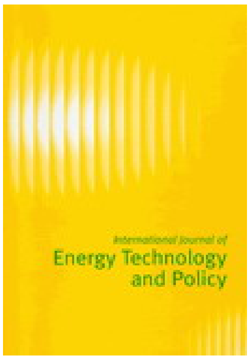

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Construction of urban sewage treatment environment model based on energy and ecological restoration concept

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Abstract: This study aimed to apply a mathematical model of USTS based on the ecological restoration concept to optimise the urban sewage treatment process and improve treatment efficiency and environmental protection level. By analysing the structure and treatment process of USTS, a mathematical model of the sewage treatment system was established. The back propagation (BP) neural networks algorithm was used to train and optimise the model to improve its prediction and control capabilities. The effectiveness and reliability of the model were verified through practical application and validation. The experiment in this article showed that the reliability of the mathematical model of USTS based on ecological restoration concept was between 95%–98%, and the effectiveness of the mathematical model of USTS based on ecological restoration concept was between 93%–97%. The results show that the mathematical model of urban sewage treatment systems incorporating ecological restoration concepts can significantly reduce energy consumption and operating costs.

Keywords: urban sewage treatment; ecological restoration; mathematical models; sustainable utilisation; water quality improvement; back propagation; BP.

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1 Introduction

As urbanisation accelerates and the population grows, urban sewage treatment has become a critical issue for global environmental protection and sustainable development. Urban sewage treatment is the key to protect water resources, preventing environmental pollution and ensuring public health, promoting the recycling of resources, supporting sustainable development, maintaining ecological balance, and healthy urban development. To this end, how to study an efficient, low-cost, and environmentally friendly USTS has been a hot issue in urban environmental protection. New technologies include microbial fuel cells, an amino oxidation, photocatalytic degradation, combining nanomaterials and phosphorus recovery technology to improve efficiency, reduce energy consumption and realise resource recycling. USTS, with the concept of ecological restoration, has high purification efficiency, low operating costs, and ecological protection, making it a sustainable water management model.

There are several issues worth exploring when constructing an environmental model for urban sewage treatment based on the concept of ecological restoration. The actual adaptability of the model is questionable. Although the BP neural network showed high prediction accuracy in simulation experiments, the actual sewage composition is complex and changeable, and there are differences between the simulated wastewater formula and the real sewage, which may affect the reliability of the model in real scenarios. Heavy metals or emerging pollutants in industrial wastewater were not included in the experimental design, and the model's ability to treat these special components has not been verified. Long-term stability data is missing. The study only verified the model effect through short-term experiments, and lacked observations on the long-term operation of the system. Ecological restoration technology relies on the synergy of plants and microorganisms. Seasonal changes and climate fluctuations may affect their activity and thus change the treatment efficiency. If low temperatures in winter inhibit microbial metabolism, or drought causes plants to wither, it is still unknown whether the model can maintain stable performance. The economic analysis is oversimplified. The study listed the costs of different technologies, but did not compare the full life cycle costs of traditional treatment methods. The initial construction cost of the ecological restoration system may be low, but the maintenance costs (such as plant replacement and soil filter layer renovation) have not been quantified. If the comprehensive cost advantage is not significant, the promotion value will be greatly reduced. There are barriers to engineering implementation. The model relies on multi-level ecological pools in series and green infrastructure, but urban space is limited, especially in built-up areas where it is difficult to lay plant ponds or storage pools on a large scale. The study did not propose a specific solution for achieving technology integration in high-density urban areas. These problems expose the disconnect between theory and practice, and the defects need to be remedied through real sewage verification, long-term monitoring and modular design.

This article aimed to construct a mathematical model of USTS based on the concept of ecological restoration to explore the operating mechanism and optimisation plan of the system. This article first reviewed and analysed the concept of ecological restoration, USTS, and related technologies, and further elaborated on the application of ecological restoration concept in urban sewage treatment. This article used a model of USTS based on the coexistence of microorganisms and plants, and constructed and predicted a mathematical model of USTS based on ecological restoration concept using BP neural networks. Next, this article conducted simulation experiments using the model to verify its effectiveness and stability. Through the evaluation of the model, it was found that the system had high processing efficiency and could effectively reduce pollutant concentration, which had broad application prospects. Through simulation verification, the model can significantly improve the efficiency of sewage treatment, reduce the concentration of pollutants, provide efficient and low-cost ecological solutions for urban sewage treatment, and help sustainable water management.

