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Biological contact oxidation and an artificial floating island for black odorous river purification

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ABSTRACT

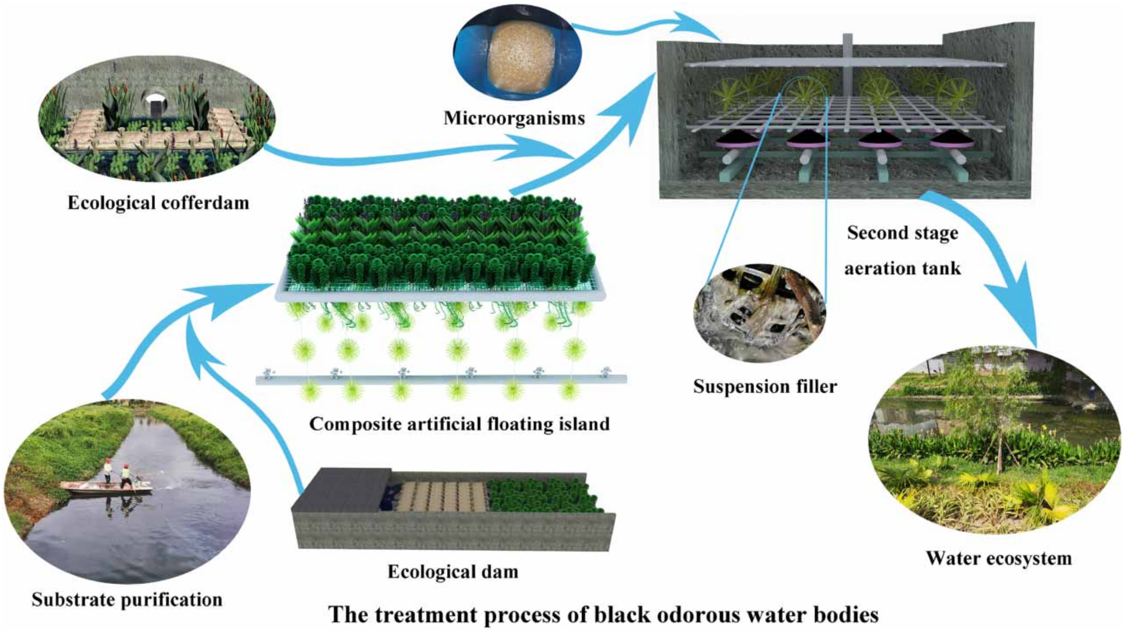
Due to destruction caused by urbanization and anthropogenic activities, various methods for treating black odorous rivers have been proposed. Herein, a treatment scheme was put forward for a black odorous river in Dongguan City, Guangdong Province. The river was treated using composite artificial floating island and improved biological contact oxidation processes as the core, supplemented by source control, substrate purification, and water ecosystem construction. The transparency, dissolved oxygen, ammonia nitrogen (NH_3-N), and total phosphorus (TP) of the water body met the China Surface Water Environmental Quality Standard (GB3838-2002) V. The oxidation–reduction potential was remarkably improved and the black odor phenomenon was eliminated. The composite artificial floating island had the highest TP removal rate of 38.30%, while the improved biological contact oxidation process had the highest NH_3-N removal rate of 43.08%. The process is effective in improving the quality of black odorous rivers and has high applicability; thus, the process provides a reference for the treatment of other black odorous water bodies.

Key words: artificial floating island, biological contact oxidation, black odorous river, process improvement, water quality improvement

HIGHLIGHTS

- Combine aeration, biofilm with artificial floating island.
- Improve the traditional biological contact oxidation tank with good ammonia nitrogen removal.
- A complete and effective treatment process for black and odorous water bodies is designed.
- River black and odor are eliminated, and pollutants are removed substantially.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Accelerated industrialization and rapid economic development in China have rapidly deteriorated the environment, intensified water pollution, and caused serious ecological damage, among other problems (Wang & Yang 2016). In China, numerous urban rivers seasonally or permanently turn black and carry an unpleasant smell, posing a severe water problem (Ji *et al.* 2017; Zhang *et al.* 2019). According to the data released by China's Ministry of Housing and Urban–Rural Development–Ministry of Ecology and Environment in October 2021, the total number of black odorous water bodies in China is 2,869, of which 556 are under treatment; however, there are still black odorous rivers that continue to pollute the environment (Ministry of Housing and Urban–Rural Development of China 2022). Compared with normal rivers, black odorous water bodies are typically characterized by a low dissolved oxygen (DO) content, oxidation–reduction potential (ORP), and pH, as well as high nitrogen and phosphorus levels. For example, the DO content is mainly maintained between 0 and 1 mg/L, NH_3-N levels vary from 2 to 50 mg/L, and total phosphorus (TP) levels may exceed 17 mg/L (Cao *et al.* 2020). The reasons for the black color of these water bodies include the consumption of oxygen by organic matter, low ORP of the water body, and presence of metal sulfides (Rong *et al.* 2020). The unpleasant smell is mainly caused by volatile organic sulfides, hydrogen sulfide, and various algal metabolites (Cao *et al.* 2020). Remediation of black odorous water bodies can be divided into physical, chemical, and bio-ecological remediation techniques (Xie *et al.* 2020). Artificial aeration, water cycling (artificially connecting rivers or lakes to make water flow and cycle), and substrate dredging are physical remediation techniques, whereas chemical remediation techniques include chemical flocculation, chemical sedimentation, and chemical algal removal. Compared with traditional physical and chemical remediation methods, bio-ecological restoration is more effective at removing organic matter and has a lower impact on the environment, making it an appropriate long-term strategy (X. Wang *et al.* 2020).

