90% [28–32].



Schematic diagram of converting an ordinary aeration tank into a pure oxygen aeration cycle tank

Schematic diagram of multistage series pure oxygen aeration

Figure 4. Process flow chart of pure-oxygen-aerated activated sludge method.

By supplying pure oxygen, the process can greatly improve the diffusion capacity of oxygen in solution and reduce the volume of gas, thus reducing aeration time, aeration energy consumption and carbon footprint. However, it still cannot achieve good sustainable development and utilization of resources in the disposal of sludge operation management. In addition, the structure and management requirements of the equipment are relatively high, which increase the operating costs of the treatment process.

2.6. Sequential-Batch Activated Sludge Process

The sequential-batch activated sludge process is also known as the SBR process because of the intermittent form of operation, so each reaction tank is a batch of sewage treatment; hence the name. Because of the high flexibility of the SBR operation, it can replace the continuous activated sludge process in most situations to achieve the same or similar results. By changing the operation mode of the SBR, you can simulate the operation mode of the full hybrid and push-flow processes. In the reaction stage, the organic matter in the reaction tank is degraded by microorganisms, and the wastewater concentration becomes lower and lower, which is very similar to the steady-state push flow, except that it is a kind of temporal push flow. If the influent period is long and the accumulation of organic matter in the wastewater of the reaction tank is very small during this period, then the situation is close to a complete mixture. The technological process is shown in Figure 5. When the reference values of the various design parameters used in the treatment of urban sewage are the same as 2.2, the removal rate of BOD, COD and TSS can reach 90% [33–37].

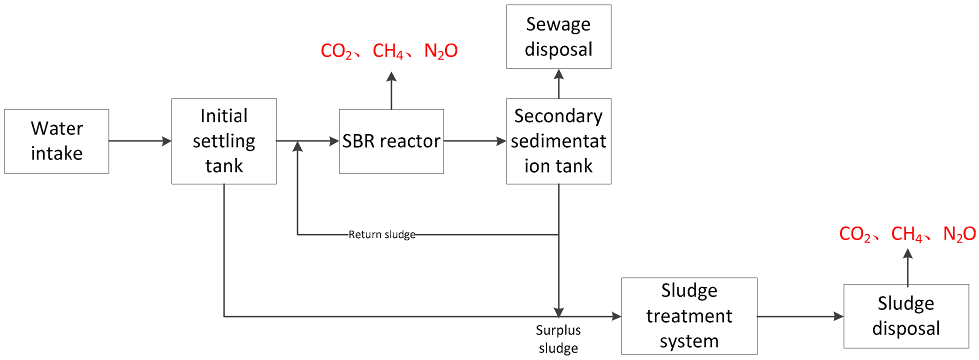


Figure 5. Process flow chart of sequential-batch activated sludge method.

The process improves on the traditional push-flow activated sludge method, and can simulate a complete mixture in certain cases, which can better make up for some problems, such as long aeration time and easy sludge swelling caused by sludge disposal. However, it still fails to solve the fundamental problems of aeration energy consumption and sludge resources, there are still problems of high operation, management and maintenance costs, and the process has relatively high requirements for drainage equipment. During the whole treatment process, when the sewage is biochemically treated by an activated sludge system, a large amount of external energy is consumed for the oxygen supply, and a large amount of greenhouse gases such as CO_2, CH_4 and N_2O are released during the treatment process. However, there are many ways to dispose the residual sludge. Simple treatment such as random accumulation and landfill will also result in the emission of CO_2, CH_4 and N_2O due to anaerobic fermentation and other factors.