2 Related works

A mathematical model of USTS has been established, which provides a theoretical basis for the design, optimisation, and evaluation of USTS. Zhang et al. (2020) proposed and analysed a mathematical model for microbial treatment of livestock and poultry wastewater. The results indicated that the system had a microbial extinction cycle. When a certain threshold was less than one, the system was globally asymptotically stable. When a certain threshold was greater than one, the system was permanent (Zhang et al., 2020). Guo et al. (2022) proposed an intelligent industrial decision-making system graph embedding-sewage treatment processes (GE-STP) based on graph embedding (GE) for complex sewage treatment processes (STP). He used the GE scheme to enhance feature extraction and used neural computing structures to simulate uncertain biochemical transformations within STP. Introducing GE not only improved the fineness of the feature space, but also enhanced the representativeness of the model for complex industrial processes (Guo et al., 2022). Peng Li established a practical ultraviolet visible spectrum chemical oxygen demand (COD) detection method. The COD estimation model was globally calibrated using wastewater from rural sewage treatment plants (Li et al., 2020). Ozgun (2019) used anaerobic digestion model No. 1 to evaluate the performance of full-scale anaerobic sludge digester. By calibrating the most sensitive parameters used in the anaerobic digestion model No. 1, the model output was very consistent with the measured data obtained from the full-size digester operation (Ozgun, 2019). The above scholars believe that establishing a mathematical model for USTS is of great significance for promoting sustainable development and improving urban living standards and quality of life.

Ecological restoration is aimed at restoring and reconstructing the functions and structures of ecosystems, providing ecological services, protecting the environment, and promoting sustainable development. Aronson et al. (2020) believed that ecological restoration was a direct response to ecosystem degradation and destruction worldwide, and proposed six practical and feasible strategies to enhance the effectiveness of ecological restoration and expand work. Wainwright et al. (2018) believed that community ecology was often used to supplement and guide ecological restoration. The research results emphasised the wide application of deterministic system of community structure in restoration design. Higgs et al. (2018) discussed how the ecological restoration association defines best practices. He believed that principles first methods were more flexible than standards based methods, were in line with the development stage of recovery, and were more effective on a global scale. Perring et al. (2018) believed that ecological restoration became necessary due to the scale of environmental changes caused by the growing global population, as well as the related needs for food, fibre, energy, and water. The above scholars believe that many ecosystems have been damaged due to human activities. A series of measures need to be taken to restore and rebuild the ecosystem.

3 Application of ecological restoration concept in USTS

3.1 Application of plants and soil

Due to the continuous expansion of urban area, the interaction of many factors such as population, economy, politics, environment, culture, and society has brought challenges to the use and management of water resources (Oral et al., 2020). Water scarcity can be addressed by reusing resources from urban wastewater. Fossil energy consumption can be reduced, and global nutritional needs can be satisfied (Kehrein et al., 2020). Viridiplantae is one of the commonly used ecological restoration methods in USTS. By planting plants with strong adaptability and rapid growth, pollutants in USTS are converted into nutrients and energy required for plant growth, thereby achieving the goal of purifying water quality. Meanwhile, viridiplantae can also absorb carbon dioxide in the atmosphere and reduce greenhouse gas emissions. Green plants can absorb nitrogen, phosphorus and other nutrients, organic matter and ammonia nitrogen in urban sewage, degrade pollutants through root adsorption and microorganisms, and promote the self-purification capacity of water bodies.

Aquatic organisms are another common ecological restoration method used in the USTS. Aquatic organisms convert pollutants in USTS into nutrients and energy they need through feeding and adsorption, thereby purifying water quality. Additionally, aquatic organisms can also increase the oxygen content in water and promote the decomposition and chemical reactions of organic matter in water.

Soil filtration is a common ecological remediation method used in the USTS. By passing the water flow in the USTS through appropriate soil layers, pollutants can be removed or converted into harmless substances. Meanwhile, soil filtration can also increase the oxygen content of water and promote the growth of microorganisms in the water. The advantages of soil filtration include low energy consumption depends on natural processes and low maintenance cost, enhanced purification through microbial degradation and adsorption, stable water quality and groundwater replenishment, no chemical additives to avoid secondary pollution; and wide applicability of different sizes.

3.2 Application of ecological restoration concept

Biological infiltration system, biological filter, rain garden and constructed wetland are green infrastructure systems implemented at the ground level to infiltrate water from different sources (Pearlmutter et al., 2020). The application of ecological restoration concept in urban sewage treatment mainly includes: phytoremediation technology: Phytoremediation technology is a technology that uses plants and their roots to absorb, transform and stabilise pollutants. USTS based on the concept of ecological restoration can significantly improve the efficiency of pollutant removal, reduce energy consumption and operation cost, and enhance carbon sink capacity and ecological service function through microbial-plant coordinated degradation, multi-level ecological pool series and green infrastructure integration. In urban sewage treatment, phytoremediation technology can be used to use plants to absorb nutrients and organics in sewage, and degrade pollutants through biodegradation, so as to achieve the purpose of purifying sewage.

