Mitigating Nutrient Pollution in Agricultural Drainage Water: A Survey of Adsorption, Catalysis, Phytoremediation, Ion Exchange, and Nanomaterials

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Abstract

Agricultural drainage water, rich in nitrogen and phosphorus from fertilizers, significantly contributes to nutrient pollution, leading to environmental challenges such as eutrophication. This survey explores multifaceted approaches to mitigate this issue, focusing on adsorption, catalysis, phytoremediation, ion exchange, and nanomaterials. Adsorption techniques, utilizing natural materials like kokopit and engineered solutions such as poly (triazine imide), demonstrate potential in pollutant capture. Catalysis, particularly through single atom catalysts, enhances pollutant degradation efficiency. Phytoremediation strategies, employing wetland buffer zones and microalgae systems, offer sustainable nutrient uptake solutions. The study highlights the role of ion exchange processes and nanomaterials, with advanced materials like heteropolymer gels and nanoceria playing crucial roles in efficient nutrient management. Future research should optimize bioremediation techniques across various agricultural contexts, refine adsorption models, and explore the effects of environmental conditions on pollutant dynamics. Interdisciplinary research, integrating materials science, environmental engineering, and computational modeling, is vital for advancing nutrient removal technologies. These innovations can contribute to sustainable water management practices, addressing scalability, environmental impact, and long-term stability challenges, ultimately mitigating nutrient pollution in agricultural settings.

1 Introduction

1.1 Environmental Impact of Nutrient Pollution

Agricultural drainage water, laden with fertilizers and agrochemicals, significantly contributes to nutrient pollution, primarily through nitrogen (N) and phosphorus (P) runoff, which presents serious environmental challenges [1]. The increased use of fertilizers to satisfy rising food production demands has intensified non-point source pollution, disrupting nitrogen and phosphorus cycles and posing substantial global risks with potentially unknown environmental repercussions. Nutrient enrichment from nitrate-N and dissolved phosphorus in subsurface drainage systems is a primary driver of eutrophication, leading to oxygen depletion in aquatic ecosystems and threatening aquatic life [2].

Additionally, the improper disposal of industrial wastewater rich in ammonium exacerbates eutrophication in water bodies, posing significant threats to safe drinking water and human health [3]. The mobility of phosphorus in soil is particularly concerning due to its critical role in plant growth and the challenges related to its limited availability, which can adversely affect nutrient cycling and ecological balance [4]. The presence of emerging pollutants, such as sulfonamides used in treating bacterial infections, raises further environmental concerns due to their persistence and potential health risks [5].

