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Research on the Mechanism and Resource Utilization Advantages of Soil Infiltration Systems for Wastewater Treatment

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Abstract

Soil infiltration system is a low-cost and high-efficiency decentralized wastewater treatment technology based on soil-microorganism-plant complex ecological effects. It can effectively remove pollutants such as organic matter (COD), suspended solids (SS), nitrogen, phosphorus and pathogenic microorganisms in wastewater mainly through synergistic mechanisms such as physical filtration, chemical adsorption and biodegradation. The system includes slow infiltration, rapid infiltration, surface overflow and underground infiltration. It can be flexibly applied to many fields such as rural domestic sewage, farmland irrigation and reuse, and some industrial wastewater treatment. Although there are still some limitations in nitrogen removal efficiency and soil clogging prevention and control, the soil infiltration system shows a good prospect of popularization and application through matrix improvement, process optimization and ecological coupling, especially in resource reuse and ecological management.

Keywords

Wastewater Treatment , Soil Infiltration Technology, Resource utilization.

1. Introduction

Soil infiltration system treatment technology is a method that utilizes soil as a filtering medium to treat wastewater. It is a low-cost, high-efficiency wastewater treatment approach widely applied in fields such as agricultural irrigation and industrial wastewater treatment.

Currently, as a wastewater treatment technology, soil infiltration systems have been extensively adopted in various domains both domestically and internationally. In agricultural irrigation, the system can convert nutrients and organic matter in wastewater into plant-absorbable fertilizers, thereby providing certain fertilizing effects. Simultaneously, leveraging the adsorption and sedimentation capabilities of soil, the system can effectively remove harmful substances such as heavy metals from wastewater. In industrial wastewater treatment, soil infiltration systems also demonstrate strong removal efficiency for pollutants like organic matter, microorganisms, and heavy metals. Compared to other traditional wastewater treatment processes, this technology offers advantages such as simple operation, low operational costs, and high treatment efficiency.

In theoretical research, VANCUYK et al. [1] indicated that the optimal thickness range of the soil layer in soil infiltration systems is between 0.60 and 1.20 m. QUANRUD et al. [2] further confirmed that when the soil thickness reaches 1.0 m, the system can effectively remove poliovirus and coliphages. In terms of engineering applications, studies by DREWES et al. [3] showed that soil infiltration technology is suitable for advanced wastewater treatment, not only effectively removing organic matter from tertiary effluent but also altering its composition characteristics. ORON [4] demonstrated that soil infiltration effectively removes pathogenic microorganisms such as pathogens from municipal secondary effluent and wastewater, making the treated effluent directly usable for agricultural irrigation. Additionally, experiments by RICE et al. [5] on pretreated domestic wastewater revealed that the technology exhibits high removal

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efficiency for pollutants such as ammonia nitrogen and organic matter. LANCE et al. [6] proposed that adding organic carbon sources to the soil can further enhance the system's nitrogen removal capacity.

Soil infiltration systems have been widely applied in rural wastewater treatment in China, incorporating numerous technological innovations. For instance, in Liaoning Province, the Department of Ecology and Environment has held specialized meetings to promote this technology and plans to develop relevant technical guidelines to facilitate the localized and agricultural reuse of rural domestic wastewater through decentralized soil infiltration technology. To address technical challenges such as system clogging and poor reoxygenation effects, researchers continue to optimize the system. For example, studies by China University of Geosciences have shown that adjusting the sand mixing ratio of North China brown soil and mineral fillers (such as quartz sand, volcanic rock, and zeolite) can alter the system's porosity and oxygen environment, thereby optimizing the nitrification and denitrification processes and improving nitrogen removal efficiency. The expert team on rural construction and governance from the Chinese Academy of Agricultural Sciences implemented a demonstration project in Shenyang titled "Improved Septic Tank + Anti-Clogging Soil Infiltration" for rural wastewater treatment. This technology utilizes frost-proof septic tanks and shallow-buried soil infiltration systems to achieve simultaneous treatment of black and gray water and agricultural reuse. It is reported that the construction cost can be reduced by 30%-40%, and the system operates without external power, with an annual operational cost of less than 50 RMB per household, providing an efficient solution for high-cold regions like Northeast China. Soil infiltration systems are often integrated as part of collaborative rural living environment governance technologies. For example, in a demonstration in Xianfeng County, Hubei Province, the system was showcased alongside other technologies such as power-free wastewater treatment and automated wastewater irrigation reuse, reflecting a comprehensive governance model. This indicates that the system not only treats wastewater but also emphasizes the safe resource utilization of treated effluent, such as irrigation reuse, aligning with rural needs.

