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Research Progress on Control Technology of Farmland Runoff Pollution

Yuxuan Yao[1, 2, 3, 4, 5], Shenglan Ye[1, 2, 3, 4, 5]

[1]Shaanxi Provincial Land Engineering Construction Group Co., Ltd. China

[2]Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co., Ltd. China

[3]Key Laboratory of Degraded and Unused Land Consolidation Engineering, Ministry of Natural Resources, China

[4]Shaanxi Engineering Research Center of Land Consolidation, China

[5]Land Engineering Technology Innovation Center, Ministry of Natural Resources, China

Abstract

This paper introduces the sources of agricultural runoff pollution and reviews control technologies for agricultural runoff pollution from the perspective of "source control-process interception." It analyzes integrated technology cases in real-world scenarios, using the Taihu Basin in Jiangsu Province and Jiaxing City in Zhejiang Province as examples to illustrate the application effects of the "source control + process interception" and "smart monitoring + dynamic regulation" systems. These integrated technology models have significantly reduced pollutant levels in agricultural runoff and improved water quality in surrounding waters, providing an effective solution for controlling non-point source pollution from agriculture. Current ecological measures still face challenges such as insufficient long-term effectiveness and technical-economic conflicts. To address these issues, it is recommended to innovate modular technologies, implement policy mechanisms, establish an integrated mechanism for infrastructure construction, management, and utilization through diversified funding mechanisms, and build intelligent platforms to enhance system efficiency. Ultimately, a three-step strategy of "pilot breakthrough-regional promotion-national networking" will achieve large-scale, intelligent, and sustainable governance of agricultural non-point source pollution.

Keywords

Farmland Runoff; Runoff Pollution.

1. Foreword

Agricultural runoff pollution is one of the primary sources of non-point source pollution in agriculture. Nitrogen, phosphorus, pesticides, and organic pollutants present on the land surface and in the soil enter water bodies through surface runoff and groundwater infiltration, leading to eutrophication, degradation of ecological functions, and risks to drinking water safety. With the development of intensive agriculture, the problem of agricultural runoff pollution has become increasingly prominent. This paper systematically reviews domestic and international approaches to controlling agricultural runoff pollution from a comprehensive perspective covering "source reduction—process interception—end-of-pipe treatment," providing a reference for green agricultural development and water environmental protection.

2. Current Situation of Farmland Runoff Pollution

2.1. Pollution Comes in Many Forms

Nitrogen, phosphorus, and other nutrients: Excessive use of fertilizers such as urea and diammonium phosphate in farmland leads to excessive nitrogen and phosphorus content in the soil. Under the influence of runoff, these substances can be washed away with water. Studies show that in some regions of China, the total nitrogen concentration in agricultural runoff can reach 10-30 mg/Lmol/L, and the total phosphorus concentration can reach 0.5-2 mg/L [1]/L. Pesticide residues: Organochlorine and organophosphorus pesticides are difficult to degrade in the environment and can easily enter water bodies through runoff. In rice-growing areas of southern China, pesticide residues such as chlorpyrifos and triflubenzuron are often detected in paddy field runoff, although at low concentrations, long-term accumulation can pose potential ecological hazards [2]. Sediment and suspended solids: Under the influence of rainfall erosion and irrigation water flow, farmland soil is prone to form sediment particles and suspended solids that enter runoff. These particles not only make water turbid and affect water quality but may also adsorb other pollutants, increasing the pollution load. In mountainous or sloping farmland, soil erosion is more severe, leading to significantly higher sediment content in runoff.

2.2. Pollution is Intermittent and Uncertain

Significant Impact of Rainfall: The intensity, frequency, and duration of rainfall directly affect the generation of agricultural runoff and the migration of pollutants. Heavy rain can cause a large amount of runoff to occur in a short period, carrying substantial pollutants into water bodies. In contrast, during drought periods, agricultural runoff is minimal, resulting in relatively low pollutant emissions. In North China, the concentration of pollutants in agricultural runoff significantly increases after summer heavy rains, while during winter droughts with less rainfall, runoff pollution is relatively lighter. Influence of Irrigation Methods and Management: Unreasonable irrigation methods, such as flood irrigation, can lead to waterlogging in farmland and runoff loss, increasing the risk of pollution. Additionally, differences in fertilization and pesticide application times and amounts also result in significant variations in the types and concentrations of pollutants in runoff at different times, making pollution more unpredictable.