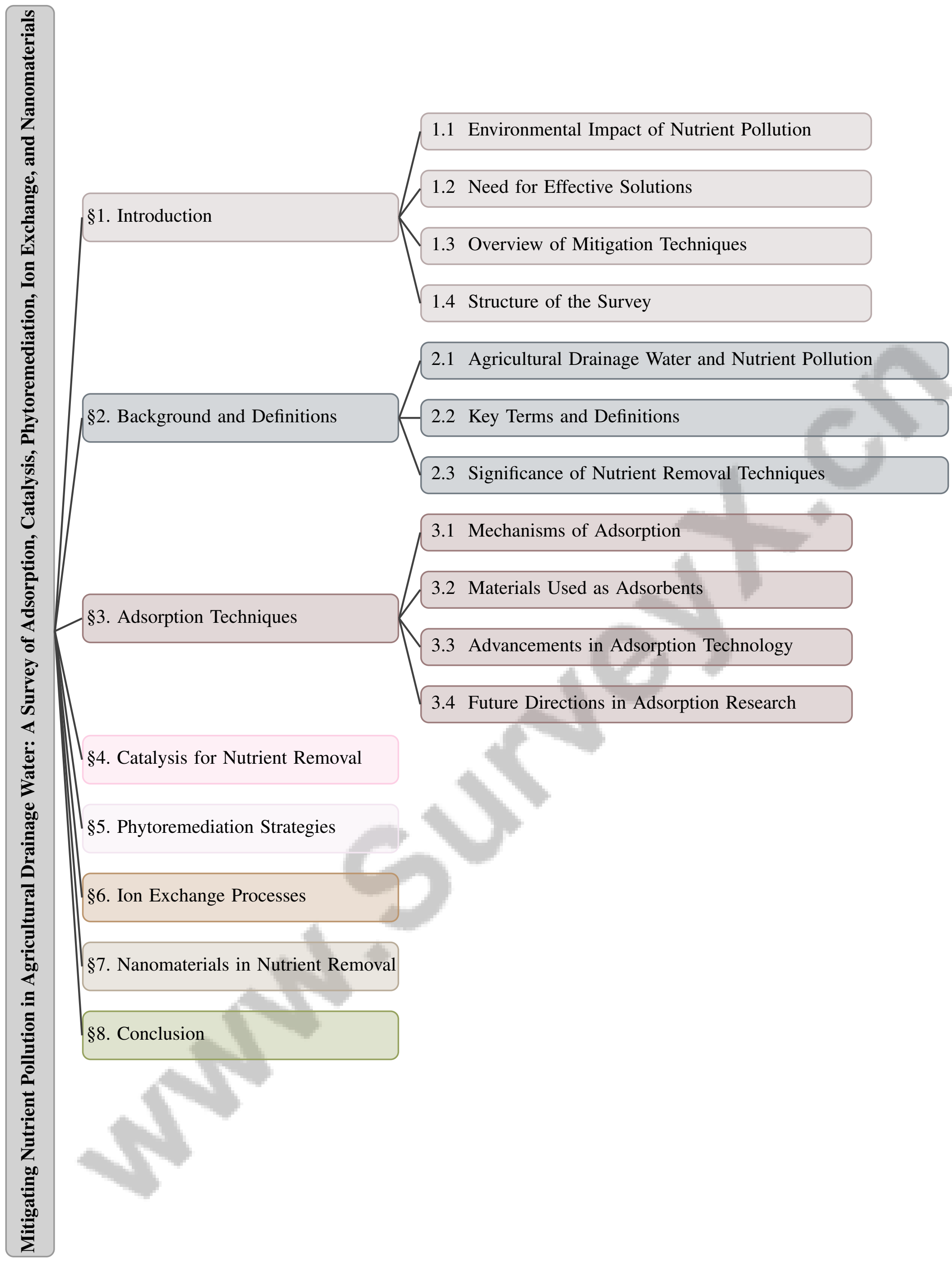

Figure 1: chapter structure

Anthropogenic pressures, including sediment loading, increase turbidity and reduce light penetration to seabeds, impacting the productivity and health of vital ecosystems like seagrass meadows [6]. Moreover, rising atmospheric CO2 levels and nutrient releases from wastewater treatment plants (WWTPs) are linked to various ecosystem impacts, emphasizing the urgency of addressing nutrient pollution [7]. The contamination of agricultural soils and drainage water with potentially toxic elements (PTEs) poses additional health risks to consumers via the food chain [8]. These multifaceted challenges highlight the necessity of developing effective mitigation strategies to combat nutrient pollution in agricultural drainage water, thereby protecting both environmental and human health.

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1.2 Need for Effective Solutions

The need for effective solutions to mitigate nutrient pollution in agricultural drainage water is underscored by the complex challenges posed by excessive nutrient inputs, particularly from non-point sources, complicating control and mitigation efforts [9]. The variability in phosphorus loads and forms, coupled with limitations of farm-scale practices, necessitates the development of effective edge-of-field technologies adaptable to local conditions [10]. This complexity is exacerbated by industrialization, urbanization, and population growth, which intensify water pollution and call for efficient remediation technologies [11].

Current methods, such as activated carbon adsorption, often face limitations in capacity and selectivity, especially for complex contaminants like sulfonamides, necessitating innovative materials and technologies [5]. The variability in environmental conditions, including pH levels and ionic compositions, affects adsorption processes, as illustrated in studies on apigenin adsorption on clays [12]. This underscores the need for adaptive and versatile solutions that can function effectively across diverse conditions.

Furthermore, the lack of understanding of bacterial community responses to environmental changes complicates effective ecosystem management, highlighting the need for research to inform more adaptive and integrated management practices [13]. The enzyme-like catalytic activities of materials such as cerium oxide nanoparticles present promising avenues for mimicking natural processes in nutrient removal, yet the underlying mechanisms require further elucidation [14].

Innovative approaches, including the use of heteropolymer gels for selective adsorption and capacitive deionization methods with enhanced ion transport and adsorption capacities, represent critical advancements needed to address current technological inefficiencies. The effective removal of highly toxic contaminants such as Cr(VI), known for its solubility and environmental persistence, further emphasizes the necessity for targeted remediation strategies [15].

The study of Coelastrum morus, which investigates the effects of varying nitrate and phosphate concentrations and N:P ratios on growth and nutrient removal ability, underscores the urgency for effective solutions that optimize nutrient removal in diverse scenarios [16]. The integration of advanced materials, enhanced understanding of ecological interactions, and innovative technological approaches is essential to overcoming existing method limitations and achieving sustainable water management solutions.

1.3 Overview of Mitigation Techniques

Mitigating nutrient pollution in agricultural drainage water involves a combination of advanced techniques, each contributing uniquely to pollutant reduction. Adsorption processes are crucial, utilizing natural adsorbents like kokopit to effectively lower nutrient concentrations [17]. The development of poly (triazine imide) (PTI) through electrochemical synthesis enhances photocatalytic properties for improved pollutant adsorption [18]. Catalysis, particularly using 3D transition metal single-atom catalysts (SACs), offers high catalytic activity for the adsorption and reduction of contaminants like Cr(VI) [15]. Additionally, cerium oxide nanoparticles leverage their Ce^{3+} and Ce^{4+} oxidation states for effective nutrient removal [14].