2.7. Summary Discussion

Activated sludge is the main pollutant-removal process. In the cell composition of activated sludge microorganisms, carbon (C), hydrogen (H), oxygen (O) and nitrogen (N) account for about 90–97%, and the rest (3–10%) are inorganic nutrient elements, mainly phosphorus (P). The treatment of domestic sewage generally does not require additional nutrients, and some industrial wastewater treatment do require additional nutrients. In conventional aerobic treatment, N and P nutrients are added in accordance with BOD:N:p = 100:5:1. The removal rate of nutrients by the activated sludge method is more than 95%. A 5000 m^3/d municipal sewage treatment plant will produce a residual sludge volume of 7–19 g/(L·d) when treating municipal wastewater by the activated sludge processes described in 2.1, 2.2, 2.5 and 2.6. The 2.3 adsorption-regeneration activated sludge method can make full use of the regenerating tank to activate and reuse the residual sludge and reduce the sludge discharge. The amount of residual sludge produced is about 1–8 g / (L·d) [41–44]. The 2.4 organic load of the delayed aerated activated sludge method is low, the sludge is continuously in a state of endogenous metabolism, and the residual sludge is basically absent. The sludge produced by the activated sludge process needs to be transported to the dewatering plant and then treated. After the initial dewatering treatment of the sludge enrichment tank, it is further dehydrated through a plate-and-frame filter press and other measures. In this process, the main energy consumption is the electric energy of the plate-and-frame filter press, as well as the auxiliary energy consumption of the sludge transport conveyor belt. In the process of wastewater treatment, the main energy consumption in the biochemical reaction tank is air blast aeration and electricity consumption of some auxiliary equipment. An urban sewage treatment plant with a 15,000 m^3/d treatment capacity requires more than 3 blowers and at least 1 plate-and-frame frame filter press. Therefore, based on the calculation of 3 blowers and 1 plate-and-frame filter press, the daily energy consumption produced by full load operation would be 2582.68 Kw·h [45,46]. However, the wastewater produced in this process can be reused for greening, flushing, and so on. The dehydrated sludge can be used as plant fertilizer, building materials, and so on.

In the process of sewage treatment, which consumes much external energy, the form of pollution is actually changed from water pollution to air pollution and sludge pollution, which is obviously not in line with the concept of sustainable development. The COD in sewage can also be used for anaerobic digestion to produce CH_4 and fermentation to produce hydrogen. The CH_4 and H_2 produced can be reused as part of the plant thermal raw materials. The generated surplus sludge can also be used, and the best utilization is incineration capacity. The concept of resource reuse is also implemented to achieve sustainable development, realize low-carbon treatment of sewage and reduce carbon footprint [47].

In addition, in terms of resource utilization, traditional sewage treatment mainly recycles treated water for greening irrigation, washing or industrial cooling, but ignores the problem that sewage itself contains rich carbon resources [48]. Sewage is actually a carrier of resources and energy. It is estimated that the potential chemical energy of urban sewage with a COD of 400–500 mg/L is 1.5–1.9 kW·h/m^3 [49], and a metabolic heat of 0.14×10^8 J can be generated per kg of COD [50]. The heat generated by an increase or decrease of 5 °C of sewage is almost equal to the annual power generation of 332 large power plants, and about 4 times the metabolic heat of organic matter [51]. Sewage contains such a huge amount of energy that if the chemical energy or even heat energy of part of the COD were rationally utilized and converted into electric energy, it could theoretically achieve self-sufficiency in energy consumption, and even output energy (electric energy, heat energy) for use outside of the plant. There is much theoretical evidence to prove that new sewage treatment plants in the future could be not energy consumers, but energy suppliers [52]. However, the traditional sewage treatment process uses energy to supply oxygen to remove COD, which results in a large amount of chemical energy and heat energy in sewage not being extracted and utilized, which goes against the concept of sustainable development. Therefore, recycling and utilization of potential energy in sewage treatment has important practical significance, and plays an immeasurable role in practicing the concept of low-carbon development and promoting the low-carbon operation of sewage treatment.

3. Low-Carbon Sewage Treatment Technology

As one of the major sources of greenhouse gas emissions, the current sewage pollution removal technology mainly relies on energy dissipation and pollution transfer. The treatment process has high energy consumption and emits a large amount of greenhouse gases such as CO_2, CH_4 and N_2O. To effectively control the greenhouse gas emissions from sewage treatment plants and achieve the emission reduction requirements under the dual-carbon target, the traditional concept of sewage treatment must be challenged. It is required that the process of sewage treatment should be as low-carbon as possible, to realize self-sufficiency in energy and full utilization of resources in the process of sewage treatment, and make up for energy consumption and recycle resources by relying on the energy and resources contained in sewage treatment plants or the sewage itself [53].

The removal process of activated sludge in conventional municipal sewage treatment technology still has serious problems of high energy consumption. The removal rate of nutrients and pollutants in sewage can reach more than 95%, but the consumption of aeration energy and waste sludge cannot be ignored. In a hypothetical calculation, a municipal sewage treatment plant with a treatment capacity of 15,000 m^3/d consumes 2582.68 Kw·h of electricity in the biochemical treatment unit and sludge disposal alone, not including air pollution and greenhouse gas emissions produced in the treatment process. Thus it can be seen that the application of low-carbon wastewater treatment technology is very important.