- Ecological detention tank technology: ecological detention tank is a technology that utilises the principles of natural ecosystems for sewage treatment. In urban sewage treatment, ecological retention tank technology can be used to introduce sewage into the ecological retention tank. Through sedimentation, biodegradation, and biosorption, pollutants such as organic matter, nitrogen, and phosphorus in the sewage can be removed. At the same time, the plants and microorganisms in the retention tank can also increase the landscape effect.
- Rain garden technology: rain garden is an urban greening facility that collects, purifies and utilises rainwater. In urban sewage treatment, the Rain garden technology can be used to collect sewage and rainwater separately and introduce sewage into the garden for purification and utilisation, so as to reduce the pressure of urban sewage treatment and improve the efficiency of water resources utilisation. Wastewater treatment is an important component of water management in the circular economy model (Flores et al., 2018).
- Green roof technology: green roof is a kind of green facilities built by using roof space, which can provide urban ecosystem services. In urban sewage treatment, green roof technology can be used to green the roof, and absorb rainwater and purify sewage through plants, thereby reducing the pressure of urban sewage treatment and improving the quality of living environment.

3.3 Urban sewage treatment system

The pollutants of urban sewage are relatively simple, mainly to remove COD, nitrogen and some suspended solids (Sun et al., 2019). The USTS based on the concept of ecological restoration is composed of active ponds, plant ponds, and microbial communities.

Active pool is the core part of USTS, which converts organic matter, nitrogen, phosphorus and other pollutants into inorganic matter and microbial biomass through biodegradation. The active pool is mainly composed of microbial communities, particulate matter, and water bodies. The microbial community is the main component of the active pool, including anaerobic and aerobic microorganisms.

Plant ponds are an auxiliary part of USTS, which further reduce the concentration of pollutants through the absorption and degradation of plants. The plant pool is usually composed of aquatic plant and sediments. Aquatic plant can promote the exchange of oxygen and carbon dioxide in the water body and improve the oxidation reduction potential of the water body by absorbing and degrading pollutants.

The microbial community is a key component of the USTS and acts as a catalyst for biochemical reactions in the sewage treatment process. The type and quantity of microbial communities determine the efficiency and stability of sewage treatment. In the active pool, anaerobic microorganisms are mainly responsible for the decomposition of organic matter and nitrogen removal, while aerobic microorganisms are mainly responsible for ammoxidation and nitration. The microbial community in the plant pond is mainly responsible for the removal of organic matter and nitrogen from sediment.

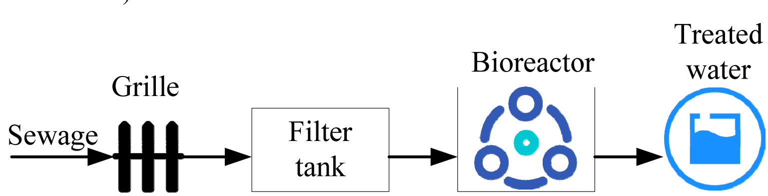
The working principle of an USTS based on the concept of ecological restoration is as follows: Firstly, the sewage enters the active pool and undergoes the action of aerobic and anaerobic microorganisms, gradually transforming organic matter, nitrogen, phosphorus and other pollutants into inorganic matter and microbial biomass. The treated sewage enters the plant pond and further reduces the concentration of pollutants through the absorption and degradation of plants. Finally, after multiple cycles of treatment, the treated water can meet the discharge standards, achieving effective treatment of urban sewage.

3.4 Mathematical model construction of USTS

The mathematical model construction of USTS needs to be divided into several sub-models. The inlet model is the inlet of the USTS, which describes the basic characteristics of inlet flow, water quality, and water temperature. In the inflow model, it is necessary to consider the variation pattern of inflow and its impact on the sewage treatment system, such as seasonal changes in inflow flow rate and fluctuations in inflow water quality.

- Bioreactor model: bioreactors are the core part of USTS, which perform biological treatment on wastewater, converting organic substances in wastewater into biomass and gases required for microbial growth. In the bioreactor model, it is necessary to consider the growth kinetics of microorganisms, the mixing characteristics of the reactor, and the changes in parameters such as dissolved oxygen (DO).
- Sedimentation tank model: sedimentation tanks are equipment used for settling suspended solids in USTS. In the sedimentation tank, suspended solids settle to the bottom, forming a sludge layer. In the sedimentation tank model, factors such as sedimentation rate, depth of sedimentation tank, and sludge concentration need to be considered. Wastewater treatment sludge consists of excess biomass, difficult-to-degrade particulate COD, and mineral particles (Cao et al., 2020).
- Filtration model: the filtration model is the final purification process of USTS, which removes microorganisms and suspended solids from sewage through filtration media. In the filtering model, factors such as the type of filtering medium, filtering speed, and thickness of the filtering medium need to be considered. The filter model predicts the removal effect of microorganisms and suspended solids, improves the filtration efficiency and stability, reduces the operating cost, and provides a quantitative basis for equipment design and process improvement.