2.3. Spatial Distribution is Very Different

Differences caused by varying topography and soil conditions. In mountainous areas, the terrain is rugged with fast-flowing water, leading to severe soil erosion and primarily sediment and nitrogen-phosphorus loss from agricultural runoff; in contrast, plains have flat terrain with slower flow rates. However, due to concentrated farmland use and high application of fertilizers and pesticides, nitrogen-phosphorus and pesticide pollution are more prominent. In southwestern China's mountainous regions, agricultural runoff has higher sediment content, while in the North China Plain, nitrogen-phosphorus pollution is more severe. Differences also arise from different crop planting structures. Fields planted with vegetables, flowers, and other cash crops often have higher pollutant concentrations in runoff due to frequent fertilization and pesticide application compared to fields planted with food crops.

2.4. Other Factor

Some farmers lack sufficient awareness of the hazards of agricultural runoff pollution and have insufficient environmental consciousness and knowledge of scientific agricultural production. In agricultural practices, there is a tendency to blindly pursue high yields through excessive fertilization and pesticide use, with little attention paid to protecting the ecological environment of farmland. They view agricultural runoff pollution as a natural phenomenon

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unrelated to their own activities. Public participation is low; controlling agricultural runoff pollution requires the involvement of the entire society, yet currently, public concern about this issue is low, and enthusiasm for participating in pollution control efforts is not high. Besides farmers, other social groups such as enterprises, social organizations, and ordinary citizens also show limited participation in controlling agricultural runoff pollution. The lack of effective supervision and support mechanisms makes it difficult to form a collective effort for governance across society.

3. Technology Path Classification and Progress

3.1. Source Control Technology

3.1.1. Optimizing Fertilization

Management with Precision Fertilization, precise detection of soil nutrients is combined with the nutritional needs of crops at different growth stages to develop personalized fertilization plans. By utilizing Geographic Information Systems (GIS) and Global Positioning Systems (GPS), variable-rate fertilization can be achieved. Sensors monitor real-time soil nitrogen, phosphorus, potassium levels, and soil moisture, generating precise fertilization prescription maps through intelligent decision-making systems. Based on these maps, fertilizer application equipment can adjust the amount of fertilizer applied to different plots during operations. Research data shows that compared to traditional fertilization methods, precision fertilization reduces nitrogen fertilizer use by 20-30% and phosphorus fertilizer use by 15-20%, without affecting crop yields. This not only reduces waste of fertilizers and lowers production costs but also significantly decreases the levels of nitrogen and phosphorus pollutants in runoff due to over-fertilization.

3.1.2. Priority should be Given to the Use of Biopesticides

(such as Bt insecticides) and low-toxicity chemical pesticides. In tea gardens in Zhejiang, Bt insecticides are used to control pests like the tea planthopper. Studies show that Bt insecticides are as effective as traditional chemical pesticides in controlling pest populations, with a pest control effectiveness of over 85%. However, the residual period of Bt insecticides in the environment is short; after one week of application, the residual levels in tea leaves and soil are almost undetectable. In contrast, traditional chemical pesticides can remain in the soil for several months and have higher residues in tea leaves. Additionally, tea gardens using biopesticides have significantly lower levels of pesticide-related pollutants in surrounding water bodies compared to those using traditional pesticides.

3.1.3. Precision Pesticide Application Technology:

Utilizing drones and variable rate spraying to improve pesticide efficiency and reduce drift pollution. In rice-growing areas of Jiangsu, drones are used for pesticide spraying operations. Equipped with high-precision sensors and intelligent control systems, drones can precisely adjust the amount and range of pesticide application based on the terrain of the paddy fields, crop growth conditions, and pest distribution. Compared to traditional manual backpack sprayers, drone application increases pesticide efficiency by 20-30% and reduces pesticide usage by 15-20%. Moreover, drone application effectively avoids damage to rice caused by walking during manual spraying, while also reducing pesticide drift pollution in non-target areas and minimizing the impact on beneficial organisms in the agricultural ecosystem.