Phytoremediation employs plant-based systems, such as microalgae strains in photobioreactors, to sustainably remove nutrients, with specific nutrient content and N:P ratios enhancing efficiency [16]. Ion exchange processes contribute by selectively swapping harmful ions with benign ones, improving water quality. Capacitive deionization (CDI) represents a promising approach, utilizing electrochemical adsorption in porous carbon electrodes for efficient nutrient removal [19].

The application of nanomaterials, including carbon nanotubes (CNTs) and graphene oxide (GO), is critical in environmental remediation, providing effective solutions to combat water contamination [11]. These materials enhance charge transfer and pollutant degradation, as shown by titanium dioxide nanowires functionalized with organic dyes [20]. Furthermore, edge-of-field practices, such as constructed wetlands and vegetated buffer strips, play a vital role in improving water quality by intercepting and treating runoff before it enters water bodies [10].

The diverse strategies outlined in the literature emphasize the necessity of a comprehensive and multifaceted approach to effectively address the intricate challenge of nutrient pollution from agricultural runoff. This approach must integrate innovative materials, advanced technologies, and sustainable practices, including edge-of-field technologies like constructed wetlands and vegetated buffer strips, alongside best management practices and regulatory frameworks. By uniting these elements, stakeholders—including government agencies, NGOs, and farmers—can collaboratively mitigate the impacts of pollutants like phosphorus and pesticides on water quality and aquatic ecosystems, ultimately fostering healthier and more sustainable agricultural systems [10, 1].

1.4 Structure of the Survey

This paper is structured to provide a comprehensive examination of nutrient pollution mitigation in agricultural drainage water through various advanced techniques. The survey begins with an overview of nutrient pollution, detailing its significant environmental repercussions, such as degradation of aquatic ecosystems and water quality, along with implications for human health and food security. It emphasizes the urgent need for effective mitigation strategies, involving a collaborative approach among stakeholders, including government agencies, NGOs, and farmers, to implement best management practices and regulatory measures aimed at reducing pollution from agricultural sources [21, 1]. Following the introduction, the paper delves into the background and definitions, providing insights into agricultural drainage water, nutrient pollution, and key terms associated with mitigation techniques.

The core sections of the paper explore specific mitigation strategies, starting with adsorption techniques, where the role of adsorption in nutrient removal, mechanisms, materials used, and recent advancements are discussed. This is followed by an exploration of catalysis for nutrient removal, focusing on types of catalysts, mechanisms, and innovative approaches. Phytoremediation strategies are then examined, detailing the use of plants in nutrient removal, supported by case studies and advancements.

The survey continues with an analysis of ion exchange processes, highlighting principles, materials, and recent developments in the field. The role of nanomaterials in nutrient removal is also explored, emphasizing their catalytic properties and innovative applications. Each section is designed to build upon the previous, providing a holistic view of the current state of research and technology in nutrient pollution mitigation.

The paper concludes with a summary of the key findings from each section, discussing the overall effectiveness of the techniques and highlighting areas for future research and potential improvements. Additionally, the organization of the paper includes a discussion of the kokopit method, experimental results, and conclusions regarding its efficacy [17].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Agricultural Drainage Water and Nutrient Pollution

Agricultural drainage water significantly contributes to nutrient pollution by transporting excess nitrogen and phosphorus to aquatic ecosystems via irrigation and precipitation [17]. These nutrients, while essential for plant growth, cause environmental issues like eutrophication when present in excess, leading to oxygen depletion and biodiversity loss [16]. The interaction between organic species and natural minerals complicates pollutant mobility and sorption dynamics, with anions such as carbonate and bicarbonate affecting nutrient transport modeling [22]. Changes in materials like graphene oxide under UV light further influence their adsorptive capabilities, necessitating innovative removal strategies [23].

Efforts to mitigate nutrient pollution focus on edge-of-field technologies to retain phosphorus in tile-drained catchments, a significant source of surface water eutrophication [10]. Utilizing specific microalgae species for wastewater treatment is a sustainable approach for nutrient load reduction [16]. A comprehensive strategy involving integrated water quality management is crucial for addressing the environmental impacts of agricultural drainage water. This strategy requires collaboration among stakeholders, including government agencies, NGOs, and farmers, to implement best management practices, regulatory measures, and innovative technologies. Key components include using cover crops to minimize nitrate runoff, establishing wetland buffer zones for pollutant filtration, and adopting precision agriculture techniques to optimize resource use and reduce waste [21, 1, 24].

