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Research on current situation of farmland runoff pollution and ecological treatment technology

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Abstract. Farmland runoff pollution, caused by excessive use of fertilizers and pesticides, poses serious threats to water quality and aquatic ecosystems. To address this issue, various ecological treatment technologies have been developed and applied, such as vegetated ditches, constructed wetlands, and bioaugmentation techniques. These systems aim to reduce nutrient and pesticide concentrations in runoff water and enhance soil quality and biodiversity. This study reviews the current state of farmland runoff pollution and the existing ecological treatment methods. It also presents the results of our comparative analysis of the performance and efficiency of different treatment systems across multiple study sites with diverse climatic conditions. We demonstrate that ecological treatment technologies can effectively remove pollutants from runoff water and improve soil properties and microbial activity. We also discuss the implications and challenges of applying these technologies for agricultural sustainability and environmental protection.

1 Introduction

Agricultural runoff pollution, caused by excessive use of fertilizers and pesticides, poses serious threats to water quality and aquatic ecosystems [1]. Runoff from agricultural lands can carry various pollutants, such as nutrients, pesticides, and sediments, into water bodies [2]. These pollutants can cause serious ecological problems, such as eutrophication, hypoxia, toxicity, and turbidity, affecting the health and diversity of aquatic life [3]. According to a report by the Food and Agriculture Organization of the United Nations, agricultural runoff is the main source of nutrient input to the global coastal zone, accounting for 38% of nitrogen and 26% of phosphorus [4]. In China, agricultural runoff is estimated to be responsible for 52% and 54% of the total loading of nitrogen and phosphorus, respectively, in Taihu Lake Basin [5]. Likewise, in the USA, agricultural runoff is considered the dominant source of nutrients in lakes and streams [6].

To address this issue, various ecological engineering approaches have been developed and applied, such as vegetated ditches, constructed wetlands, artificial floating islands, vegetation filter belts, and riparian buffer vegetation [7]. These systems aim to reduce nutrient and pesticide concentrations in runoff water and enhance soil quality and biodiversity [8]. However, the performance and efficiency of these systems vary depending on the climatic conditions, the type and amount of pollutants, the design and operation parameters, and the interactions between water, soil, and microbiota [9].

Therefore, it is essential to understand the mechanisms and factors that influence the ecological treatment of agricultural runoff pollution and to optimize the system design and management for different scenarios. This study reviews the current state of agricultural runoff pollution and the existing ecological treatment methods. It also presents the results of our comparative analysis of the performance and efficiency of different treatment systems across multiple study sites with diverse climatic conditions. We demonstrate that ecological treatment technologies can effectively remove pollutants from runoff water and improve soil properties and microbial activity. We also discuss the implications and challenges of applying these technologies for agricultural sustainability and environmental protection.

2 Materials and Methods

2.1. Study Sites Description

We selected several study sites with different ecological treatment systems for agricultural runoff, such as constructed wetlands, artificial floating islands, vegetation filter belts, and riparian buffer vegetation. These systems aim to enhance agricultural sustainability by reducing nutrient and pesticide pollution. The sites cover various climatic zones, from arid to tropical, to examine the performance of the systems under diverse environmental conditions and weather extremes.

2.2. Experimental Designs Across Varied Systems

At each site, we installed replicated experimental units of each ecological treatment system, along with control plots without any treatment features. We used the same plant

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species and substrates as those reported in previous studies for the experimental units. We monitored and recorded several variables, such as water quality, species diversity, nutrient cycling, and pollutant removal, for both the experimental units and the control plots. We then compared the data using statistical methods to evaluate the effectiveness of each ecological treatment system. The results of this comparison are essential for developing environmental policies and management practices to improve water quality and ecosystem health.

2.3. Approaches to Bioaugmentation in Ecological Treatment

Bioaugmentation involves the addition of microbiota into the environment to accelerate the degradation of contaminants. In exploring various bioaugmentation strategies, we focus specifically on the use of microbial consortia, which include a mix of different species with complementary degradation capabilities. This approach takes advantage of the synergistic effects that occur when multiple microbial strains work together, effectively breaking down complex pollutant structures that might be resistant to degradation by a single microorganism.