3.1.4. Resource Utilization of Agricultural Waste:

Straw Returning to Fields and Covering: Straw is crushed and returned to the field or covered on the surface to reduce surface runoff erosion. In the wheat-corn rotation areas of Henan, straw crushing returning technology has been implemented. Studies show that after straw is returned to the field, soil organic matter content increases year by year, with a 0.2-0.3 percentage point increase in three years. At the same time, due to straw covering the surface, it

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effectively reduces direct raindrop impact on the soil, lowering soil erosion and reducing sediment content in surface runoff by 30%-40%. Additionally, straw returning to the field can improve soil structure, increase soil porosity, enhance soil water and nutrient retention, benefit crop growth, and reduce farmland runoff pollution caused by soil erosion and nutrient loss.

3.1.5. Livestock and Poultry Manure is Processed Through Composting

anaerobic digestion, and other technologies to avoid direct discharge. Pig manure undergoes anaerobic fermentation to produce biogas, which can be used as an energy source for the farm's production and living activities. The digestate and supernatant are then used as high-quality organic fertilizers for nearby farmland. Studies have shown that [4], treated livestock and poultry manure has significantly reduced levels of pollutants such as chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). Compared to direct discharge without treatment, the COD in the discharged biogas slurry after anaerobic digestion is reduced by 70-80%, TN by 40-50%, and TP by 30-40%. Moreover, applying the digestate and supernatant to farmland not only reduces the use of chemical fertilizers but also enhances soil fertility, promotes crop growth, and achieves resource utilization of livestock and poultry waste and effective control of agricultural runoff pollution.

3.2. Process Blocking Technology

3.2.1. Integrated Water and Fertilizer Technology

combining drip irrigation, sprinkler irrigation, and other methods to achieve simultaneous nutrient and water supply. In cotton cultivation in Xinjiang, large-scale use of drip irrigation and fertilization technology is common. By adding soluble fertilizers to the drip irrigation system, these fertilizers are precisely delivered to the vicinity of cotton roots along with water. Studies show that this integrated water and fertilizer technology increases fertilizer efficiency from 30-40% in traditional irrigation and fertilization methods to 60-70%, while water savings reach 30-40%. At the same time, both yield and quality of cotton have significantly improved, effectively reducing the loss of fertilizers due to surface runoff caused by flood irrigation, and lowering the risk of pollution in nearby water bodies.

3.2.2. Constructed and Controlled Artificial Wetlands Simulate the Functions of Natural Wetland Ecosystems in Wastewater Treatment Systems

Based on traditional agricultural drainage ditches, ecological renovations are carried out to build ecological channels and buffer zones. Aquatic plants such as reeds and calamus are planted in the channels, utilizing their root systems to absorb nitrogen, phosphorus, and other nutrients from runoff. Zeolite, biochar, gravel, and other materials are added at the bottom or sides of the channels. These materials can adsorb pollutants and provide attachment surfaces for microorganisms, promoting the decomposition and transformation of pollutants by microorganisms. The water flow rate in ecological channels is relatively slow, increasing contact time between pollutants and plants and microorganisms, enhancing purification efficiency. The system primarily relies on natural physical, chemical, and biological processes for purification, requiring minimal mechanical equipment and energy consumption, thus keeping operational and maintenance costs relatively low. With high aesthetic value, the rich aquatic vegetation in artificial wetlands creates unique landscapes that beautify the surrounding environment and provide habitats for wildlife, enhancing regional biodiversity.

3.2.3. The Bioretention System Involves Establishing Vegetation Zones Around Farmland, Rivers, or Lakes as Buffer Strips

Composed of vegetation layers, planting soil, sand, gravel, and drainage systems, when runoff from farmland enters the bioretention system, it is first intercepted by the vegetation layer, slowing down its flow and allowing some pollutants to be absorbed and adsorbed by the plants. As runoff passes through the planting soil layer, microorganisms in the soil decompose organic

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pollutants, while soil particles adsorb nutrients such as nitrogen and phosphorus. The sand and gravel layers further filter fine particles from the runoff and provide a surface for microbial attachment and growth, enhancing pollutant removal efficiency. Excess runoff is then discharged through the drainage system. The buffer strip also slows down the flow rate of runoff, increases infiltration, and reduces the amount of pollutants carried by surface runoff into receiving water bodies. In some areas around farmland in the suburbs of Beijing, bioretention systems have been constructed. These systems effectively reduce pollutants in runoff from farmland, achieving TN removal rates of 40%-60% and TP removal rates of 50%-70%. They also reduce the volume of rainwater runoff around farmland, playing a positive role in protecting the surrounding water environment and ecosystem.