The most serious problem of the push-flow activated sludge method is that the sludge at the head and tail of the tank receives the aeration time unevenly, which leads to a large amount of wasted aeration, resulting in unnecessary energy consumption. The characteristic problem of the push-flow reaction tank is that the BOD concentration is high where the water flows in, and low where the water flows out, so the number of aerators should decrease along the long direction of the tank, that is, to increase the spacing between aerators. In this way, the BOD concentration of the effluent can be met, one-time input can be reduced, and unnecessary aeration can be reduced [54]. The author believes that an intelligent aeration management system can be designed, through which the aeration capacity and aeration time of the push-flow gallery can be intelligently regulated, to make the oxygen demand of the sludge just enough to achieve the purpose of low carbonization and energy savings [55,56]. The completely mixed activated sludge method is a unified operation mode after the sludge and wastewater are completely mixed. Compared with the push-flow activated sludge method, it has no major problems in aeration energy consumption, but because it is a completely mixed operation, it is prone to sludge expansion and the production of excessive residual sludge, which affects effluent quality. In the face of the problems of the process system, it is necessary to monitor the process operation management in detail and continuously observe the water quality changes to prevent sludge buildup. In case of emergency, drugs can be added to enhance sludge settlement performance or directly kill filamentous bacteria through emergency measures [57]. Both the pure-oxygen-aerated activated sludge method and the SBR process are relatively mature. The biggest common problem is that the equipment is more complex and the requirements for management personnel are higher. In addition, these four process systems have two common problems that most need to be solved: aeration energy loss and sludge disposal energy loss. The essence of the activated sludge method is the adsorption and metabolism of activated sludge microorganisms to remove pollutants, and the metabolism needs to absorb oxygen, and the energy consumption of aeration is difficult to avoid. Therefore, in order to solve this problem, Tan Tiepeng [58] described the research process of oxygen demand in the activated sludge process at home and abroad, and the energy-saving technology of the microporous aeration system, and compared the microporous aerator with the perforated tube; it was proven that the former saves 4.4% more electricity compared with the latter. Wang Xian [59] et al. proposed a design concept of subsection control of dissolved oxygen concentration in an aeration tank by discussing oxygen demand and its distribution in the aeration tank, and applying oxygen transfer theory. If this design concept is applied to engineering practice, compared with the conventional design method, the energy consumption and equipment capacity of an aeration system can be reduced by about 15%. The author believes that energy consumption can be properly reduced through intelligent regulation of aeration equipment. At the same time, the metabolism mode of activated sludge microorganisms can be acclimated or changed to reduce the consumption of oxygen, or even operate without oxygen, or be combined with photosynthetic bacteria to achieve metabolism through photocooperation instead of oxygen energy consumption; these studies are very meaningful. As for the problem of sludge disposal, the author believes that the energy consumption of sludge disposal can be compensated by incineration power generation to achieve low carbonization as far as possible. In addition, the treated sludge can also be recycled as building materials and land fertilizer, to achieve the purpose of sustainable development [60–62]. The adsorption-regeneration activated sludge method and delayed aerated activated sludge method make good use of the residual sludge and reduce the sludge load. The sludge remains in a state of endogenous metabolism, thus greatly reducing the generation of residual sludge. Therefore, the problem of low carbonization in these two process systems is mainly the energy consumption of aeration. Similarly to the above four process systems, to solve the problem of aeration energy consumption, it is still necessary to change the microbial nature of activated sludge or reduce energy consumption as much as possible.

At present, Dai Xiaohu et al. [63], considering the development stage and international development trend of our country, put forward the development concept of "green, low-carbon, resource recycling, environmentally friendly, locally-adapted conditions" and corresponding key measures. Ruan Xiaoyang et al. [64] proposed that sludge is a pollutant with utilization value, and can become a resource as long as the sludge is treated and disposed by certain means. This is of great significance for improving the ecological environment, while also helping to reduce the consumption of natural resources and promote the sustainable development of cities in the process of recycling. For low-carbon sewage treatment technology, the main emission reduction measures are summarized as follows: resource recovery carbon conversion and reuse, comprehensive treatment of low carbon and carbon sequestration, operation parameter optimization and process improvement, reasonable carbon distribution, and other related upgrading and renovation treatment technologies. The discussion of the low-carbon operation modes in these sewage treatment processes is summarized in Table 2 below. All kinds of water treatment technologies are gradually upgraded and reformed. While high water treatment efficiency is required, clean treatment technologies such as low-carbon emission continue to emerge, and some sewage treatment plants have put them into use and achieved good results [65–67]. Therefore, this paper analyzes the current research status of low-carbon sewage treatment technology and the prospects for development in the future, so as to provide guidance for more understanding of low-carbon sewage treatment technology.