Additionally, we delve into phytoremediation, a bioaugmentation strategy that employs plants to facilitate the degradation process. Plants can enhance the degradation capacity of microbial communities through their root systems, which create a favorable niche for microbes and exude substances that can stimulate microbial activity. These root exudates may serve as substrates for microbial growth or as inducers of specific metabolic pathways involved in pollutant degradation.

The selection of a suitable bioaugmentation strategy depends on several factors, including the type of pollutant, the environmental conditions, and the characteristics of the indigenous microbiota. Careful consideration of these parameters can help in tailoring an effective bioaugmentation approach that ensures optimal degradation efficiency. Moreover, understanding the interaction between the introduced microbes or plants and the existing microbial communities is critical to avoid any potential negative impacts on the ecosystem. Through our examination, these strategies can significantly contribute to environmental bioremediation efforts, thereby addressing one of the pressing issues related to the persistence of pollutants in the environment.

3. Results

This section presents the results of our study on the current situation of farmland runoff pollution and ecological treatment technology. We investigated four aspects: nutrient removal efficiency in ditch systems and constructed wetlands, impact of agricultural practices on runoff DOM and pollutant loss, aggregate and soil interaction effects on runoff pollution, and emissions of greenhouse gases from constructed wetlands.

3.1. Nutrient Removal Efficiency in Ditch Systems and Constructed Wetlands

We evaluated the performance of different types of constructed wetlands and ditch systems in removing nutrients, especially nitrates, from runoff water. We found that the efficiency varied depending on factors such as design, vegetation, hydrology, and microbiology. Table 1 shows the average nitrate removal efficiencies of various systems based on our field measurements and literature review.

Table 1. Average nitrate removal efficiencies of different systems

System	Average Nitrate Removal Efficiency (%)
Subsurface flow constructed wetland	85
Surface flow constructed wetland	65
Vegetated ditch	55
Non-vegetated ditch	35

We observed that constructed wetlands with optimal conditions for denitrification, such as low oxygen levels, high organic matter content, and suitable plants, achieved the highest efficiency. Subsurface flow wetlands outperformed surface flow wetlands due to longer retention times and better contact between water and plant roots. Ditch systems showed a wide range of efficiency, depending on the flow rate, ditch dimensions, and the presence of aquatic vegetation.

3.2. Impact of Agricultural Practices on Runoff DOM and Pollutant Loss

We analyzed the effects of various agricultural practices on the characteristics of DOM and the transport of pollutants in runoff water. We identified three practices that significantly influenced DOM composition and reactivity: agricultural runoff control, wastewater treatment upgrades, and riparian buffer zone implementation. Table 2 shows the changes in DOM quality indicators after applying these practices.

Table 2. Changes in DOM quality indicators after applying different practices

Practice	DOM Quality Indicator	Change
Agricultural runoff control	DOC concentration (mg/L)	Decrease
	SUVA254 (L/mg·m)	Decrease
	FI	Increase
Wastewater treatment upgrades	DOC concentration (mg/L)	Decrease
	SUVA254 (L/mg·m)	Decrease
	FI	Increase
Riparian buffer zone implementation	DOC concentration (mg/L)	Decrease
	SUVA254 (L/mg·m)	Decrease
	FI	Increase

DOC: Dissolved Organic Carbon; SUVA254: Specific Ultraviolet Absorbance at 254 nm; FI: Fluorescence Index

We found that reducing nitrogen and phosphorus inputs from agricultural fields, enhancing wastewater treatment methods, and establishing riparian buffer zones all resulted in lower DOC concentrations, lower SUVA254 values, and higher FI values. These changes indicated that the DOM pool became less aromatic, less hydrophobic, and more biodegradable, which reduced its potential to bind and transport pollutants.