Being an effective ecological restoration method for water purification, artificial floating island (AFI) technologies have been widely used in rivers, lakes, and reservoirs for 40 years in China (Kong *et al.* 2019). An AFI is a soilless planting structure composed of floating bodies, aquatic plants, and the associated microbial communities (Yeh *et al.* 2015). AFIs have various functions, including absorbing nitrogen and phosphorus from water through plants, intercepting suspended materials, providing microbial attachment vehicles, reducing light penetration, and inhibiting algal growth (Lu *et al.* 2015). However, the coverage of AFIs may cause hypoxia in water bodies, the use of non-native plants may lead to species invasion, and decaying plants and floating island materials may become a source of pollution. Research has shown the combination of aeration and AFIs can prevent suspended substrates from sinking, strengthen the contact between microorganisms and dissolved oxygen, and help eliminate water pollutants, such as organic matter, nitrate nitrogen (NO_3-N), and phosphate ions (Liu *et al.* 2014).

The biological contact oxidation (BCO) process, also known as the integrated biofiltering or contact aeration process, is a hybrid wastewater treatment system that combines the advantages of the activated sludge process and biofilm method (Ateia *et al.* 2016). In this process, pollutants are absorbed and degraded by microorganisms on biofilm attached to a carrier, thereby purifying the water. Owing to its tolerance to high NH_3-N levels and strong resistance to shock loading, this process is widely used for treating organic wastewater (Li *et al.* 2021). The basis of the BCO process is the selection of a suspension carrier filler that directly affects the water quality and operation management of BCO (Tang & Sun 2018). Traditional BCO tanks use continuous aeration to remove organic matter and NH_3-N; however, continuous aeration has the disadvantages of high energy and carbon consumption. In addition, continuous aeration is not conducive to denitrification, resulting in low nitrogen removal efficiencies. Moreover, intermittent aeration can alter the environment and improve pollutant removal (Zhang *et al.* 2021).

Owing to the unclarified mechanism of water blackening and odorization, a single technique cannot ensure the purification and long-term remediation of black odorous water bodies (Fan *et al.* 2019). Herein, a combination of source control, substrate purification, composite AFI, improved BCO, and water ecosystem reconstruction was used to treat a severely polluted black odorous river in Dongguan City, Guangdong Province. The water quality before treatment was as follows: transparency of 3–7 cm, DO content of 0.1–0.4 mg/L, NH_3-N of 15.22–19.27 mg/L, TP content of 1.66–2.28 mg/L, and ORP of −261 to −294 mV. We require the quality of the water bodies to reach standard V at the surface, with transparency >25 cm and ORP >50 mV, to ensure that the black odor phenomenon is eliminated, pollutants are substantially removed, and the environment is improved.

2. MATERIALS AND METHODS

2.1. Study area

The study was conducted in Guangdong Province in southern China, in the town of Shipai in the northeast of Dongguan City, with geographic coordinates of 23.35 °N and 113.38 °E. The region experiences a subtropical monsoon climate, with annual temperature and rainfall averages of 22.1 °C and 1,724 mm, respectively, and an average of five frost days annually. The target river in Shipai town is a natural tributary of the Nanshelang River, with an overall length of 3.15 km, an average width of 8 m, a depth of approximately 1.5–2 m, and an annual average flow rate of approximately 800 m^3/h (Figure 1). Some parts of the

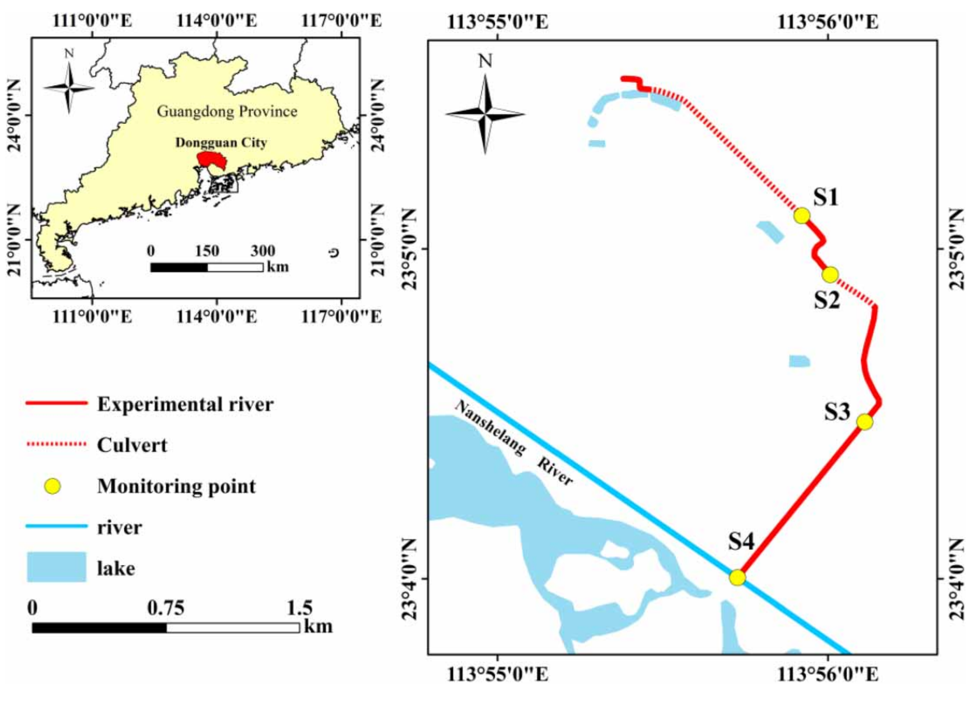


Figure 1 | Geographical location of the experimental river.

river exist as culverts, and massive outfalls are present in the upper reaches of the river and culverts, whereas fewer outfalls are present in the lower reaches.