Figure 1 Schematic diagram of urban sewage treatment process flow (see online version for colours)



In constructing these sub-models, it is necessary to pay attention to the interaction relationships between the models, such as the influence of factors such as viscosity and sludge concentration between the bioreactor model and the sedimentation tank model. At the same time, it is also necessary to determine the parameters, variables, and solution methods of the model. For example, for a bioreactor model, it is necessary to determine parameters such as microbial growth rate, inhibition factor, DO, and use differential formula methods to solve the model. The schematic diagram of urban sewage treatment process is shown in Figure 1.

3.5 Mathematical model construction of USTS based on ecological restoration concept

Based on the concept of ecological restoration, this paper constructs a mathematical model of USTS, which mainly includes: the pollutant transfer model is the core part of the USTS mathematical model, which is mainly used to simulate the transfer, transformation, and removal process of pollutants in USTS; the ecological restoration model is a crucial part of the USTS mathematical model, which is mainly used to simulate the changes in ecosystem structure and function during the ecological restoration process; the economic evaluation model is another essential part of the USTS mathematical model, which is mainly utilised to assess the economic benefits and costs of USTS.

4 Model design based on BP neural networks

Deep learning models have become a common tool in the fields of science and engineering (Lillicrap et al., 2020; Wright et al., 2022). BP neural network has been applied to train and optimise complex nonlinear models to improve the generalisation ability of sewage treatment models (Taloba, 2022; Wang, et al., 2022). BP neural networks do have strong nonlinear approximation and learning abilities, and can handle complex nonlinear problems and high-dimensional data. Due to its flexibility and wide applicability, BP neural networks are often used as basic network models for modelling and prediction. BP neural network optimises USTS model parameters through nonlinear mapping and back propagation (BP) algorithm to improve the prediction accuracy of pollutant removal; combines the data normalisation and elastic adjustment strategy, enhances the model stability and dynamic control ability to realise efficient adaptive regulation of sewage treatment.

4.1 Forward transmission of information in neural networks

The output of the i^{th} neuron in the hidden layer is as follows:

$$q_i = f_i \sum_{l=1}^{n} w_{il} x_l + p_i (l = 1, 2, ..., n; i = 1, 2, ..., c) \tag{1}$$

The output of the j^{th} neuron in the output layer is as follows:

$$y_j = f_{2j} \sum_{i=1}^{c} w_{2ji} q_i + p_j (j = 1, 2, ..., m) \tag{2}$$

In the formula: q is the output value of the hidden layer; p is the teacher signal.

4.2 Learning algorithm for error backpropagation and weight correction

The transition from the output layer to the hidden layer is as follows:

$$w_2(k+1) = w_2(k) + \Delta w_2(k) = w_2(k) - \mu \frac{\partial E}{\partial w_2} \quad (3)$$

$$p_2(k+1) = p_2(k) + ?\, p_2(k) = p_2(k) - \mu \frac{\partial E}{\partial p_2} \quad (4)$$

From the hidden layer to the input layer, the formulas are as follows:

$$w_1(k+1) = w_1(k) + \Delta w_1(k) = w_1(k) - \mu \frac{\partial E}{\partial w_1} \quad (5)$$

$$p_1(k+1) = p_1(k) + \Delta p_1(k) = p_1(k) - \mu \frac{\partial E}{\partial p_1} \quad (6)$$

In the formula, μ is the learning rate.

However, due to the use of an *s* (sigmoid) type excitation function, when the input is large, the slope of the excitation function is almost zero, resulting in a small gradient amplitude in the reverse genetic algorithm and possibly causing the weighted correction work to pause. To this end, the following steps were taken:

1 The input data of the sub network is normalised and the formula is as follows:

$$q_n = 2 * (q - \min q) / (\max q - \min q) - 1 \quad (7)$$

The denormalisation of output data is as follows:

$$q = 0.5\left(q_{n+1}\right) * (\max q - \min q) + \min q \quad (8)$$

Among them, q_n represents the normalised data.