Table 2. Discussion and summary of low-carbon operation modes in the sewage treatment process.

Low-Carbon Operation Mode	Low Carbonization Pathway	Concrete Measure	Low-Carbon Achievement
Resource recycling carbon conversion and reuse	recycle water	After the sewage treatment is up to standard, it will be used for factory reuse.	"Turning waste into treasure" rationally utilizes all valuable and usable substances produced in the process of sewage treatment, maximizes the concept of sustainable development, reduces carbon emissions and carbon loss from all aspects, and reduces carbon footprint.
	Energy-carrying gas	Energy-carrying gases such as CH4 and H2 are used for fuel.	
	heat energy	Heat generated by microorganisms during sewage treatment is used for heating.	
	sludge	Recovery disposal sludge is used in a burning capacity.	
Comprehensive treatment of low carbon and carbon sequestration	energy-saving and cost-reducing	According to the nature of wastewater, the appropriate treatment process can be selected to reduce the energy consumption such as aeration.	To keep up with the pace of the times, the production and processing equipment is updated over time, and the low-carbon energy-saving equipment is used as much as possible to reduce carbon emissions. Actively develop and utilize new sewage treatment microorganisms to reduce energy consumption and carbon emissions as much as possible and reduce carbon footprint.
	equipment replacement	Upgrade equipment such as old blowers or mixers.	
	Development and utilization of carbon sequestration microorganisms	Reasonable development and utilization of photosynthetic bacteria and other microorganisms for low energy consumption and carbon sequestration methods.	
Operation parameter optimization and process improvement	Operation parameter optimization	Intelligent parameter control is carried out for each processing unit.	Under the premise of ensuring the standard of sewage treatment, the operation parameters of each treatment unit should be controlled, so as to achieve the standard of sewage treatment with the lowest energy consumption possible of each physical unit. The treatment process of each treatment unit should be updated in time, and the sewage treatment should be completed according to the concepts of sustainable development and low-carbon treatment.
	combined technology	According to the nature of sewage, can choose a lower carbonization treatment method combined treatment.	
	technology improvement	The low carbonization process was improved.	

3.1. Research Status

3.1.1. Resource Recovery Carbon Conversion and Reuse

In the process of sewage treatment, there are many resources that may be neglected and not fully utilized, for example, some of the energy and heat lost, the transfer of pollutants and the existing sludge. In fact, these can be converted into carbon to achieve recycling.

After treatment, those that can reach the standard of reuse can be reused in the factory for greening irrigation, washing or industrial cooling water and other methods of recycling, which is conducive to the dual carbon goal. The chemical and heat energy, and other energy resources generated in the sewage treatment process, may be directly consumed or discharged in the traditional treatment process without effective use, resulting in a great waste of resources. The heat energy may be relatively small, but it could still be put to effective use. Miricioiu et al. [68] prepared materials for CO_2 adsorption by activating the residual sludge generated during sewage treatment. After many tests, the adsorption capacity of the material was 11.87 cm 3/g, the separation efficiency was high, and the CO_2 recovery rates were 99.68 and 98.11%, respectively. Studies [69,70], have shown that the heat energy can be recycled through water source heat pump technology and used for heating the sewage treatment plant or surrounding facilities, which can more fully utilize energy resources, reduce carbon emissions, and realize the low-carbon potential of the sewage treatment plant. In addition, in sewage treatment plants with biological sewage treatment, the sludge discharged often contains many substances such as nitrogen and phosphorus converted from sewage. These resources can also be reused to reduce the use of new carbon, to achieve the purpose of relatively low carbonization. Studies [71] have shown that sludge containing nitrogen and phosphorus can be used as fertilizers for composting. And some concentrated sludge that does not contain harmless ingredients can be used as raw materials for incineration power generation after treatment, so that they are valuable for power generation, which can also effectively realize the purposes of energy saving, reuse and low carbonization.