2.2. Water quality characteristics

The river not only has a dark color and low transparency, but also some garbage floating on the surface, a large number of plants growing on both banks of the river, and a distinctly unpleasant smell. Sampling was conducted at monitoring sites S1, S2, S3, and S4 (Figure 1) every 10 d from 9:00 to 10:00 AM from October 2020 to April 2021 for water quality monitoring (Table 1). The samples were collected at a 0.5 m depth underwater in the middle of the river of the monitoring point and were immediately sent to a laboratory to measure the NH_3-N and TP contents. The transparency, DO content, pH, and ORP were measured in-situ, and sampling was conducted three times and the average was calculated. According to the *Working Guidelines for the Treatment of Urban Black-Odorous Water 2015* (*Working Guidelines for the Treatment of Urban Black-Odorous Water 2015*) and *Environmental Quality Standards for Surface Water* (GB 3838-2002) (*Environmental Quality Standards for Surface Water* (GB 3838-2002)), the transparency, DO content, and ORP of the river were very low, while the NH_3-N and TP values exceeded standard V at the water surface by approximately eight and five times, respectively. This indicates that the river was a severe black odorous water body that failed to meet standard V at the water surface before treatment.

2.3. Water quality testing

The water quality analysis included measuring the transparency; DO, NH_3-N, and TP contents; and ORP. Water quality detection was conducted according the *Analytical Methods for Water and Wastewater Monitoring 2002* (4th edition) (State Environmental Protection Administration 2002) released by the Chinese State Environmental Protection Administration and the *Standard Methods for the Examination of Water and Wastewater 1998* (20th edition) (APHA/AWWA/WEF 1998) published in the USA. The testing methods and instruments used are shown in Table 2.

2.4. Process design

According to the characteristics of the river and its water quality and quantity, source control was used to reduce exogenous pollution entering the river, and a substrate improver was used to decrease endogenous pollution. Composite AFIs, modified BCO, and water ecosystem reconstruction were then applied to treat the remaining pollutants (Figure 2).

2.4.1. Source control

The sewer line was intercepted and modified such that the sewage discharged into the sewer network. Presently, the river has 61 outfalls, of which 35 have been intercepted. During this process, an ecological cofferdam was established ahead of the river outfalls to reduce the impact of sewage on the river. An ecological cofferdam is a fence-like structure composed of wooden stakes to hold the sewage filtering agent (Figure 3), with aquatic plants (including *Myriophyllum elatinoides* Gaudich., *Thalia dealbata* Fraser, *Vallisneria natans* (Lour.) Hara, and *Typha orientalis* Presl.) planted interiorly and exteriorly. Moreover, the outfall of the culvert section is located in a dark place underground, making it difficult to construct there; thus, the ecological dam was established at the outlet of the culvert. The ecological dam is a permeable dam formed by using wooden piles to hold the sewage filtering agent in place. Each dam was approximately 5 m long, and three groups were established at approximately 15 m intervals (Figure 3), with *M. elatinoides* species planted between each group. A filtration bag is an environmental protection bag consisting of a sewage filtering agent with good water permeability. A sewage filtering agent is a new type of material composed of a mixture of materials, including modified zeolite and rare-earth modified bentonite, that can adsorb nitrogen and phosphorus and eliminate odor. After sewage passes through the filtering package, some

Table 1 | Water quality characteristics

Water quality index	pH	Transparency (cm)	DO (mg/L)	NH_3-N (mg/L)	TP (mg/L)	ORP (mV)
Water quality at monitoring sites S1–S4	6.9–7.5	3–7	0.1–0.4	15.22–19.27	1.66–2.28	−261 to 294
Slightly black odorous water bodies	–	10–25	0.2–2.0	8.0–15	–	−200 to 50
Severe black odorous water bodies	–	<10	<0.2	>15	–	<−200
Surface water Grade V standard	6–9	–	>2	<2.0	<0.4	–

Table 2 | Water quality testing methods and instruments

Testing index	Testing methods and analytical instruments	Detection limit
Transparency	SD20 Secchi disc	–
DO	JPB-607A dissolved oxygen tester	0.01 mg/L
NH_3-N	Nessler's reagent spectrophotometry (HJ535-2009)	0.025 mg/L
TP	Molybdate spectrophotometry (GB11893-1989)	0.01 mg/L
ORP	CD-PH810 portable ORP meter	1 mV

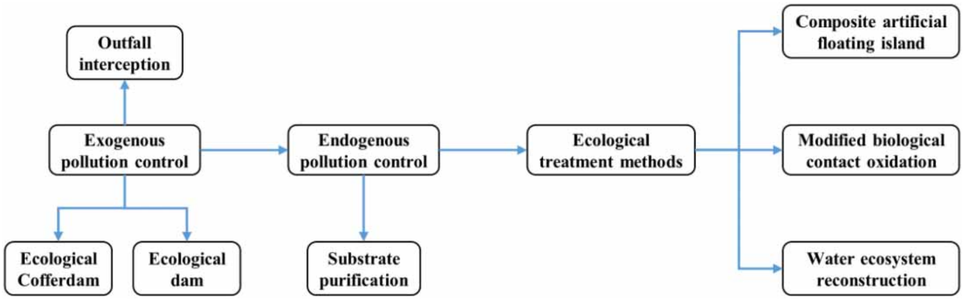


Figure 2 | Technical route.

Figure 3 | Ecological cofferdam and ecological dam under construction (left: ecological cofferdam; right: ecological dam).

pollutants are adsorbed and degraded. Meanwhile, plants also have the ability to absorb nitrogen and phosphorus and improve the appearance of the environment.