2.2 Key Terms and Definitions

Understanding key terms related to nutrient pollution mitigation is essential for effective management of agricultural drainage water. Adsorption, where molecules adhere to surfaces, plays a vital role in nutrient removal and is often modeled using the Langmuir adsorption isotherm, which describes solute interactions with adsorption sites, particularly in porous media where viscous fingering may occur [25]. The adsorption of ions such as Na^+ and Ba^{2+} on clay models illustrates the process's complexity in environmental remediation [26].

Catalysis, which involves substances that accelerate chemical reactions without being consumed, enhances pollutant degradation rates and nutrient removal efficiency [20]. Density Functional Theory (DFT) is frequently used to study catalytic processes, providing insights into the electronic structure and adsorption energy of molecules on surfaces [27].

Phytoremediation utilizes plants to absorb and degrade contaminants, offering a sustainable solution for nutrient pollution [20]. Ion exchange replaces unwanted ions in a solution with ions from a solid medium, effectively improving water quality [20]. Nanomaterials, with their high surface area and reactivity, are increasingly employed in nutrient removal processes, enhancing adsorption and catalytic activities crucial for advanced water treatment technologies [28].

Integrating various approaches, including best management practices, regulatory frameworks, and stakeholder collaboration, forms a robust foundation for developing innovative strategies to mitigate nutrient pollution. Each component enhances the effectiveness of environmental remediation efforts, particularly in addressing the challenges posed by agricultural runoff and its impact on ecosystems and water quality [6, 21, 1].

2.3 Significance of Nutrient Removal Techniques

Nutrient removal techniques are crucial for addressing nutrient pollution's adverse effects in agricultural drainage water, which can lead to eutrophication, oxygen depletion, and biodiversity loss in aquatic ecosystems. These techniques are essential for effectively capturing and removing pollutants, thereby promoting environmental health and sustainable agricultural practices [17]. Advanced adsorption techniques, utilizing both physical and chemical mechanisms, are critical for enhancing nutrient removal efficiency [29]. Understanding adsorption kinetics, considering factors such as particle shape, size, and gravitational effects, is key to optimizing these processes [30].

Innovative biochemical remediation methods, such as nanoceria, show promise for enhancing catalytic activities in nutrient removal systems, improving their efficiency [14]. Developing realistic models for ion adsorption dynamics in clay minerals is crucial for refining nutrient removal strategies [26].

Edge-of-field technologies have proven effective in phosphorus retention, enhancing water quality and ensuring compliance with environmental regulations [10]. These technologies are particularly beneficial in drainage systems where topography influences nutrient fluxes [31]. The application of 3D transition metal single-atom catalysts (SACs) addresses challenges such as the slow reaction rates in natural Cr(VI) reduction, emphasizing the need for effective catalytic solutions [15].

Capacitive deionization (CDI) systems, despite challenges related to ion transport and adsorption, represent a promising method for nutrient removal. Advances in modeling ion transport and enhancing adsorption in porous structures are crucial for improving CDI performance [19].

Nutrient removal techniques are essential for mitigating the environmental consequences of nutrient pollution in agricultural drainage water, reducing harmful contaminants like phosphorus and nitrogen entering aquatic ecosystems. These techniques, including edge-of-field technologies such as constructed wetlands, vegetated buffer strips, and filter materials, are crucial for mitigating eutrophication and improving water quality. By managing nutrient loads before they reach downstream waters, these strategies support a healthier ecosystem and sustainable agricultural practices amid increasing food production demands due to global population growth [10, 1]. Integrating advanced materials, innovative technologies, and sustainable practices offers a comprehensive approach to effectively addressing nutrient pollution.

In recent years, the field of adsorption technology has garnered significant attention, particularly in the context of nutrient removal from agricultural drainage. This review aims to elucidate the various adsorption techniques and their implications for environmental sustainability. As illustrated

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in Figure ??, the hierarchical classification of these techniques provides a comprehensive overview of the mechanisms involved, the materials utilized, and the advancements made in the field. The figure highlights the interplay between physical and chemical mechanisms, as well as the role of computational modeling and innovative materials. Such interdisciplinary approaches are crucial for optimizing adsorption technology and addressing future research directions in nutrient removal. By integrating these elements, we can better understand the complexities and potential of adsorption techniques in environmental management.

Figure 2: This figure illustrates the hierarchical classification of adsorption techniques, detailing the mechanisms, materials used, advancements, and future research directions in nutrient removal from agricultural drainage. It highlights the interplay between physical and chemical mechanisms, computational modeling, and innovative materials, underscoring the importance of interdisciplinary approaches for optimizing adsorption technology.