3.1.2. Comprehensive Treatment of Low Carbon and Carbon Sequestration

The traditional activated sludge treatment process requires a large amount of carbon source input and aeration, both of which increase the utilization of carbon. The extensive use of aeration consumes a large amount of external energy for sewage treatment, which leads to the waste of resources, and the generated CO_2 and other gases increase air pollution. The traditional activated sludge method also produces a large amount of activated sludge, which represents a certain amount of sludge pollution, and does not conform to the concept of low carbonization. Compared with the activated sludge method, anammox technology can directly generate nitrogen by the reaction of nitrous nitrogen and ammonia nitrogen, which can greatly save the energy consumption of aeration and the input of carbon sources, but also reduce the production of sludge, greatly realizing the goal of low-carbon sewage treatment. It is a relatively clean biological nitrogen removal water treatment technology and has a good development prospect.

The annual energy consumption of the Sheboygan Wastewater Treatment Plant in the United States accounts for 3% of the total social energy consumption and is the most energy-consuming public facility [72]. In order to achieve the goals of energy self-sufficiency in wastewater treatment and sustainable utilization of resources, the United States Water Environment Research Foundation (WERF) has indicated that all wastewater treatment plants in the United States must achieve carbon-neutral operation by 2030 [73]. The Sheboygan Wastewater Treatment Plant is the first to start the practice of carbon neutral operation. Based on the operational goal and implementation plan of "zero energy consumption" of the "Wisconsin Focus Energy" project, the Sheboygan Wastewater Treatment Plant carried out a series of energy recovery plans from 2002 to 2011, adding 12 30 kW micro gas turbines and 4 heat recovery treatment plants. By 2012, the plant could generate 16,800 kW·h/d of electricity and 16,120 kW·h/d of heat by using cogeneration technology, which offset about 90% of the power consumption and 85% of the heat demand of the sewage plant, basically achieving energy self-sufficiency. In terms of sludge disposal, the equipment for sludge enrichment and dewatering disposal has been upgraded to achieve dehydration treatment with lower energy consumption. At the same time, the treated sludge can make up for the energy consumption of sludge disposal through incineration and power generation, and can also be used for farmland soil remediation, building materials, etc., to fully realize the sustainable development concept of low carbonization and resource recycling [74,75]. In the process of treating part of the industrial wastewater, additional nutrients need to be added, and underutilized nutrients can be recycled to reduce carbon loss. The wastewater discharged is to the standard of reuse for plant greening and equipment washing. In addition, the sewage plant self-funded nearly 1.1 million US dollars for a series of energy-saving upgrading and operation optimizations, updating the pump and blower and other mechanical equipment for energy savings of 20 and 13% respectively, installing a flow control valve (energy saving 17%), updating the digestion tank heating equipment, upgrading the programmable logic controller (PLC), supervisory control and data acquisition (SCADA) and so on, greatly reducing energy consumption. By 2013, the Sheboygan Sewage Treatment Plant had achieved a ratio of electricity production to electricity consumption of 90–115% and a ratio of heat production to heat consumption of 85–90%, basically close to the goal of carbon neutral operation.

The technology of the Sheboygan Wastewater Treatment Plant is worth studying for domestic sewage treatment plants. The energy treatment of sludge can not only effectively relieve the difficult situation of sludge disposal, but also relieve the pressure of fossil energy consumption, and greatly reduce the impact on the environment. Through the double measures of open source and cost reduction, a series of energy saving transformations has been carried out, which provides valuable experience for other sewage treatment plants.

As for low-carbon water treatment, it is still difficult to change only in the aspect of energy saving and carbon reduction. It still needs some technologies that can sequester carbon, directly use or otherwise not emit CO_2 and require low energy from the outside world. At present, it has been found that sewage treatment by photosynthetic bacteria and other organisms can absorb nitrogen and phosphorus and other substances in water for their own use without treatment, and CO_2 can also be absorbed and converted into organic carbon for internal use by photosynthesis [76–79].