2.4.2. Substrate purification

River sediment, which can exchange material and energy with water as well as adsorb and degrade certain pollutants, plays an important role in self-purification (Zhang *et al.* 2019). However, the large amounts of pollutants deposited at the bottom of a river weaken the river's self-purification capacity, and nutrients such as nitrogen and phosphorus in the sediment are easily released into the water column, resulting in secondary pollution (Z. Wang *et al.* 2020). Dredging is a commonly used substrate treatment method and achieves complete removal of pollutants; however, the removed substrate needs further treatment, which is costly and creates secondary pollution. (Wang *et al.* 2019). In recent years, substrate in-situ remediation technologies have been widely used to remediate black odorous rivers. In this study, a substrate improver with zeolite, magnesium-aluminum hydrotalcite, calcium peroxide, polymeric aluminum chloride, and other materials was used to remediate black odorous water bodies by reducing the capacity of substrates, removing nutrients, and fixing heavy metals. This would activate indigenous microorganisms and restore the ecological chain.

Shipboard machinery was used to stir and convert the substrate into a suspended state, and then the substrate improver was added. The surface area of the river is approximately 12,600 m^2, the depth of the substrate is approximately 0.3–0.5 m, and the amount of substrate improver used was 0.5 kg/m^2. Five days after the first dosing, the sediment was stirred again in the same manner, and dosing was conducted every five days for 20 d.

2.4.3. Composite AFI

Artificial floating islands (AFIs) mainly purify water bodies by absorbing nutrients, such as nitrogen and phosphorus, in water from cultivated aquatic plants, while microorganisms decompose organic matter on the biofilm formed by plant roots (Yang *et al.* 2021). However, due to the limited plant area, the pollutant removal rate of traditional AFIs is inefficient. Most aquatic plants with shallow roots on floating islands can only remove pollutants from the water surface; thus, restoration of deep-water bodies is limited. Meanwhile, the very low dissolved oxygen content of black odorous water bodies is harmful to the growth of plants and affects the activity of microorganisms (Lv *et al.* 2019). This study improves the traditional AFI in the following ways: (1) Additional aeration pipes for aeration placed at the bottom of black odorous rivers can increase the low dissolved oxygen content in the water column and change the state of suspended matter. (2) Modified fiber balls suspended under a floating island increase the adsorption capacity of organic matter and utilize microorganisms to remove pollutants from deep water bodies. (3) *T. dealbata* and *M. elatinoides*, which have strong pollution resistance among native plants, were selected for planting. As the two plants have different rooting depths, they not only cooperate during river restoration, but also grow and reproduce rapidly. (4) Aerobic microbial strains, including nitrifying bacteria and *Bacillus subtilis*, were chosen to accelerate film hanging.

A PVC pipe was used to construct a rectangular floating island frame that was 10 m long and 5 m wide, with ⌀=90 mm and a plastic foam board fixed in the middle. *M. elatinoides* was cultivated on both sides at a planting density of 45 plants/m^2, and *T. dealbata* was planted in the foam boards at a density of ten plants/m^2. Modified fiber balls, made from polypropylene material, were suspended under the floating island as microbial carriers, with ⌀=100 mm, a distribution of four strips/m^2, and a length of 1.5 m. The AFI was fastened in the middle region of the river by steel wires, while a perforated aeration pipe made of polyethylene (DN150) was installed at the centerline of the bottom of the floating island. Moreover, a submerged blower with power P=7.5 kW and blower volume Q=7.8 m^3/min was established. Thereafter, approximately 1.0×10^9 CFU/mL of aerobic microbial strains, including nitrifying bacteria and *B. subtilis*, were added, with an injection volume of 1 L/m^3 and a total injection volume of approximately 3,000 L. After approximately 20 d of continuous aeration, a yellow–brown film-like material was observed adhering to the modified fiber balls (Figure 4).

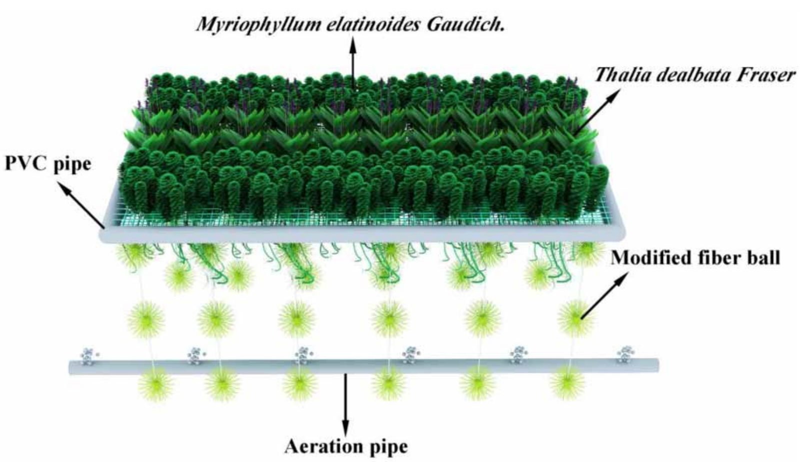


Figure 4 | Composite artificial floating island.

2.4.4. Improved biological contact oxidation

Traditional BCO ponds are easily clogged and exhibit low nitrogen and phosphorus removal rates, making them unsuitable for the remediation of black odorous rivers. In this study, the traditional BCO pond was improved as follows: (1) The shape and design of the conventional BCO basin was altered to suit the river. (2) New filler combinations were adopted to increase the pollutant removal rate. (3) The flow direction was transformed into a folded flow to increase the contact and hydraulic retention time of the water body and filler. (4) The aeration mode was changed – intermittent aeration was used to hang the biofilm to create alternating anaerobic, anoxic, and aerobic conditions, which is useful for increasing the nitrogen and phosphorus removal rates. (5) Compound microbial strains were added to increase efficiency of nitrogen and phosphorus removal and shorten the reactor start-up time.