3 Adsorption Techniques

3.1 Mechanisms of Adsorption

Method Name	Adsorption Mechanisms	Structural Features	Computational Techniques
CKA[17]	Chemical And Physical	Surface Modifications	-
Hetero-IOCC[32]	Charged Defects	Heterophased Grain Boundaries	-
CC[26]	Ionic Adsorption Capacities	Unit Cell Compositions	Molecular Dynamics Simulations
Zeolite-NH4+[33]	Ionic Exchange Capacity	Chemical Treatments	Statistical Analyses
SAC[15]	Density Functional Theory	High Surface Area	Dft Calculations
PSM[19]	Electrochemical Adsorption	Porous Electrodes	Pore-scale Model
PTI[18]	Van Der Waals	High Specific Surface	Molecular Dynamics Simulations

Table 1: Summary of adsorption methods, mechanisms, and computational techniques used in nutrient removal from agricultural drainage. The table outlines various methodologies, highlighting the specific adsorption mechanisms, structural features, and computational techniques employed in each approach. These insights are crucial for understanding and optimizing adsorption processes in environmental applications.

Adsorption plays a critical role in nutrient removal from agricultural drainage, characterized by molecule adhesion on solid surfaces through physical and chemical mechanisms. Physical adsorption relies on van der Waals forces, while chemical adsorption involves covalent bonding, both essential for efficient nutrient capture [29]. The kokopit method exemplifies the effective use of natural materials, leveraging inherent properties for nutrient removal [17]. Adsorption complexity arises from adsorbate-adsorbent interactions, with larger particle adsorption at liquid-solid interfaces influenced by kinetic factors and structural characteristics, including irreversible adsorption and geometric blockage [30]. Heterophased grain boundaries in adsorbents enhance active site availability, improving interactions with cationic and anionic species [32].

As illustrated in Figure 3, the hierarchical structure of adsorption mechanisms is categorized into various types, advanced techniques, and enhancements. This figure underscores the significance of both physical and chemical adsorption, as well as advanced computational techniques and enhancements such as pore-scale models and functional groups. Advanced computational techniques, such as molecular dynamics simulations, offer insights into dynamic interactions between organic molecules and clay minerals under natural conditions [26]. The Tanaka equation aids in understanding gel affinity for target molecules, categorizing adsorption based on gel state and interaction nature [28]. Surface modifications enhance adsorption, as seen with chemically treated zeolites improving ionic exchange capacities for ammonium ions [33]. The unique electronic structure and high surface area of 3D Transition Metal Single Atom Catalysts (SACs) facilitate strong interactions with contaminants like Cr(VI), underscoring the importance of surface characteristics in adsorption efficacy [15].

Pore-scale models provide detailed simulations of ion transport and adsorption in porous electrodes, enhancing understanding and optimization of adsorption systems [19]. Incorporating functional groups, such as in poly (triazine imide) (PTI), improves adsorption by enhancing coupling efficiency and generating reactive radicals [18]. A comprehensive understanding of physicochemical interactions and structural dynamics is vital for effective nutrient removal via adsorption, enhanced through advanced computational techniques and experimental methodologies. Utilizing datasets from high-frequency monitoring systems in wastewater treatment plants supports optimization of operational strategies and predictive model development, improving nutrient removal efficiency [34, 35, 36, 29]. Table 1 provides a comprehensive overview of different adsorption methods, elucidating their respective mechanisms, structural features, and computational techniques, which are critical for enhancing nutrient removal efficiency in agricultural drainage systems.

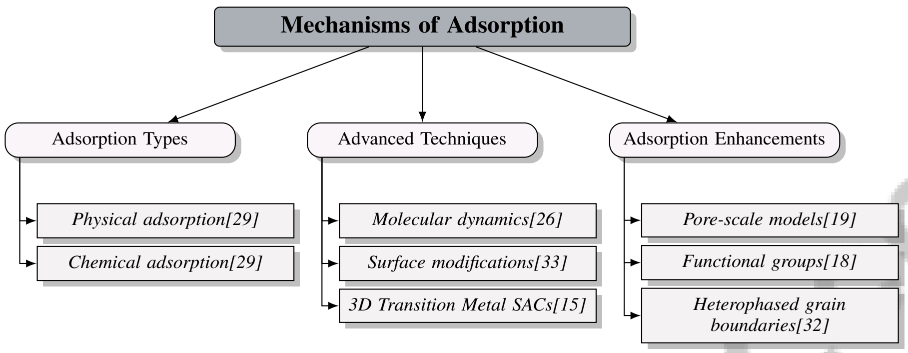

Figure 3: This figure illustrates the hierarchical structure of adsorption mechanisms, categorized into adsorption types, advanced techniques, and adsorption enhancements. It highlights the significance of physical and chemical adsorption, advanced computational techniques, and enhancements like pore-scale models and functional groups.