3.1.3. Operation Parameter Optimization and Process Improvement

According to the water quality of different sewage, the treatment process selected by the sewage treatment plant will be different. When facing a specific sewage, the operation parameters of the different treatment process will also change slightly. Only by adjusting the most appropriate operation parameters can the treatment be most effective and require the lowest energy consumption. Duan Steel [80] envisioned the application prospect of energy-saving and low-carbon technology in sewage treatment through the construction of a precise aeration system. Liu Guitao [81] et al., based on fuzzy control of three-level inverter frequency conversion speed regulation energy-saving technology, studied the frequency conversion speed regulation system control of a high-powered pump in a sewage treatment plant, and finally realized effective control of a high-powered motor, which can significantly improve the energy-saving effect of a high-power motor in sewage treatment. Through the application of frequency converters in the energy-saving transformation of an aeration fan in a sewage treatment station, Mu Jian [82] adapted the frequency conversion to start slowly, effectively avoiding fan surge, effectively reducing starting current and running current, thus achieving the purpose of energy savings, and at the same time reducing the influence of an overly large or small opening of an intake valve on the load of the rear system. Ma Yong [83] et al. adjusted the sludge layer height of a secondary sedimentation tank to control the sludge return flow of the A/O process, and took the sludge layer height of secondary sedimentation tank as the control variable to establish the sludge return control strategy and controller. An A/O process pilot test device was used to treat real domestic sewage, and the established controller was verified. The results showed that the average effluent ammonia and total nitrogen concentrations were reduced by about 8 and 15%, respectively, compared with the traditional constant sludge reflux ratio control. With an increase in the returned sludge concentration, the sludge discharge and sludge return flow decreased correspondingly. The returned sludge concentration increased by 25.6% on average, and the sludge return flow decreased by 20% on average. The average SS concentration of effluent was reduced by 35.3%, which could avoid sludge loss and maintain the stable operation of the system. Compared with the traditional constant sludge reflux ratio control, the controller has great advantages in terms of system stability, operation cost and effluent quality by adjusting and improving the high- energy-consumption electrical equipment in the whole sewage treatment plant, especially the high-powered equipment such as the water pump and blower. Appropriate adjustment of operating parameters and process optimization can better realize the low-carbon sustainable development concept of sewage treatment. In the whole water treatment process, different water quality will lead to different treatment intensity of each treatment unit in the process. For example, with different concentrations of nitrogen and phosphorus, COD and BOD in the water, the treatment units are also different, so each unit needs to be adjusted to the most suitable operating parameters, to ensure the best treatment effect under the conditions of the lowest energy consumption and low carbon [84].

Traditional sewage treatment processes use physical or chemical methods to remove colloidal substances in sewage, and biological methods to treat organic pollutants in sewage. Existing studies [16] have shown that the improvement of the SBR process adds a pre-anoxic zone on the basis of the original, and the preliminary denitrification of the sewage is carried out through the pre-anoxic process, which provides a good reaction environment for the subsequent treatment, optimizes the selection of carbon sources in the distribution of raw water, and improves the efficiency of the sewage treatment overall and the recovery and utilization rate of water resources. With the improvement of the A2O process, the anaerobic phosphorus removal area and low oxygen aeration area are set next to the settlement area in order to form an integrated setting, which is conducive to improving work efficiency and shortening sewage treatment time. Making full use of the principle of air pressure, a low-oxygen aeration area in front of the air push zone is established to provide natural force and reduce energy consumption and impact load. The unique dissolved-oxygen control system can enhance the removal of COD, total nitrogen TN and total phosphorus TP. At the same time, the process has a wide range of applications, mainly in the efficient treatment of municipal sewage and various types of industrial waste water. It is the main process of urban sewage treatment with low-carbon sources.

For the first time, the coupling process of SHARON and anammox was successfully applied to the treatment of sludge digestion solution with high ammonia nitrogen in the Dokhaven Sewage Treatment Plant in Rotterdam, Netherlands. Compared with the traditional nitrification and denitrification process, the coupling process of SHARON and anammox can reduce the CO_2 emission by 88% and the operating cost by 90%. Domestic studies on this process are mostly in the pilot stage. Zhao Qing et al. [85] treated landfill leachate through the short-cut nitrification-coupled anammox process, and found that the average removal rate of ammonia nitrogen and nitrite nitrogen in this system was over 95%. Nimazelang et al. [86] started and acclimated the one-stage short-cut nitrification and anammox process in SBR. When the process reached stable operation, the SBR effluent was put into the filter column with different volume filling ratios of slow-release carbon sources to conduct in-depth nitrogen removal research. The results show that after 176 days of start-up and acclimation in SBR, stable operation of the one-stage short-cut nitrification and anammox process is successfully achieved, with the removal rate of ammonia nitrogen up to 98% and the total nitrogen removal rate up to 73%. Beijing Drainage Group adopted the anaerobic ammonia oxidation process to treat sludge digesters, with a total treatment scale of 15,900 m^3/d, which can reduce carbon emissions by 10,500 t per year [71].