The modified BCO pond was approximately 0.3 m above the normal water level of the river and was constructed inside the river and controlled with a gate. Therefore, it did not influence the safety of the river during flooding. The daily treatment capacity of the modified BCO tank was 1,000 m^3/d, and the hydraulic retention time (HRT) was approximately 4–6 h. The tank consisted of a sand sedimentation tank, primary, second, and tertiary aeration tanks, and a sludge hopper that was slightly wider than the river. Concrete retaining walls were used to separate the tanks, and the sewage flowed from the retaining walls to form a folded flow. The bottom of the aeration tank was laid with an aeration pipe that was connected to an aeration disk, and the filler was fixed with galvanized iron mesh above the aeration pipe. A submerged aerator (TSW-10075) with power $P=10$ kW, blast volume $Q=12$ m^3/min, aeration main DN90, aeration branch DN50, PVC materials, aeration disk $\varnothing=300$ mm, and a pool vapor ratio of approximately 8.64–17.28 was used. Watermelon-type polypropylene material suspension balls were used in the primary and secondary aeration tanks for hanging the film, with $\varnothing=120$ mm, a specific surface area of approximately 800 m^2/m^3, and a porosity $\geq$97%. A volcanic rock suspension ball was used in the tertiary aeration tank to hang the film and filter the shed biofilm. The specific structure of the improved BCO tank is shown in Figure 5, and its specific mechanism was as follows: first, the sewage flowed into the sand sedimentation tank to remove inorganic and organic particles with high densities and prevent clogging. As the sewage passed through the primary and secondary aeration tanks, pollutants were removed by microorganisms. The sewage then passed through the tertiary aeration tank for aeration filtration and finally through the sludge bucket for sedimentation and separation.

As the sewage flowed into the tank, the compound microbial strain was injected. The compound microbial strains included nitrifying bacteria, denitrifying bacteria, and *B. subtilis*. The concentration of bacterial solution was approximately 1.0×10^9 CFU/mL, the dose was 3 L/m^3, and the total dose was approximately 1,000 L. After intermittent aeration at approximately 20–25 °C for 12 h per day for 20 d, a yellowish-brown, white membranous material was observed hanging from the filler (right in Figure 6), which is where the rotifers, nematodes, and oligochaetes were observed by microscopy. The quality of the inlet and outlet water changed significantly, indicating that the improved BCO tank can improve water quality. The aeration disk, aeration tube, and suspended materials are to be replaced every three to five years. The construction, operation, and film-hanging of the improved BCO tank are shown in Figure 6.

2.4.5. Water ecosystem reconstruction

Water ecological reconstruction refers to the adoption of engineering and non-engineering measures to promote the restoration of water ecosystems to a more natural state. Plants play an important role in water purification and ecosystem

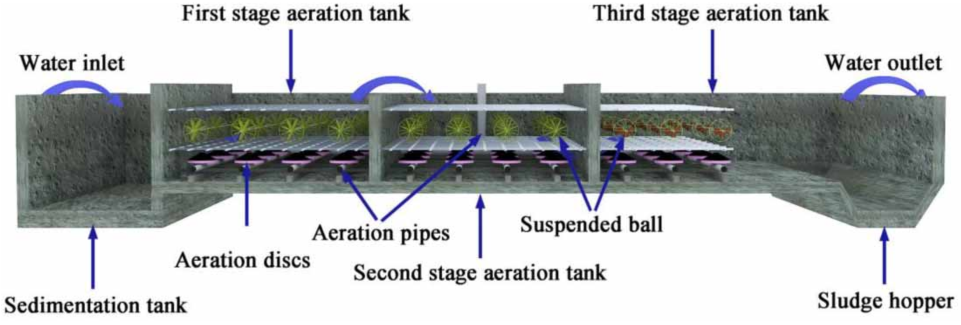


Figure 5 | Improved biological contact oxidation tank.

Figure 6 | Improved biological contact oxidation tank construction, operation and film attachment (left: under construction; middle: in operation; right: biofilm already growing).

restoration by absorbing and assimilating excess nitrogen and phosphorus in water (Yu *et al.* 2019). The removal of nitrogen and phosphorus occurs mainly because of the synergy between plant roots and microorganisms, and only a few are directly absorbed by plants (Su *et al.* 2019). Studies have shown that combining aquatic plants and aquatic animals helps to remove pollutants, stimulates the growth of aquatic plants, and improves water transparency (Gao *et al.* 2017).

Within 300 m behind the modified BCO pond, submerged plants *Vallisneria natans* (Lour.) Hara, *Ceratophyllum demersum* L., and *M. elatinoides* were planted, together with emergent plants *Nelumbo nucifera* Gaertn. and *Canna indica* L., covering an area of approximately 2,400 m^2 and accounting for 19.1% of the water surface. The compound microbial strains were added, including nitrifying bacteria, denitrifying bacteria, and *B. subtilis*. The concentration of bacterial solution was approximately 1.0×10^9 CFU/mL, the dose was 0.5 L/m^3, and the total dose was approximately 1,800 L. Fish can clean up phytoplankton, while mussels can filter microscopic organisms and organic debris suspended in the water and *Sinotaia quadrata* secretes pro-flocculating substances, and the presence of the appropriate aquatic animals, including *Cyprinus flammans* (Richardson), *Carassius auratus*, *Sinotaia quadrata*, and *Anodonta woodianawoodiana*, all of which are native species, can improve the transparency of water. The density of the fish casting was approximately 20–40 fish/100 m^2, with 30–50 g/strip and a total casting of approximately 1,200–2,600; the density of the *Sinotaia quadrata* casting was approximately 5–10 strip/m^2, with 2–10 g/strip and a total casting of approximately 32,000–64,000; the density of the *Anodonta woodianawoodiana* casting was approximately 1–2 strip/m^2, with 10–15 g/strip and a total casting of approximately 6,400–12,800.