3.2.4. Field Leachate System: Leachate Ponds or Trenches are Set up in Farmland

filled with specific media such as sand, gravel, and soil conditioners. When runoff from the fields enters the leachate system, it first passes through physical filtration by the sand and gravel to remove larger suspended particles. Subsequently, pollutants in the runoff are adsorbed onto the surface of the media as they penetrate downward. Meanwhile, the rich microbial communities in the media break down organic pollutants, converting large organic molecules into smaller substances or carbon dioxide and water. Nitrogen is nitrified and denitrified, converting ammonium nitrogen to nitrate nitrogen and further reducing it to nitrogen gas that escapes from the system, thus purifying the field runoff.

4. Technology Integration Case

Rural runoff pollution is multi-source, complex and dynamic, so it is difficult to achieve efficient control by a single technology. Through the coordination of multiple technologies, the limitations of a single measure can be broken through, forming a closed-loop system of "pollution reduction-resource utilization-ecological restoration".

4.1. "Source Control + Process Blocking"

In the Taihu Basin of Jiangsu Province, the "soil testing and formula fertilization + ecological interception ditch" model has been widely promoted. For example, in the farmlands of Wuzhong District, Suzhou, technicians first collect soil samples from different plots and use professional instruments to analyze soil nutrient content. They found that some areas had excessively high phosphorus levels and relatively low nitrogen levels. Based on this, and considering the nutrient requirements of crops and fertilizer effects, combined with the growth characteristics of major crops in the Taihu Basin such as rice, wheat, and rapeseed, they scientifically designed fertilizer formulas. For fields lacking nitrogen, they appropriately increased nitrogen fertilizer application while controlling phosphorus use to avoid over-application risks leading to eutrophication of water bodies. In the paddy fields of Yixing City, after adopting soil testing and formula fertilization, the nitrogen fertilizer application rate decreased by 15-20% compared to the past, but rice yields did not decrease; instead, due to more reasonable nutrient supply, there was a 3-5% increase in production. This technology has changed farmers' outdated notion of "frequent fertilization and watering without human intervention," shifting fertilization from blind broadcasting and surface application to precise deep application, significantly improving fertilizer utilization rates and reducing fertilizer waste and nutrient loss in runoff.

The ecological interception ditches in the Taihu Lake Basin are ingeniously designed. These ditches are typically set up around farmland or along drainage paths, with their internal structures meticulously planned. The bottom and walls of the ditches are filled with various functional materials, such as zeolite, biochar, and gravel. Zeolite's excellent ion exchange properties can effectively adsorb ammonium nitrogen and other pollutants from runoff;

biochar can adsorb organic pollutants and provide habitats for microorganisms, promoting pollutant degradation; gravel serves as a substrate for microbial attachment, enhancing biological purification. Additionally, a large number of water-loving and highly efficient aquatic plants, like calamus and water onion, are planted within the interception ditches. When agricultural runoff enters the ditches, it is first blocked by plant stems and leaves, slowing down the flow rate and causing suspended particles to settle. Plant roots act like "nutrient absorbers," absorbing large amounts of nitrogen, phosphorus, and other nutrients from the runoff for their own growth. In an ecological interception ditch in Huishan District, Wuxi, tests have shown that it can remove 35-50% of total nitrogen and 40-60% of total phosphorus from agricultural runoff. Moreover, these ecological interception ditches also serve multiple functions such as flood control, soil stabilization, climate regulation, and landscape beautification, becoming part of the rural ecological landscape in the Taihu Lake Basin.

The synergistic effect of the "soil testing and formula fertilization + ecological interception ditch" model is highly significant. On one hand, it reduces the unreasonable use of chemical fertilizers at the source, decreasing the amount of pollutants generated in agricultural runoff. On the other hand, ecological interception ditches intercept, adsorb, and purify pollutants during the transport process. In Wujin District of Changzhou City, by promoting this integrated model, the water quality around farmland has significantly improved, with a substantial reduction in nitrogen and phosphorus concentrations in the water bodies. The aquatic ecosystem is gradually recovering, and some previously extinct aquatic organisms such as snails and river shrimp have reappeared, making significant contributions to the environmental improvement of the Taihu Lake Basin.