3.2 Materials Used as Adsorbents

Method Name	Material Types	Performance Factors	Optimization Techniques
CKA[17]	Natural Adsorbents	Adsorption Efficiency	PH Adjustment
Zeolite-NH4+[33]	Natural Zeolite	Ionic Exchange Capacity	Acid And Alkaline
Hetero-IOCC[32]	Iron Oxide/carbon	Heterophased Grain Boundaries	Thermal Treatment
UV-GO[23]	Graphene Oxide	Structural Properties	Acid And Alkaline

Table 2: Summary of various adsorbent materials, their performance factors, and optimization techniques used for nutrient removal in agricultural drainage systems. The table highlights the diverse methods, ranging from natural adsorbents to engineered nanomaterials, showcasing their unique properties and treatment processes for enhanced adsorption efficiency.

Optimizing nutrient removal from agricultural drainage hinges on selecting effective adsorbent materials, with natural and engineered options offering unique advantages. Table 2 provides a comprehensive overview of different adsorbent materials and their corresponding performance factors and optimization techniques, crucial for optimizing nutrient removal from agricultural drainage. Natural adsorbents like kokopit effectively capture pollutants through inherent properties [17]. Natural clay minerals, such as clinoptilolite, are favored for high cation exchange capacities, enhanced through acid and alkaline treatments to boost ammonium adsorption [33].

Engineered nanomaterials, including superparamagnetic composites, are noted for superior adsorption capacities. The synthesis of hetero-IOCC, combining -Fe_2O_3 and -Fe_2O_3 phases with distinct grain boundaries, exemplifies magnetic properties for easy recovery and improved performance [32]. Structural changes in materials like graphene oxide, particularly under UV irradiation, affect adsorption capacity for contaminants like arsenic, highlighting structural optimization's role in enhancing efficiency [23].

Graphene and its derivatives, known for high surface area and unique electronic properties, significantly enhance adsorption performance. Encapsulating graphene oxide within alginate-based beads improves adsorption capacity while ensuring safety and reusability. An electric dipole layer at the surface generates a strong local electric field, facilitating electron transfer and effective thermalization crucial for adsorption [37].

The diversity of materials used as adsorbents in nutrient removal processes illustrates the intricate nature of these systems. Studies employing machine learning for heavy metal adsorption in soils and comprehensive reviews of fixed-bed column adsorption methods emphasize surface chemistry, process parameters, and operational dynamics' critical role in optimizing removal efficiencies [34, 35, 36]. Continuous development and optimization of both natural and engineered adsorbents are essential for enhancing efficiency and sustainability of nutrient removal strategies in agricultural contexts.

3.3 Advancements in Adsorption Technology

Method Name	Technological Innovations	Material Utilization	Modeling and Optimization
CKA[17]	Kokopit Technique	Natural Materials	-
SAC[15]	Kokopit Technique	3D Transition Metals	Dft Calculations
CC[26]	-	-	Claycode
PSM[19]	Pore-scale Modeling	Porous Carbon Electrodes	Pore-scale Model

Table 3: Comparison of recent technological advancements in adsorption methods, detailing innovations, material utilization, and modeling techniques. The table highlights the application of the Kokopit technique, the use of 3D transition metals, and the role of computational models in enhancing adsorption processes for environmental remediation.

Recent advancements in adsorption technology have significantly improved nutrient removal efficiency from agricultural drainage water. The kokopit method has achieved up to a 20% reduction in nutrient levels, showcasing its potential as an effective adsorption technique [17]. This method highlights progress in utilizing natural materials for pollutant capture, offering a sustainable solution to nutrient pollution. Table 3 provides a comparative analysis of contemporary adsorption technologies, illustrating the integration of innovative methods, material applications, and optimization models that contribute to improved nutrient removal efficiency.

The development of Single Atom Catalysts (SACs) represents a promising innovation in environmental remediation, leveraging the high catalytic efficiency and atomic precision of 3d transition metals as a cost-effective alternative to scarce platinum group metals [15]. SACs have shown remarkable potential in enhancing adsorption processes within complex environmental systems.

Advancements in computational modeling contribute significantly to the field, with tools like ClayCode automating clay model preparation, thereby improving the accuracy of molecular dynamics simulations [26]. These simulations yield valuable insights into adsorbate-clay mineral interactions, facilitating the optimization of adsorption materials.

The versatility of heteropolymer gels as smart materials capable of mimicking biological functions has been demonstrated through significant advancements in their design for practical applications [28]. These gels present a novel approach to adsorption, adapting to varying environmental conditions and pollutant profiles.

Moreover, pore-scale modeling methods enable a deeper understanding of the complex interactions between fluid dynamics and electrochemical processes at the pore scale [19], enhancing the optimization of adsorption systems for efficient nutrient removal.

Despite these advancements, challenges persist in fully optimizing adsorption processes. Ongoing research is necessary to improve adsorption efficiency, particularly for materials like clinoptilolite, due to complex interactions with various adsorbents and contaminants and the influence of environmental conditions on adsorption mechanisms. Factors such as pH, ionic species, and chemical treatments significantly affect zeolite adsorption capacity for ammonium ions, while machine learning models reveal intricate patterns in heavy metal adsorption across different soil types. These findings highlight the importance of refining adsorption technologies for effective environmental remediation [36, 12, 6, 35, 33]. Advancements in adsorption technology reflect a concerted effort to develop sustainable solutions for nutrient pollution, with future research likely focusing on integrating these technologies with other remediation strategies for comprehensive nutrient management.