2 Adopting elastic BP algorithm: the update value *A* is taken to be equal to the first correction weight of $\Delta w_1(k)$. When $k \geq 2$, $\Delta w(k)$ is as follows:

$$\Delta w = \mu \cdot sign \frac{\partial E}{\partial w} \cdot A \cdot \alpha,\ sign \frac{\partial E}{\partial w}(k+1) = sign \frac{\partial E}{\partial w}(k) \quad (9)$$

$$\Delta w = \mu \cdot sign \frac{\partial E}{\partial w} \cdot A \cdot \beta,\ sign \frac{\partial E}{\partial w}(k+1) \neq sign \frac{\partial E}{\partial w}(k) \quad (10)$$

In the formula, α and β are adjustment coefficients, usually taken as $1.1 < \alpha < 1.5$ and $0.3 < \beta < 0.7$. The specific values of α and β are determined by experiments.

From the formulas, it can be seen that as the network training oscillates, the amount of weight change gradually decreases. As all weights change, the amount of weight change gradually increases, which greatly improves the learning convergence of the network.

4.3 Application of BP neural network in ecological restoration efficiency evaluation

In the ecological restoration wastewater treatment system, the core role of BP neural networks lies in quantifying the nonlinear relationship between ecological factors and pollutant removal efficiency. Traditional mathematical models struggle to accurately depict the dynamic process of microbial-plant synergy, whereas neural networks, through data-driven approaches, can adaptively learn the complex coupling mechanisms among various factors in ecological restoration.

The input layer of the model contains two types of key parameters:

- Ecological parameters: plant root density, microbial community abundance, DO, soil permeability coefficient
- Pollution load parameters: influent COD, TN, TP, NH_4^+–N concentration.

Through normalisation, parameters with different dimensions are mapped to the interval [–1, 1], so as to avoid the problem of gradient disappearance during weight update.

The hidden layer simulates the threshold effect of ecological restoration through the Sigmoid activation function. For example, when DO falls below the critical value, microbial activity drops sharply, leading to a nonlinear decline in COD removal rate (RR). The network automatically captures this mutation feature during training, and its output can be expressed as:

$$h_j = f\left(\sum_{i=1}^{n} w_{ij}x_i + b_j\right) \tag{11}$$

w_{ij} is the weight from the input layer to the hidden layer, and b_j is the bias term.

The output layer is directly related to the processing efficiency index and dynamically adjusts the weight through BP. If the TN removal error is large in a prediction, the network will prioritise the correction of the weight related to the plant absorption root density and nitrifying bacterial activity, so as to strengthen the contribution of ecological factors.

The trained model can be embedded into the real-time control system: when the sensor detects that the TP of water intake exceeds the standard, the model automatically increases the hydraulic retention time of the plant pond or adjusts the amount of microbial addition to achieve dynamic optimisation. This feedback mechanism makes up for the defect of delayed response of traditional ecological restoration system.

5 Experimental design and evaluation of mathematical models for USTS

- Experimental purpose: the purpose is to construct a mathematical model of USTS based on the concept of ecological restoration, and analyse the purification effect of the system on water quality.
- Experimental material: simulated sewage: simulated urban sewage using an aqueous solution of mixed organic and inorganic substances. The simulated wastewater formula is shown in Table 1.
- Experimental methods: three methods are used for sewage treatment in this paper: activated sludge: activated sludge is a common biological treatment method, which converts organic matter into harmless substances through microbial metabolism. This method mainly includes process steps such as aeration tank, secondary sedimentation tank, and sludge reflux, which can efficiently remove organic matter and nutrient elements such as nitrogen and phosphorus in wastewater.
- Membrane separation technology: membrane separation technology is a physical and chemical treatment method that separates pollutants from water in wastewater through the special structure of the membrane. This method can efficiently remove suspended solids, colloids, microorganisms, etc. from wastewater, while also

achieving functions such as desalination and concentration. Common membrane separation technologies include microfiltration, ultrafiltration, reverse osmosis, etc.

- Oxidation method: oxidation method is an advanced treatment method that uses oxidants to oxidise and decompose organic matter and micro pollutants in wastewater into harmless substances. Common oxidation methods include ozone oxidation, hydrogen peroxide oxidation, ultraviolet oxidation, etc. This method can remove difficult to degrade organic matter, micro pollutants, and microorganisms, and has high treatment efficiency and purification ability.
- Experimental design: the control group adopts the traditional mathematical model of USTS, while the experimental group adopts the mathematical model of USTS with ecological restoration concept (the model in this article). The article used two models to treat urban sewage and analysed the treatment results.
- Experimental cost: the experimental cost price can be used to evaluate the cost of these technologies and equipment to determine the economy and practicality of the experiment. At the same time, the experimental cost price can also be used to plan and manage the experimental budget, avoiding excessive waste of resources and funds. In scientific research projects or enterprise research and development, evaluating the cost of experiments is also an important basis for approval and decision-making. The results are shown in Table 2.