In the context of rapid development, the value of development needs to be well considered. Successful development must be of good long-term value. Through the improvement of the industry, improvement of shortcomings, improvement of the quality and efficiency of the process, the process operation can produce better value. For the optimization of process operation parameters, the process and sewage quality change rapidly with various factors, so it is more necessary to monitor the operation parameters in detail, utilize the best reaction parameters, realize the most efficient process operation, and improve the process value.

3.2. Growing Trend

At present, the discharge standards of sewage treatment are very strict. All kinds of sewage treatment industries are following the discharge indicators, and vigorously developing and optimizing. At the same time, with the emergence of the development of carbon-neutral and low-carbon industry, the research on energy conservation and emission reduction has become an important task in industrial development. Therefore, although the sewage treatment industry is not a prominent carbon emission industry, its long-term water treatment projects and the accumulation of large amounts of high energy consumption will definitely contribute to carbon emissions [87]. Therefore, in the process of sewage treatment, it is very important to develop the low-carbon treatment technology of sewage through energy saving, consumption reduction and resource recovery as much as possible. However, at present, the new methods of low-carbon water treatment technology and related evaluation standards are still relatively lacking. When we are developing low-carbon water treatment technology, we also need to have an accounting of the carbon emissions in the whole treatment process, so as to promote the perfection of the certification and testing system for low-carbon sewage treatment technology. In addition, it would help us regulate put emissions requirements on CO_2 and other greenhouse gases from sewage treatment. According to the current situation, in the future we will need more advanced monitoring systems, and obtain the greenhouse gas pollutants produced in the process of sewage treatment to make the corresponding inventory descriptions, and develop a series of discharge standards. In terms of the carbon emission assessment of sewage treatment plants, more appropriate algorithms are also needed to establish a deep learning model, so as to better realize the accurate accounting of carbon emissions in the process of sewage treatment [88–90].

According to the above research status of low-carbon sewage treatment technology, we can find that it is possible to realize low-carbon sewage treatment. According to the current situation of each existing sewage treatment plant, reasonable improvements should be made under the supervision and technical support of relevant departments. Relevant departments cannot be one-size-fits-all, requiring the unified transformation of each sewage treatment plant, but specific rectifications must be carried out. The proposed resource recycling carbon conversion and reuse is the basic guarantee for the current low-carbon sustainable development. The concept of sustainable development can and must be realized under any conditions, which is the general trend of development. As for the implementation of low-carbon and carbon sequestration comprehensive treatment, optimization of operation parameters and process improvement, it is necessary for each sewage and water treatment plant to carry out the implementation according to its own regional water quality and plant conditions. Proper equipment upgrading and process optimization are beneficial, but it is also necessary to be guided by facts.

4. Conclusions

With the rapid development of urbanization and the rapid growth of population, the amount of sewage is also increasing sharply. Therefore, the problem of sewage treatment has become urgent. In addition, the waste of resources and energy consumption in the process of sewage treatment and the additional impact on the environment are also urgent matters. Since the conventional wastewater treatment activated sludge process is always achieved through activated sludge microorganisms to complete the degradation of pollutants, it necessitates oxygen energy consumption and sludge generation. No matter how the processing technology and parameters are changed, it cannot avoid energy consumption and the disposal of harmful substances. Therefore, it is difficult to achieve carbon neutrality and reduce carbon emissions. On the other hand, although some energy consumption is unavoidable, in low-carbon sewage treatment technology, low-carbon sewage treatment can be achieved through the resource recycling of carbon conversion and reuse, the generation of new methods of low-carbon carbon sequestration, and a certain degree of operational parameter optimization and process optimization, so as to implement the concept of low-carbon sustainable development as far as possible, and can be gradually improved through scientific research. Therefore, as described in this paper, on the basis of traditional conventional water treatment technology, it is also necessary to constantly study and update water treatment technology to realize the full utilization of resources and energy consumption as far as possible, as well as low-carbon water treatment technology, to reduce the production of CO_2 and CH_4 and other greenhouse gases. Promoting the innovation and improvement of sewage treatment technology and processes on the basis of saving energy and reducing consumption, high efficiency and low carbonization of sewage treatment can be realized, while the problem of sewage treatment is dealt with well.

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