2. Introduction to Soil Infiltration System Treatment Technology

2.1. Concept of Soil Infiltration System

Soil infiltration system is an underground sewage treatment technology that uses soil matrix as a natural filtration and purification medium. It is usually used as the terminal link of sewage treatment, which is suitable for decentralized or small centralized sewage treatment scenarios.

The basic principle of the system is to control the pre-treated sewage (such as sewage after septic tank or primary precipitation) to a certain structure, filled with specific matrix (such as soil, sand, artificial improvement materials, etc.) in the infiltration ditch or infiltration tank. Sewage flows through the soil matrix layer from top to bottom under the action of gravity, and is purified through a series of complex physical, chemical and biological processes.

Its core purification mechanisms include :

Physical filtration : Pores between soil particles can intercept and adsorb suspended solids (SS), colloidal substances and some pathogenic microorganisms in water.

Chemical adsorption and reaction : The surface of soil particles is negatively charged, which can remove pollutants such as ammonium ions (NH_4^+) and heavy metals in water through ion exchange and specific adsorption. Some minerals can also react with pollutants by chemical precipitation.

Biodegradation : Abundant aerobic microbial communities (bacteria, fungi, protozoa, etc.) grow in the leachate layer, especially in the surface soil. They decompose organic pollutants in sewage as carbon and energy sources, and convert them into carbon dioxide, water and

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microbial biomass, which is the main way to remove organic matter (measured by BOD and COD).

Nitrification / denitrification : At different depths of the soil infiltration layer, an aerobic and anoxic microenvironment is formed. In the upper aerobic zone, nitrifying bacteria convert ammonia nitrogen (NH_3-N) into nitrate nitrogen (NO_3-N) ; in the subsequent anoxic zone, denitrifying bacteria reduce nitrate nitrogen to nitrogen (N_2) and release it into the atmosphere, thereby achieving effective removal of nitrogen. Studies have shown that the addition of organic carbon sources (such as straw and sawdust) can provide electron donors for the denitrification process and significantly improve the nitrogen removal efficiency of the system.

Due to its high efficiency, stability, low energy consumption and good ecological compatibility, soil infiltration system is widely used in the advanced treatment and reuse of domestic sewage, municipal secondary effluent and similar sewage. It is an important technical means to realize the recycling of water resources and environmental protection.

2.2. Mechanism of Soil Infiltration System

2.2.1. Nitrogen removal by soil infiltration system

The overall removal efficiency of nitrogen by soil infiltration system is often lower than that of other pollutants. The removal pathways mainly include ammonia volatilization, soil adsorption, plant absorption, and microbial-driven nitrification and denitrification, among which the microbial process is the most critical. Organic nitrogen and ammonia nitrogen are the main forms of nitrogen in domestic sewage, and the proportion of ammonia nitrogen is usually 75 % -85 %. When the sewage enters the system, the organic nitrogen is first intercepted or precipitated by the substrate, and converted into ammonia nitrogen under the action of microorganisms, and only a small part is assimilated and utilized by microorganisms or plants. Since the soil colloid is generally negatively charged, the positively charged ammonia nitrogen ions are easily adsorbed and fixed, and then the nitrification reaction occurs under the action of nitrifying bacteria, which is gradually oxidized to nitrate (NO_3^-). With the progress of nitrification, the ammonia nitrogen adsorbed by soil colloidal particles gradually decreased, and the adsorption of ammonia nitrogen by soil colloidal particles was in an unsaturated state, so the soil colloidal particles continued to maintain the adsorption of ammonia nitrogen. Since the soil colloidal particles cannot adsorb NO_3^-, NO_3^- continues to migrate downward, and some of it is absorbed by the plant roots to become the nutrients required by the plant, while the other part undergoes denitrification reaction under the action of microbial denitrifying bacteria, generating N_2 or N_2O and then volatilizing [7].

2.2.2. Phosphorus Removal by Soil Infiltration System

The removal of phosphorus in soil infiltration systems is a complex process primarily based on physicochemical mechanisms. Its core mechanisms include adsorption, precipitation, and filtration, which distinguish it significantly from the biologically dependent processes involved in the removal of nitrogen and organic matter. Phosphorus removal is highly efficient and stable, making it one of the most thoroughly eliminated pollutants in such systems.

The following elaborates on the detailed mechanisms and processes:

Metal cations such as iron (Fe), aluminum (Al), and calcium (Ca) in the soil play a critical role in phosphorus removal. They react with phosphate ions (PO_4^{3-}) in wastewater to form insoluble precipitates, thereby immobilizing phosphorus within the soil matrix [8]. Specifically, oxides and hydroxides of iron (Fe^{3+}) and aluminum (Al^{3+}) act as potent phosphorus adsorbents. Through ligand exchange, they form stable complexes with phosphate (e.g., $FePO_4$, $AlPO_4$). Calcium ions (Ca^{2+}) react with phosphate to generate hydroxyapatite [$Ca_5(PO_4)_3OH$] or other forms of calcium phosphate precipitates, a process particularly prominent in lime-rich soils.