3. RESULTS AND DISCUSSION

3.1. Results and analysis

The system was built from April to June 2021 and began operating stably in July. According to the construction sequence, the system was divided into five parts: stage I – construction of substrate purification, an ecological cofferdam, and an ecological dam; stage II – construction and operation of a BCO tank; stage III – construction of a composite AFI; stage IV – construction of a water ecosystem; and stage V – stable operation of the system. The water transparency, DO, NH_3-N, and TP contents, and ORP were sampled at monitoring points S1, S2, S3, and S4 every 10 d during the construction and operation of the system. Among the four sampling points, S1 is the water inlet point, between S1 and S2 is the composite AFI, between S2 and S3 is the improved BCO tank, between S3 and S4 is the water ecosystem, and S4 is the final water outlet of the system.

3.1.1. Changes in water transparency

The transparency of the system increased from 5 cm to approximately 65 cm (S4), with an improvement rate of 1,200%, far exceeding the expected target of 25 cm (Figure 7). This indicates that the black odor of the river was eliminated. Possible reasons for the increased transparency are as follows: (1) Suspended pollutants are aggregated and settled by polyacrylamide and polymeric aluminum chloride in the substrate improver through adsorption and a compressed double-layer action. (2) Aeration of the modified BCO tank and the composite AFI causes tiny pollutants to adsorb to the air bubbles and float, and the suspended matter is precipitated in the sedimentation area. (3) Improved BCO tank fillers, composite AFI roots, and biofilm grown on modified fiber balls are used for microbial growth and reproduction. (4) Pollutants are intercepted, settled, and absorbed when they pass through plants, thereby increasing the transparency of the water.

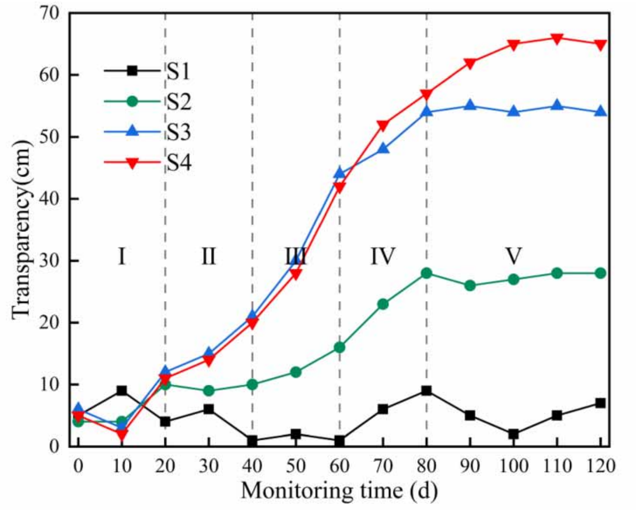


Figure 7 | Changes in water transparency at different times.

3.1.2. Changes in DO content

The DO content of the system increased from 0.2 mg/L to greater than 6.0 mg/L in S4, where the low DO content of the black odorous water body had increased, meeting standard V of DO>2 mg/L at the water surface (Figure 8). The greatest improvement in the DO content occurred through the effect of aeration on the BCO tank and composite AFI. After aeration at point S3, the DO content of the effluent reached 5.6 mg/L, with a DO increase of 4.5 mg/L. Adequate aeration kept the water body in a high-dissolved-oxygen environment for a long time, which is conducive to an increase in microbial populations and removal of nitrogen and phosphorus. In addition, the slowly released calcium peroxide in the substrate improver released oxygen continuously, thereby increasing the DO content of the water body, while phytoplankton (such as *Aphanocapsa elachista*, *Microcystis* sp. and *Scenedesmus* sp., etc.) and other aquatic plants also photosynthesized large amounts of oxygen.

3.1.3. Changes in NH_3-N

Figure 9 shows the NH_3-N changes in the water bodies at different times. The influent NH_3-N concentration fluctuated at approximately 16.25 mg/L (S1), meaning that the water quality was stable; however, the NH_3-N content significantly

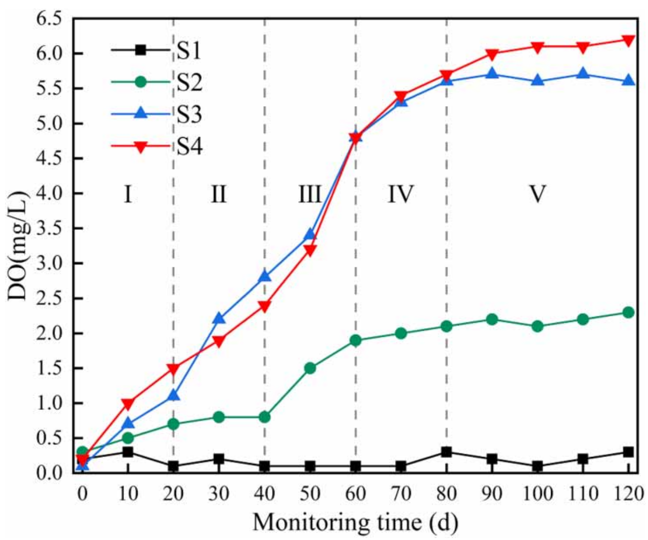


Figure 8 | Changes in DO content at different times.