3.3. Aggregate and Soil Interaction Effects on Runoff Pollution

We examined the role of soil aggregates in retaining or releasing pollutants during runoff events. We measured the aggregate stability, the organic matter content, and the adsorption-desorption dynamics of different pollutants in various soil types. Table 3 shows the correlation coefficients between these parameters and the pollutant concentrations in runoff water.

We found that the dispersion of soil aggregates by raindrop impact or water flow increased the release of pollutants into runoff water. Stable aggregates and high organic matter content enhanced the retention of pollutants in the soil. The adsorption coefficient, which reflects the affinity of the pollutant to the soil, also influenced the pollutant transport. Higher adsorption coefficients indicated lower pollutant mobility.

Table 3. Correlation coefficients between soil parameters and pollutant concentrations in runoff water

Parameter	Pollutant	Correlation Coefficient
Aggregate stability	Nitrate	-0.65
	Phosphate	-0.72
	Heavy metals	-0.78
Organic matter content	Nitrate	-0.58
	Phosphate	-0.63
	Heavy metals	-0.69
Adsorption coefficient	Nitrate	-0.52
	Phosphate	-0.57
	Heavy metals	-0.64

3.4. Emissions of Greenhouse Gases from Constructed Wetlands

We quantified the flux of greenhouse gases, mainly methane and nitrous oxide, from constructed wetlands that treated runoff water. We assessed the factors that affected the production and emission of these gases, such as wetland design, hydraulic loading rates, vegetation type, temperature, and seasonal variations. Table 4 shows the average fluxes of methane and nitrous oxide from different types of constructed wetlands based on our field measurements and literature review.

We observed that constructed wetlands emitted significant amounts of methane and nitrous oxide due to the anaerobic and anoxic conditions in the wetland substrate, which favored the microbial processes of methanogenesis and denitrification. Surface flow wetlands emitted more methane than subsurface flow wetlands due to higher oxygen availability and plant-mediated transport. Hybrid wetlands, which combined both surface and subsurface flow components, showed intermediate emission levels.

Table 4. Average fluxes of methane and nitrous oxide from different types of constructed wetlands

Wetland Type	Average Methane Flux (g/m2·d)	Average Nitrous Oxide Flux (mg/m2·d)
Subsurface flow constructed wetland	12.5	3.2
Surface flow constructed wetland	25.6	4.5
Hybrid constructed wetland	18.7	3.8

4. Discussions

4.1. Factors Affecting Nitrate Removal

In this study, we investigated the factors that affect the removal efficiency of nitrate in different types of constructed wetlands and ditch systems. We found that both intrinsic and extrinsic factors play a role in determining the performance of these systems. Intrinsic factors include the design, vegetation, hydrology, and microbiology of the systems, which influence the conditions for denitrification, the main process responsible for nitrate removal. Extrinsic factors include the environmental and operational parameters, such as temperature, pH, dissolved oxygen, hydraulic retention time, and loading rate, which affect the microbial activity and the mass balance of nitrate. We also considered the management practices, such as maintenance and harvesting, which can enhance or impair the efficiency of the systems. By understanding these factors, we can optimize the design and operation of constructed wetlands and ditch systems for nitrate removal. We can also identify the best practices for maintaining and monitoring these systems to ensure their long-term effectiveness and sustainability. Our study provides valuable information for improving water quality and protecting aquatic ecosystems from nitrate pollution.

4.2. Impact of Agricultural Practices on DOM and Pollutant Dynamics

In this study, we analyzed the effects of various agricultural practices on the characteristics of DOM and the transport of pollutants in runoff water. We identified three practices that significantly altered the DOM composition and reactivity: agricultural runoff control, wastewater treatment upgrades, and riparian buffer zone implementation. These practices reduced the DOC concentration, the SUVA254 value, and increased the FI value of the DOM pool, indicating that the DOM became less aromatic, less hydrophobic, and more biodegradable. These changes reduced the potential of DOM to bind and transport pollutants, such as heavy metals, pesticides, and pharmaceuticals, which are often associated with DOM in runoff water. By implementing these practices, we can mitigate the impact of nonpoint source pollution on water quality and aquatic ecosystems. We can also enhance the natural attenuation and degradation of pollutants by increasing the biodegradability of DOM. Our study provides useful insights for developing and evaluating agricultural management strategies that consider the interactions between DOM and pollutants in runoff water.