Table 1 Simulated wastewater formula

Medium composition	*Dosage (per L)*
Soluble starch	0.1g
Urea	0.1g
$(NH_4)_2SO_4$	0.06g
$K_2HPO_4{\cdot}2H_2O$	0.04g
$MgSO_4{\cdot}7H_20$	0.07g
$NaHCO_3$	0.3g
Tap water	2000mL

Table 2 Cost prices

Experimental method	*Amount spent (Yuan)*
Activated sludge method	3,697
Membrane separation technology	9,674
Oxidation method	5,682

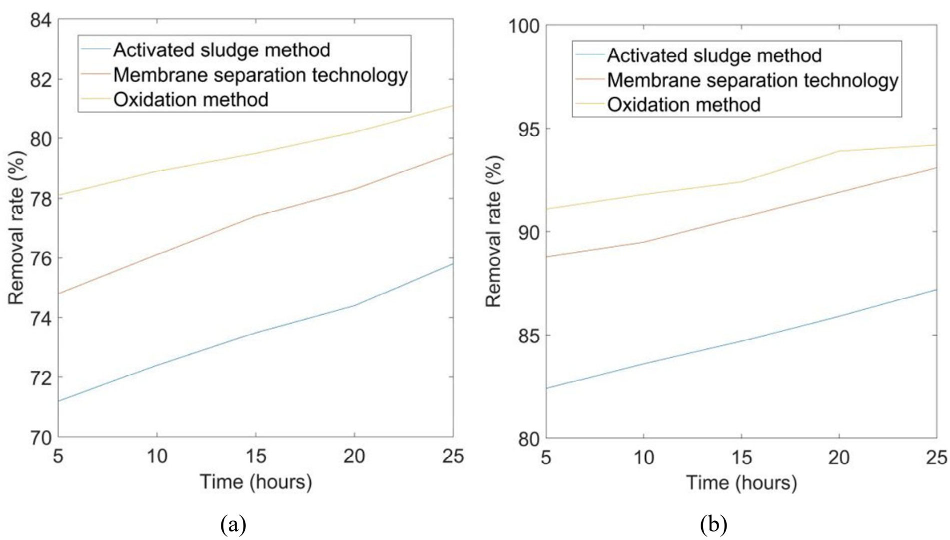
5.1 Pollutant removal rate

5.1.1 Chromium reducing (CODcr) removal effect

CODcr is COD. Wherein, cr refers to the chemical oxygen demand of chromium reducing. CODcr is the determination method of COD, which is used to determine the content of organic matter in water. The removal effect of CODcr refers to the use of various methods to reduce the concentration of CODcr in wastewater treatment. Common

CODcr removal methods include biological treatment, chemical treatment, and physical treatment. The specific removal effect depends on factors such as the nature of the wastewater, treatment methods, and the performance of the treatment equipment. Generally speaking, biological treatment can effectively remove CODcr, but it requires a longer treatment time and stable environmental conditions; chemical treatment can quickly remove CODcr, but the generated chemical byproducts may have an impact on the environment; physical treatment mainly involves the removal of CODcr through physical processes such as adsorption, precipitation, and filtration. After considering various factors comprehensively, suitable treatment methods can be selected to achieve the expected CODcr removal effect. Figure 2 shows the experimental results.

Figure 2 CODcr removal rate (a) control group (b) experimental group (see online version for colours)



In Figure 2(a), the RR of CODcr by activated sludge in the control group was 75.8% after 25 hours; the RR of CODcr by membrane separation technology was 79.5% after 25 hours; the RR of CODcr by the oxidation method was 81.1% after 25 hours. In Figure 2(b), the RR of CODcr by activated sludge in the experimental group was 87.2% after 25 hours; the RR of CODcr by membrane separation technology was 93.1% after 25 hours; the RR of CODcr by the oxidation method was 94.2% after 25 hours. In Figure 2, the CODcr removal efficiency of the experimental group was higher than that of the control group.