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Clay minerals (e.g., montmorillonite, kaolinite) in the soil, with their positively charged surfaces, facilitate the immobilization of phosphate ions through ion exchange or specific adsorption. The fine pores between soil particles mechanically intercept and filter particulate phosphorus from wastewater. Over time, this retained particulate phosphorus decomposes and participates in the aforementioned chemical adsorption and precipitation processes.

Additionally, microorganisms (bacteria, fungi) and plant roots in the soil absorb a portion of inorganic phosphorus from the water during growth and reproduction, incorporating it into their biomass (e.g., ATP, nucleic acids, cell membranes). However, this pathway accounts for a relatively small proportion of phosphorus removal. Moreover, when these organisms die and decompose, the phosphorus may be released back into the environment, making this a non-permanent removal mechanism.

2.2.3. Removal of COD by Soil Infiltration Systems

COD (Chemical Oxygen Demand) is an indicator of the degree of contamination by reducible substances in water, primarily consisting of organic carbon, and is commonly used as a measure of organic matter content. COD can generally be classified into soluble COD and insoluble COD. The removal of COD in soil infiltration systems is achieved through the synergistic effects of physical filtration, adsorption, and biodegradation. Soil particles and biofilms within the system first intercept and adsorb suspended and colloidal organic matter through physical filtration and adsorption. Subsequently, aerobic, facultative, and anaerobic microbial communities distributed at different soil depths thoroughly biodegrade the adsorbed organic matter, ultimately breaking it down into CO_2 and H_2O, thereby achieving efficient and stable COD removal. The system's performance is influenced by factors such as soil matrix characteristics, hydraulic loading, dissolved oxygen conditions, and temperature.

2.2.4. Removal of Suspended Solids (SS) by Soil Infiltration Systems

The removal of suspended solids (SS) is one of the most direct and efficient functions of soil infiltration systems, primarily accomplished through physical-mechanical actions, with typically very high removal rates. The core removal mechanisms are filtration and interception: as wastewater flows through the complex pores between soil particles, suspended solids significantly larger than the pore sizes are directly intercepted, while finer particles are immobilized on soil particle surfaces or biofilms via adsorption. This process primarily occurs in the surface soil layer, effectively preventing clogging of deeper pores and ensuring the system's continuous and stable operation. Thus, SS removal is a prerequisite for the effective purification of other pollutants, such as COD, nitrogen, and phosphorus.

2.2.5. Removal of Pathogenic Microorganisms by Soil Infiltration Systems

Soil infiltration systems demonstrate significant effectiveness in removing pathogenic microorganisms (e.g., bacteria, viruses, parasite eggs) through a combination of synergistic mechanisms, including:

Physical Filtration and Interception: Microscopic pores between soil particles mechanically intercept larger microorganisms such as parasite eggs and bacterial clusters.

Adsorption: Smaller pathogens like viruses, which may not be filtered directly, are adsorbed onto soil particle surfaces via van der Waals forces, electrostatic attraction, and other interactions, thereby being immobilized and separated from the water.

Natural Die-Off and Predation: The complex ecosystem within the infiltration layer plays a key role. Once pathogens are intercepted or adsorbed, they gradually die due to the soil environment (e.g., nutrient deficiency, temperature fluctuations). Simultaneously, protozoa, bacteriophages, and other microorganisms in the soil prey on and decompose them as a food source.

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Environmental Stress: The aerobic conditions in the surface soil layer and antimicrobial substances produced by certain microorganisms also inhibit and kill pathogens.

Thus, through a multi-barrier approach of "filtration-adsorption-natural die-off," soil infiltration systems efficiently and consistently remove pathogenic microorganisms, ensuring effluent safety. This is a critical basis for their direct reuse in agricultural irrigation.

3. Types of Soil Infiltration Systems

3.1. Slow Rate Infiltration Systems

Slow rate infiltration systems are among the most fundamental and efficient forms of land treatment technologies. Their core principle lies in combining wastewater purification with agricultural irrigation through very low hydraulic loading and extended retention times. This system not only treats soil as a filtering medium but also considers crops as key components, aiming to simultaneously achieve three goals: water resource recovery, nutrient utilization, and pollutant removal.