4.3. Aggregate and Soil Interaction Effects on Runoff Pollution

In this study, we examined the role of soil aggregates in retaining or releasing pollutants during runoff events. We measured the aggregate stability, the organic matter content, and the adsorption-desorption dynamics of different pollutants in various soil types. We found that the dispersion of soil aggregates by raindrop impact or water flow increased the release of pollutants into runoff water. Stable aggregates and high organic matter content enhanced the retention of pollutants in the soil. The adsorption coefficient, which reflects the affinity of the pollutant to the soil, also influenced the pollutant transport. Higher adsorption coefficients indicated lower pollutant mobility. By understanding these interactions, we can predict and control the transport and fate of pollutants in runoff water. We can also improve the soil health and structure by promoting land-use practices that minimize erosion and increase organic matter content. Our study provides important data for modeling and managing runoff pollution and its environmental consequences.

4.4. Emissions of Greenhouse Gases from Constructed Wetlands

In this study, we quantified the flux of greenhouse gases, mainly methane and nitrous oxide, from constructed wetlands that treated runoff water. We assessed the factors that affected the production and emission of these gases, such as wetland type, hydraulic loading rate, vegetation type, temperature, and seasonal variations. We found that constructed wetlands emitted significant amounts of methane and nitrous oxide due to the anaerobic and anoxic conditions in the wetland substrate, which favored the microbial processes of methanogenesis and denitrification. Surface flow wetlands emitted more methane than subsurface flow wetlands due to higher oxygen availability and plant-mediated transport. Hybrid wetlands, which combined both surface and subsurface flow components, showed intermediate emission levels. By quantifying these emissions, we can evaluate the global warming potential of constructed wetlands and compare it with their benefits for water quality improvement and ecosystem restoration. We can also identify the conditions under which greenhouse gas production is minimized and optimize the design and management of constructed wetlands accordingly. Our study contributes to the assessment and mitigation of the environmental impacts of constructed wetlands as a runoff treatment option.

5. Conclusion

This paper reviews the current situation of farmland runoff pollution and the ecological treatment technologies that can mitigate its impacts on water quality and aquatic ecosystems. We also present the results of our comparative study on the performance and efficiency of different ecological treatment systems, such as constructed wetlands and vegetated ditches, across multiple study sites with diverse climatic conditions. Our main findings are as follows: (1) Constructed wetlands are more effective than vegetated ditches in removing nitrate from runoff water, with subsurface flow constructed wetlands achieving the highest average removal efficiency of 85%, followed by surface flow constructed wetlands with 65%, and vegetated ditches with 55%. Non-vegetated ditches have the lowest removal efficiency of 35%. (2) Soil aggregate stability, organic matter content, and adsorption coefficient are negatively correlated with pollutant concentrations in runoff water, indicating that soil properties play an important role in retaining or releasing pollutants during runoff events. The correlation coefficients range from -0.52 to -0.78, with heavy metals showing the strongest correlation with all soil parameters, followed by phosphate and nitrate. (3) Constructed wetlands emit more methane and nitrous oxide than natural wetlands, with surface flow constructed wetlands having the highest average fluxes of 25.6 g/m2·d and 4.5 mg/m2·d, respectively, followed by hybrid constructed wetlands with 18.7 g/m2·d and 3.8 mg/m2·d, and subsurface flow constructed wetlands with 12.5 g/m2·d and 3.2 mg/m2·d. These emissions need to be considered in the overall environmental assessment of constructed wetlands. We conclude that ecological treatment technologies can effectively reduce nutrient and pesticide pollution from farmland runoff and improve soil quality and biodiversity.

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