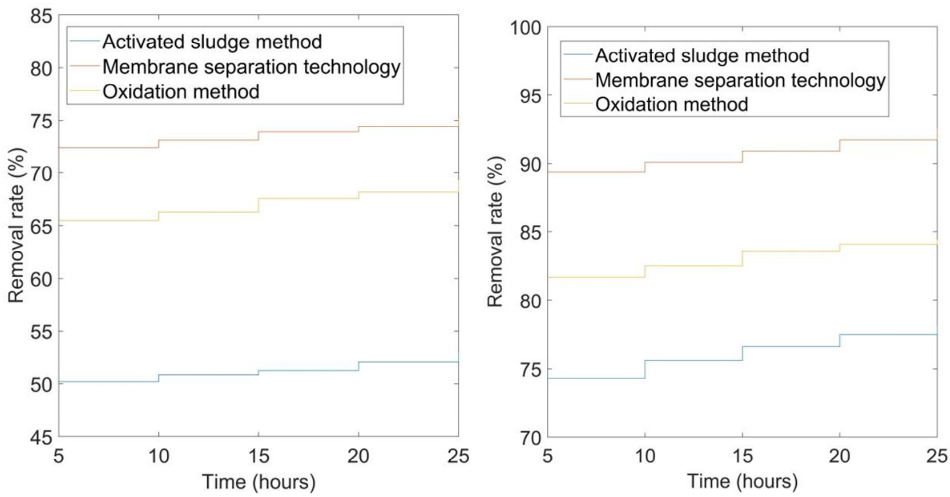
5.1.2 Total nitrogen removal effect

TN refers to the measured value of total nitrogen and is an important indicator of nitrogen pollution in water bodies. The TN removal effect refers to the reduction of TN concentration through various methods when treating wastewater. Figure 3 shows the experimental results.

In Figure 3(a), the RR of TN by activated sludge in the control group was 53% after 25 hours; the RR of TN by membrane separation technology was 75.2% after 25 hours;

the RR of TN by the oxidation method was 69.3% after 25 hours. In Figure 3(b), the RR of TN by activated sludge in experimental group was 78.2% after 25 hours; the RR of TN by membrane separation technology was 92.6% after 25 hours; the RR of TN by the oxidation method was 84.4% after 25 hours. In Figure 3, the TN removal effect of the experimental group was higher than that of the control group.

Figure 3 TN removal rate (a) control group (b) experimental group (see online version for colours)



(a) (b)

5.1.3 Total phosphorus removal effect

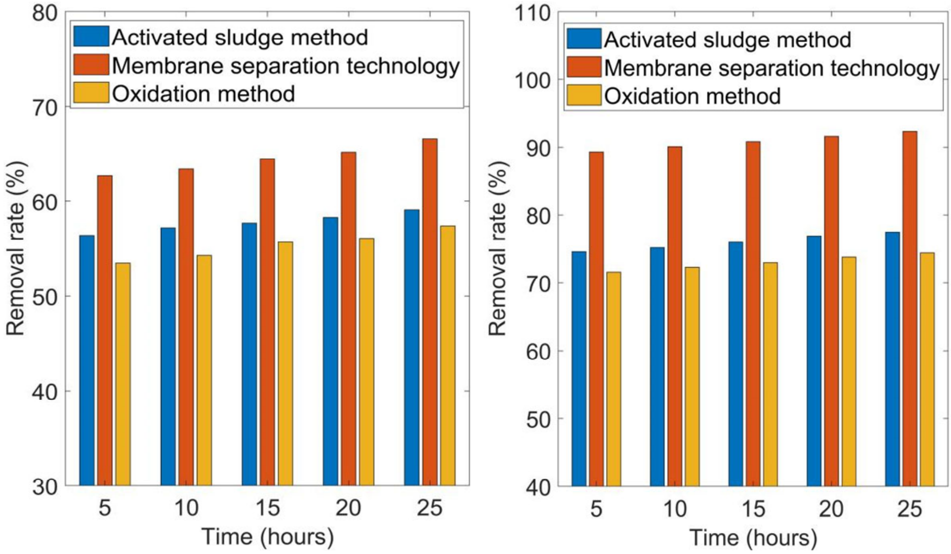
TP refers to the measured value of total phosphorus and is an important indicator of phosphorus pollution in water bodies. TP removal effect refers to the reduction of TP concentration through various methods when treating wastewater. Figure 4 shows the experimental results.

In Figure 4(a), the RR of TP by activated sludge in the control group was 59.1% after 25 hours; the RR of TP by membrane separation technology was 66.6% after 25 hours; the RR of TP by the oxidation method was 57.4% after 25 hours. In Figure 4(b), the RR of TP by activated sludge in the experimental group was 77.5% after 25 hours; the RR of TP by membrane separation technology was 92.3% after 25 hours; the RR of TP by the oxidation method was 74.4% after 25 hours. In Figure 4, the TP removal effect of the experimental group was higher than that of the control group.