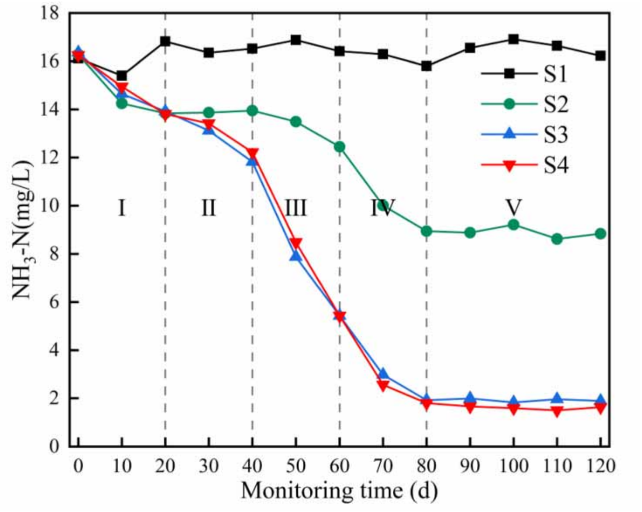


Figure 9 | Changes in NH_3-N at different times.

exceeded the standard. From days 0 to 20, the NH_3-N concentration was reduced from 16.25 mg/L to 13.86 mg/L due to the adsorption and oxidation of nitrogen-containing pollutants by the substrate improver, and the removal rate at this stage was 14.71%. During the construction and operation of the composite AFI (S2), nitrogen in the water bodies was utilized by microorganisms, allowing them to grow and reproduce considerably, while the nitrogen element in the water was absorbed by *M. elatinoides* and *T. dealbata*, resulting in a significant reduction in the NH_3-N content. The NH_3-N concentration in the effluent at this stage was 8.89 mg/L, with a removal rate of 30.58%. During the construction and operation of the improved BCO tank (S3), sufficient aeration increased the DO content in the water bodies, and intermittent aeration created alternating aerobic, anoxic, and anaerobic conditions. Microorganisms such as nitrifying bacteria formed an approximately 1–3-mm-thick biofilm on the filler, where microorganism ammonification, nitrification, denitrification, and assimilation converted nitrates into nitrogen and removed it. At this stage, the NH_3-N concentration was 1.89 mg/L in the outlet water and the removal rate was 43.08%. Finally, the outlet water, with high concentrations of plants and animals that further ensured the stability of the effluent via the water ecosystem (S4), had an NH_3-N concentration reaching 1.57 mg/L with a total removal rate of 90.34%, which is within the standard V of NH_3-N<2.0 mg/L for surface water.

3.1.4. Changes in the TP

After applying the substrate improver at stage I, phosphorus molecules were bound to form a non-soluble material and had settled down, and the TP content decreased by 0.24 mg/L (Figure 10). During the early stage II, the improved BCO tank was constructed and operated. The reasons for the inconspicuous TP content reduction during this stage are as follows: (1) An aeration disturbance caused a re-release of phosphorus from the substrate. (2) The biofilm is not fully grown at this stage. At days 40–60, the construction and operation of the composite AFIs began during stage III. When the construction was complete, the plants and microorganisms had not fully adapted to the new water bodies and, thus, made minor contributions to the removal of phosphorus. However, the entire improved BCO tank had been completely hanging film at this stage, and the activity of phosphorus-accumulating bacteria had increased. As a result, phosphorus removal was achieved via anaerobic phosphorus release and aerobic phosphorus absorption. At approximately days 60–80, the stage IV water ecosystem was rebuilt, and plant growth and reproduction required a certain adaptation period. Under continuous aeration of the composite AFI, the phosphate-accumulating organisms absorbed large amounts of phosphorus, while the plants absorbed relatively smaller amounts at this stage. At days 60–80, the stage V system operated stably, and aquatic plants and animals ensured the stability of the phosphorus effluent. Finally, the effluent TP content reached 0.26 mg/L with a total removal rate of 86.17%, meeting the standard V of TP<0.4 mg/L for surface water.

3.1.5. Changes in ORP

During biological treatment, the ORP reflects changes in the dissolved oxygen concentration, organic matter concentration, microbial activity, and process inhibition (Martin de la Vega *et al.* 2012). As a comprehensive index, a positive ORP value

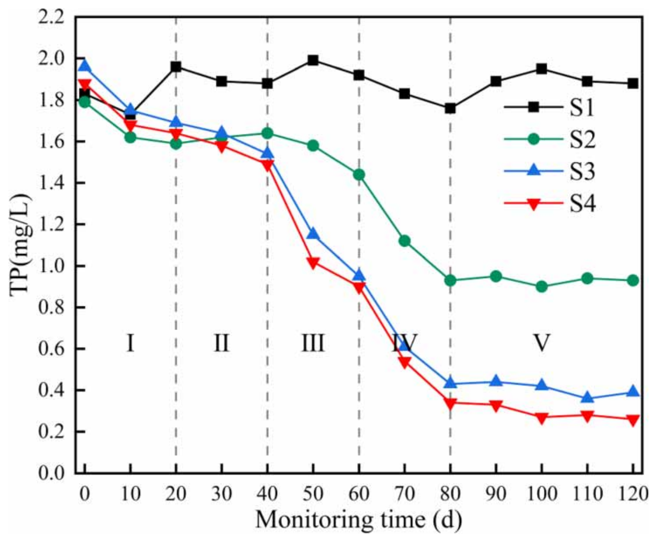


Figure 10 | Changes in TP at different times.

indicates that the water body has undergone oxidation, and the higher the ORP value, the stronger is the oxidation; a negative ORP value indicates that the water body has undergone reduction, and the lower the ORP value, the stronger is the potential reduction. The ORP value increased continuously, from an initial −280 to 261 mV, reaching the expected level of ORP>50 mV and eliminating the black odor (Figure 11). Possible reasons for the increased ORP are as follows: (1) The presence of oxidizing substances in the substrate improver, such as calcium peroxide, oxidized some organic and inorganic substances, in the sediment and water body. (2) Due to continuous aeration, the O_2 content remained high, and the ORP showed a strong positive correlation with the O_2 concentration; thus, the total ORP increased. (3) The plants and microorganisms adsorbed and purified the reductive organic pollutants and other substances.