3.4 Future Directions in Adsorption Research

Advancing adsorption technology for nutrient removal from agricultural drainage water requires thorough exploration of future research directions, particularly in developing accurate models that capture the complexities of heterogeneous surfaces and the influence of novel materials on adsorption efficiency. Computational modeling is crucial, enhancing our understanding of adsorption processes through analyzing hygroscopic behavior across different plant parts and incorporating desorption

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effects [38]. Refining current models to account for particle anisotropy and multilayer formation kinetics is essential for improving adsorption predictions [30].

Investigating interactions of larger proteins and the effects of surface curvature on binding dynamics could yield significant insights for bio-nanotechnology applications [39]. Extending existing models to encompass a broader range of materials and scenarios will validate their applicability, offering a robust framework for future studies [37]. Optimizing computational efficiency in modeling adsorption scenarios and applying these models to diverse conditions are critical for advancing adsorption technologies [40].

Future research should prioritize optimizing treatment processes to enhance zeolite adsorption capacity and mechanical strength for repeated use cycles [33]. Combining kokopit with other adsorbents presents another promising avenue for increasing nutrient removal efficiency [17]. Additionally, refining the understanding of gel dynamics, exploring novel materials and compositions, and improving imprinting techniques are vital for enhancing specificity and efficiency in molecular recognition [28].

Integrating real-world data and considering additional factors affecting heavy metal transport and transformation in soils will be crucial for the practical application of adsorption technologies [35]. Collectively, these research directions underscore the necessity for interdisciplinary approaches and innovative strategies to advance adsorption technology, ensuring sustainable nutrient management in agricultural settings.

4 Catalysis for Nutrient Removal

In the context of catalysis for nutrient removal, understanding the types of catalysts employed is essential for optimizing the efficiency of these processes. The following subsection delves into the various catalysts utilized in nutrient removal applications, highlighting their distinct characteristics and contributions to enhancing catalytic performance. By exploring the innovative materials and strategies involved, we can better appreciate the advancements made in this critical area of environmental remediation.

4.1 Types of Catalysts Used

Catalysts play a pivotal role in nutrient removal processes, offering enhanced reaction rates and improved efficiency in breaking down pollutants. The use of Single Atom Catalysts (SACs) represents a significant advancement in this field, leveraging isolated active sites to enhance catalytic performance and optimize metal resource utilization [15]. SACs differ from traditional nanoparticle catalysts by providing a higher density of active sites, which facilitates more effective interactions with target pollutants.

Figure 4 illustrates the primary types of catalysts used in nutrient removal processes, highlighting Single Atom Catalysts, Iron Oxide/Carbon Composites, and Graphitic Carbon Nitride, each with their specific applications and benefits. Iron oxide/carbon composites with heterophased grain boundaries have been proposed as effective catalysts for the removal of both cationic and anionic dyes, demonstrating their versatility and potential applicability in nutrient removal [32]. The creation of these heterophased structures enhances the interaction between the catalyst and pollutants, thereby improving the overall efficiency of the removal process.

Graphitic carbon nitride (g-CN) has been identified as a promising support material for heterogeneous dual-metal sites, which are designed to improve the performance of nitrate reduction to ammonia [41]. This approach takes advantage of the synergistic effects between the dual-metal sites and the graphitic carbon nitride support, leading to enhanced catalytic activity and selectivity.

The controlled calcination of PMOB materials to generate functional groups such as carbonyls and carboxylic acids has been proposed to interact with amines in water, providing another avenue for improving catalytic processes in nutrient removal [42]. These functional groups enhance the interaction between the catalyst and the pollutants, thereby increasing the efficiency of the removal process.

Overall, the development and application of advanced catalysts are crucial for improving the efficiency of nutrient removal processes, with ongoing research focused on optimizing catalyst structures and compositions to enhance their performance in diverse environmental conditions [11].

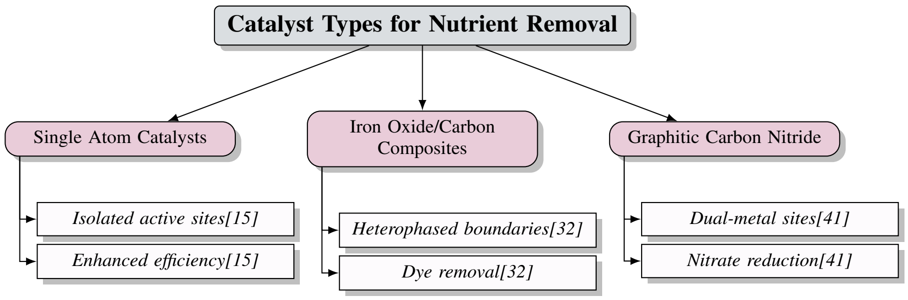


Figure 4: This figure illustrates the primary types of catalysts used in nutrient removal processes, highlighting Single Atom Catalysts, Iron Oxide/Carbon Composites, and Graphitic Carbon Nitride, each with their specific applications and benefits.