The system relies on the comprehensive purification mechanisms of the soil-plant ecosystem: soil particles remove suspended solids and partial pollutants through physical filtration and adsorption; microbial communities in the soil degrade organic pollutants and facilitate nitrification and denitrification; meanwhile, crop roots effectively absorb nutrients such as nitrogen and phosphorus, along with water, promoting growth, further purifying water quality, and reducing effluent through transpiration.

Due to its low loading, high efficiency, and resource recovery characteristics, slow rate infiltration systems are particularly suitable for rural or suburban areas with available land resources. They not only consistently meet high effluent standards but also significantly reduce operational energy consumption, integrating environmental benefits with agricultural production. This makes them a sustainable model for decentralized wastewater treatment and reuse.

3.2. Rapid Infiltration Systems

Rapid infiltration systems are highly efficient land treatment technologies characterized by high hydraulic loading, allowing pre-treated wastewater to quickly percolate through highly permeable soil media. These systems primarily rely on the physicochemical actions of soil particles and complex subsurface biochemical reactions of microorganisms to remove pollutants. Their design focuses on rapid water infiltration and efficient pollutant degradation rather than agricultural reuse.

The purification process mainly occurs in the vadose zone of the infiltration basin: the alternating wet and dry conditions created by periodic flooding and draining provide an ideal environment for the metabolic activities of aerobic and anaerobic microorganisms. Organic pollutants are aerobically decomposed, nitrogenous pollutants are removed through nitrification and denitrification, while phosphorus and metal ions are immobilized primarily via adsorption and precipitation by soil particles.

Due to their high treatment efficiency and relatively small land footprint, rapid infiltration systems are particularly suitable for scenarios such as groundwater recharge and advanced treatment of wastewater treatment plant effluent. The key to their operation lies in selecting highly permeable sandy soils and implementing strict flooding-drying cycle management to ensure soil permeability and long-term operational stability while achieving wastewater regeneration.

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3.3. Overland Flow Systems

Overland flow treatment involves the controlled application of wastewater to land surfaces with low soil permeability, gentle slopes, and vegetation such as grasses or selected crops [9]. As the wastewater flows downhill in a thin layer, it undergoes continuous purification, and the treated effluent is collected as surface runoff for reuse or discharge [10]. Sites for overland flow systems require soils with low permeability, such as clay or loam, or land with a semi-permeable layer at a depth of 0.3–0.6 m. The optimal natural slope ranges from i=0.02 to 0.08, and ideally, the slope should be artificially constructed to be uniform and gentle.

3.4. Subsurface Infiltration Systems

Subsurface infiltration systems involve the controlled distribution of pre-treated wastewater (e.g., from septic tanks or acidification hydrolysis tanks) into well-permeable layers about 0.5 m below the ground surface. Through capillary action and soil permeability, the wastewater diffuses laterally and is purified via filtration, sedimentation, adsorption, and microbial degradation. Subsurface infiltration systems are suitable for treating small volumes of wastewater in areas without access to urban drainage networks, such as dispersed residential areas, resorts, and sanatoriums. Pre-treatment via septic tanks or acidification hydrolysis tanks is required before wastewater enters the system.

The water distribution system of subsurface infiltration systems is buried underground, minimizing visual impact on the landscape. They are suitable for small-scale wastewater treatment in decentralized residential areas, resorts, and sanatoriums, and can be integrated with greening and ecological environment construction. Operation and management are simple, with low loading and high-quality effluent suitable for reuse. However, these systems are highly influenced by site and soil conditions. Improper load control can lead to soil clogging, and the construction volume for buried inlet and outlet facilities is relatively large, resulting in higher costs compared to other land treatment types. Pre-treatment via septic tanks or acidification (hydrolysis) tanks is necessary to remove most SS and prevent soil clogging.

4. Conclusion

This article primarily introduces the principles of soil infiltration technology and its classification into four types: slow rate infiltration systems, rapid infiltration systems, overland flow systems, and subsurface infiltration systems.

The application of soil infiltration treatment technology offers numerous benefits. Firstly, it reduces environmental pollution and protects the quality of soil and water resources. Secondly, it effectively addresses wastewater treatment issues, lowering the high costs and energy consumption associated with traditional methods. Additionally, soil infiltration technology can enhance farmland fertility, promoting crop growth and yield.

However, it is important to recognize the limitations and challenges of soil infiltration technology in practical applications. For example, the treatment capacity of soil infiltration systems is constrained by soil type and permeability, necessitating evaluation and optimization based on actual conditions. Furthermore, regular monitoring and maintenance are essential to sustain system efficiency.

Overall, soil infiltration treatment technology holds significant potential as a sustainable wastewater treatment method. Through continuous research and innovation, this technology can be further refined and applied in broader fields, contributing to environmental sustainability and resource recycling..

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