3.2. Processes that improved water quality

The water transparency, DO content, and ORP were improved significantly through the composite AFI. An NH_3-N removal rate of 30.58% was reached, and the TP content reached 38.30% and accounted for the largest percentage (Table 3). This

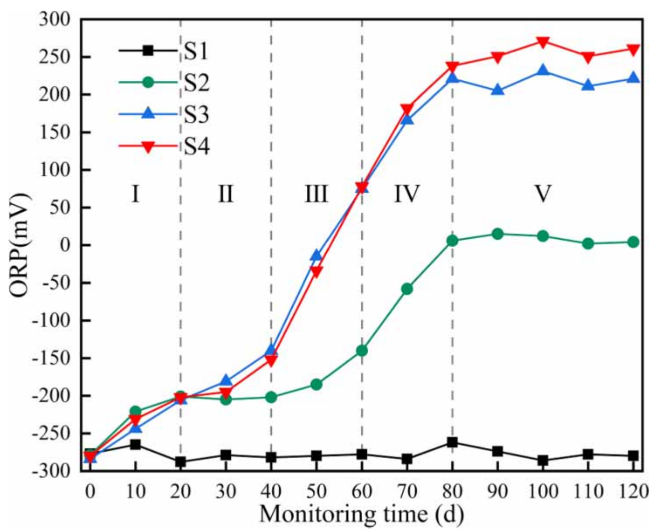


Figure 11 | Changes in ORP at different times.

Table 3 | The effect of different processes on water quality improvement

	Removal rate		Increase rate		
Treatment process	**TP (%)**	**NH_3-N (%)**	**Transparency (%)**	**DO (%)**	**ORP (%)**
Source control and substrate purification	12.77	14.71	10.00	15.25	14.23
Composite artificial floating island	38.30	30.58	30.00	20.34	38.63
Modified biological contact oxidation	28.19	43.08	43.33	55.93	39.74
Water ecosystem reconstruction	6.91	1.97	16.67	8.48	7.40

indicates that the composite AFI efficiently removes pollutants (phosphorus in particular). This is because phosphorus-accumulating bacteria, which always maintain high activity due to continuous aeration, absorb large amounts of phosphorus, and phosphorus in the water body is removed when large quantities of growing and reproducing plants are harvested. The improved BCO process had the greatest improvement on water transparency, DO content, and the ORP, and achieved the highest removal rates of 43.08% for NH_3-N while the removal rate of TP was 28.19%, respectively, indicating that it is beneficial for the purification of black odorous water bodies. The improved BCO process had the highest NH_3-N removal efficiency because intermittent aeration creates alternating anaerobic, anoxic, and aerobic conditions in the water body, and nitrogen elements are transformed into nitrogen for elimination. Moreover, source control improves water quality to an extent and reduces the load on the water body. Finally, the construction of a water ecosystem is important for ensuring water quality and improving the appearance of the environment.

3.3. Final water quality

Construction, aeration, and plant harvesting was performed for four months to stabilize the system. Long-term water quality monitoring was performed within six months of stabilizing the system, with samples taken at 10 d intervals for testing (Table 4). The results show that the effluent met the expected target, eliminated black odor, and met standard V for surface water.

3.4. Treatment cost

The total water surface area of the river is approximately 13,680 m^2. We made a rough assessment of the cost of the system, including engineering and construction, labor, and operation and maintenance costs (Table 5). The construction cost was approximately 26.76 USD/m^2, and the maintenance and management cost was approximately 4.07 USD/(m^2•yr). This provides a reference for the treatment of other black odorous rivers.

Table 4 | Water quality of the effluent

Water quality index	**Transparency (cm)**	**DO (mg/L)**	**NH_3-N (mg/L)**	**TP (mg/L)**	**ORP (mV)**
Expected water quality	>25	>2.0	<2.0	<0.4	>50
Water quality at monitoring site S4	61–68	5.9–6.4	1.21–1.68	0.22–0.34	253–265

Table 5 | Project construction cost breakdown

Items	**Source control and substrate purification**	**Composite artificial floating island**	**Improved biological contact oxidation**	**Water ecosystem reconstruction**	**Maintenance management**
Cost sources	ecological cofferdam ecological dam substrate improver	artificial floating island aeration system microorganisms	pond construction aeration system fillers microorganisms	plants animals microorganisms	labor cost electricity cost
Total cost	115,797.8 USD	128,664.2 USD	38,599.3 USD	51,465.7 USD	55,626.4 USD/yr
Average		26.76 USD/m^2			4.07 USD/(m^2•yr)

Figure 12 | Comparison of the river before, during and after construction (left: before construction; middle: during construction; right: after construction).

4. CONCLUSIONS

In this study, a heavily polluted black odorous river was treated via a composite process in which a composite AFI and improved BCO process were the basis, supplemented by source control, sediment purification, and water ecosystem reconstruction processes. Four months after the project construction and operation, the transparency, DO, NH_3-N, and TP contents, and ORP of the river reached the expected target as well as the standard V for surface water, and the black odor phenomenon was eliminated. The removal rate for NH_3-N and TP reached 90.34% and 86.17% respectively. Figure 12 shows a comparison of the river before, during, and after construction. The composite AFI had the highest phosphorus removal efficiency (38.30%), while the improved BCO had the highest NH_3-N removal efficiency (43.08%). The construction of the system will slightly disturb the river ecosystem, including by altering its biological communities. It will also negatively impact the river hydraulics, including changes in the structure of the river, the impact of the river materials, and energy transport. These issues need to be further studied. The system operation results show that the system is effective and the removal of pollutants is efficient without affecting flooding, thus providing a reference for the treatment of black odorous rivers.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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