4.2. "Smart Monitoring + Dynamic Control" System

The "Farmland-Wetland" intelligent control system constructed in Jiaxing City, Zhejiang Province, uses sensors and other devices to monitor soil moisture, nutrient content, water quality, and meteorological data in real time. By monitoring nitrogen and phosphorus levels in the soil, it can accurately track changes in nutrient conditions, providing scientific evidence for precise fertilization. This avoids excessive fertilization leading to nutrient loss through runoff, reducing the generation of agricultural runoff pollution at its source. Additionally, monitoring meteorological data helps predict rainfall conditions, allowing for preemptive measures such as adjusting water levels in farmland and enhancing wetland water storage preparations before rain, thereby reducing the concentration of pollutants in runoff. Optimizing irrigation and drainage management: Based on real-time monitoring data, the intelligent control system can optimize irrigation and drainage plans for farmland. On one hand, it promotes "water-saving thin-film irrigation" technology, using automatic water-saving valves and enhanced management of water distributors to precisely control the depth of water layers during different growth stages of rice, reducing the frequency and volume of field drainage, thus lowering the amount of pollutants lost through drainage. On the other hand, installing double-leaf overflow gates at the outlet of paddy fields ensures some water retention, achieving no drainage on sunny days and minimal drainage on rainy days, further reducing the generation of agricultural runoff and lowering the risk of pollutant flow into surrounding water bodies.

Ecological interception and purification: The wetland sections of the system play a crucial role in ecological interception and purification. Before agricultural runoff is discharged into rivers, it first flows through ecological nitrogen and phosphorus interception ditches and wetlands. These ditches are planted with fast-growing aquatic plants that have strong purification capabilities, such as calamus and water onion. These plants can adsorb, degrade, and absorb nutrients like nitrogen and phosphorus from the water, while also slowing down the water flow to promote the settling of suspended particles. Wetlands further purify agricultural runoff by removing pollutants through the combined effects of soil, plants, and microorganisms, thereby improving water quality. For example, in some pilot areas of Pinghu City, the average interception rates for total nitrogen, ammonia nitrogen, and total phosphorus in ecological ditches reached 28.5%,32.5%, and 27.5%, respectively, effectively reducing the pollutant content in agricultural runoff.

Resource Recycling: The "Farmland-Wetland" Smart Control System has achieved the resourceful utilization of farmland runoff. By using part of the treated runoff for irrigation or other agricultural production processes, it enhances water use efficiency and reduces dependence on external water resources. Meanwhile, nutrients absorbed by plants in wetlands can be recovered through harvesting and used to make organic fertilizers, achieving nutrient recycling and reducing chemical fertilizer application, further lowering the risk of farmland runoff pollution.

Improving Management Efficiency and Decision-Making Scientificity: The intelligent joint control system provides an efficient platform for managing agricultural runoff pollution. Managers can monitor and analyze data remotely to promptly understand the operational status of farmland and wetlands, quickly identify issues, and take appropriate measures. Additionally, the system can establish models and conduct data analysis to provide scientific decision support for preventing agricultural runoff pollution. For example, it can help formulate reasonable plans for wetland construction, optimize planting structures and fertilization schemes, thereby more effectively controlling agricultural runoff pollution and protecting the regional water environment.

5. Challenges and Prospects

5.1. Insufficient Long-term Effectiveness of Ecological Measures:

The degradation mechanism "plant absorption saturation" means that after continuous pollutant absorption by wetland plants (such as reeds) for 3-5 years, their root adsorption capacity significantly decreases due to metal ion accumulation or nutrient competition. Adsorbent materials like zeolite and biochar in ecological ditches lose permeability within 2-3 years due to sedimentation or thickening microbial films, leading to a shortened hydraulic retention time. Technical and Economic Contradictions: High-load areas require frequent maintenance, but farmers have low willingness to pay.

5.2. Innovate and Develop Modular Technology to Address the Issue of "Affordability,"

lowering the threshold for construction funds; implement policy mechanisms to solve the problem of "willingness to use," stimulating farmers' initiative; through diversified financing mechanisms, focus on grain-producing areas and ecologically fragile regions, establishing an integrated mechanism for infrastructure construction, management, and utilization, promoting a "reward instead of subsidy" approach to encourage village collectives to participate in maintenance; build intelligent platforms to ensure "good usability," enhancing system efficiency. Ultimately, through a three-step strategy of "pilot breakthrough-regional promotion-nationwide networking," achieve large-scale, smart, and sustainable governance of agricultural non-point source pollution.

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