5.1.4 NH4+-N removal effect

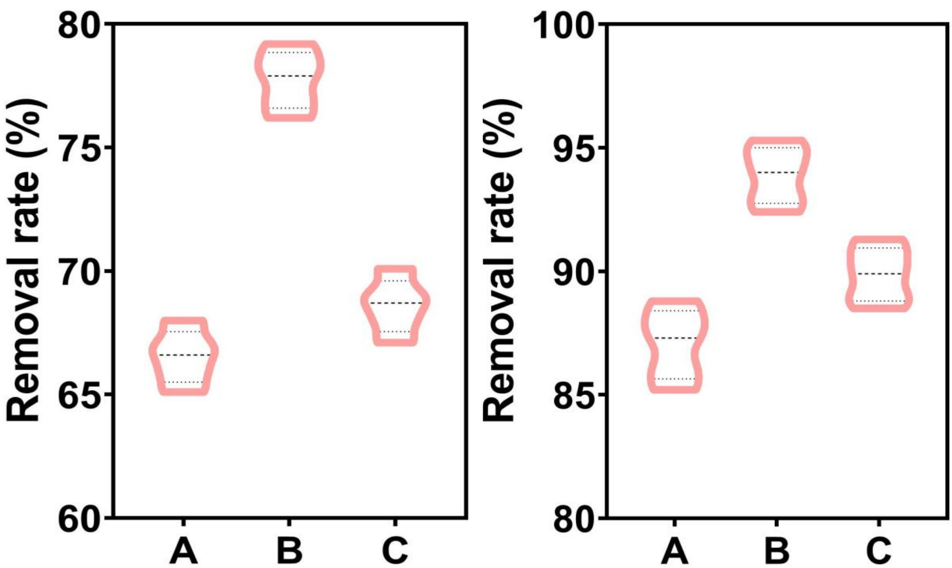
$NH4^{+}$–N is the measured value of ammonia nitrogen and an important indicator of ammonia nitrogen pollution in water bodies. The $NH4^{+}$–N removal effect refers to the reduction of ammonia nitrogen concentration through various methods when treating wastewater. This article records the $NH4^{+}$–N removal effects for 5, 10, 15, 20, and 25 hours, and Figure 5 shows the experimental results. Among them, A is the activated sludge; B is the membrane separation technology; C is the oxidation method.

Figure 4 TP removal rate (a) control group (b) experimental group (see online version for colours)



(a) (b)

Figure 5 NH4+–N removal rate (a) control group (b) experimental group (see online version for colours)



(a) (b)

In Figure 5(a), the RR of NH4^{+}–N by activated sludge in the control group was 68% after 25 hours; the RR of NH4^{+}–N by membrane separation technology was 79.2% after 25 hours; the RR of NH4^{+}–N by the oxidation method was 70.1% after 25 hours. In

Figure 5(b), the RR of $NH4^{+}$_N by activated sludge in the experimental group was 88.8% after 25 hours; the RR of $NH4^{+}$_N by membrane separation technology was 95.3% after 25 hours; the RR of $NH4^{+}$_N by the oxidation method was 91.3% after 25 hours. In Figure 5, the $NH4^{+}$_N removal effect of the experimental group was higher than that of the control group.

5.2 Reliability and effectiveness testing

Reliability and effectiveness are two key indicators for urban sewage treatment, which ensure the treatment process's stability and removal efficiency, thereby achieving the safety of effluent quality, maximising resource utilisation, and reducing operating costs. They are of great significance for urban environmental protection and sustainable development. To verify the reliability and effectiveness of the model, multiple experiments were conducted and Figure 6 shows the test results.

In Figure 6, the reliability of the mathematical model of the USTS based on the ecological restoration concept was between 95%–98%, and the effectiveness of the mathematical model of the USTS based on the ecological restoration concept was between 93%–97%.

6 Conclusions

The USTS based on ecological restoration has many advantages, including high treatment efficiency, low cost, and environmental friendliness. This article established a mathematical model of USTS based on ecological restoration, and verified the effectiveness and stability of the model through simulation experiments. Through the evaluation of the model, it was found that the system had high processing efficiency and could effectively reduce pollutant concentration, which had broad application prospects. The research results of this article provided new ideas and methods for the field of urban sewage treatment, and provided reference for the treatment and management of urban sewage. This paper does not verify the stability of the model in the long-term operation of real sewage, and the economic analysis lacks horizontal comparison, does not explore the impact of complex environmental variables (such as temperature, flow fluctuations) on the system, the feasibility of practical engineering integration also needs further study. In the future, the stability of the model in the long-term operation of actual sewage can be further verified, and the influence of complex environmental variables on system performance can be explored. In addition, economic analysis and engineering practice should be combined to promote the large-scale application, optimisation and upgrading of the model in urban sewage treatment.

Declarations

The author declares that there are no conflicts of interest regarding the publication of this article.

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