4.2 Mechanisms and Effectiveness

Benchmark	Size	Domain	Task Format	Metric
WBZ-Harvest[21]	1,000	Wetland Ecology	Nutrient Removal Assessment	N Removal Efficiency, P Removal Efficiency
PBR[43]	1,000	Environmental Engineering	Nutrient Removal	Nitrogen Removal Efficiency, Phosphorus Removal Efficiency
N-Cat-Bench[44]	1,000	Nitrogen Chemistry	Benchmarking OF Exchange-correlation Functionals	RMSE, MAE
SWC-MB[45]	48	Environmental Microbiology	Arg Transport Assessment	Mann–Whitney U test
Agtrup[34]	1,000,000	Wastewater Treatment	Time Series Forecasting	Mean Absolute Error, Root Mean Squared Error

Table 4: Table illustrating various benchmarks used in the assessment of nutrient removal processes across different domains. Each benchmark is characterized by its size, domain, task format, and the metrics employed to evaluate performance. This comprehensive overview aids in understanding the diverse methodologies and evaluation criteria applied in environmental and chemical research.

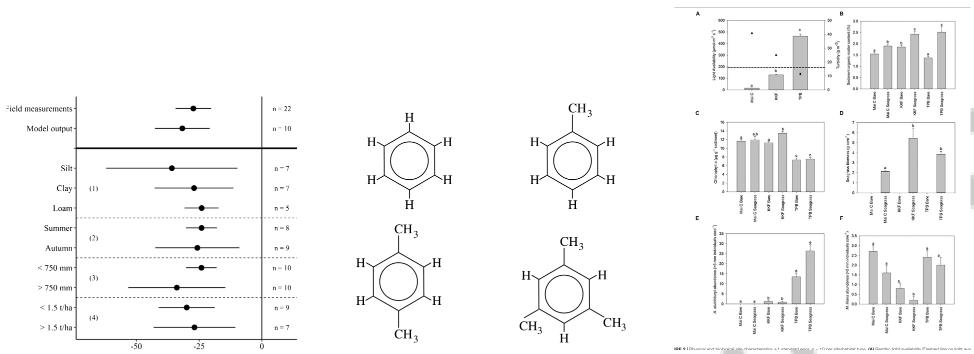
The effectiveness of catalysis in nutrient removal is primarily determined by the catalytic mechanisms that facilitate the breakdown of pollutants. Catalysts function by lowering the activation energy required for chemical reactions, thereby increasing reaction rates and enabling more efficient nutrient removal. One of the key challenges in catalytic processes is the kinetic stability and activity of the catalysts, particularly when dealing with inert molecules such as nitrogen, where the strong NN bond presents a significant barrier [41]. Addressing these challenges requires the development of catalysts with enhanced kinetic properties and active sites that can effectively interact with target molecules.

The creation of functional groups on the surface of catalyst materials, such as those achieved through the calcination of PMOB materials, plays a crucial role in enhancing catalytic properties. This method allows for the generation of diverse functional groups, including carbonyls and carboxylic acids, which improve the interaction between the catalyst and pollutants, thereby enhancing the overall catalytic activity [42]. These functional groups facilitate the adsorption and subsequent breakdown of nutrients, contributing to more effective removal processes.

Microbial dynamics also significantly influence phosphorus availability in nutrient removal processes. Traditional models often fail to capture these interactions, highlighting the need for more comprehensive approaches that consider microbial contributions to nutrient cycling [4]. The integration of microbial activity into catalytic processes can enhance nutrient removal efficiency by promoting the breakdown of complex molecules and facilitating nutrient uptake.

The performance of catalytic systems can be assessed by evaluating parameters such as salt removal rates, energy consumption, and current efficiency, as demonstrated in studies involving cyclic operation of capacitive deionization (CID) cells [46]. These metrics provide insights into the effectiveness of catalytic processes and the potential for optimization in nutrient removal applications. Table 4 presents a detailed comparison of benchmarks utilized in the evaluation of nutrient removal mechanisms, highlighting the diversity in domain applications and assessment metrics.

Overall, the mechanisms of catalysis in nutrient removal are multifaceted, involving the optimization of catalyst structures, the introduction of functional groups, and the consideration of microbial dynamics. The combination of various factors, including the implementation of advanced treatment techniques like electrocoagulation, the establishment of wetland buffer zones, and the adoption of best management practices, significantly enhances the efficiency of catalytic processes aimed at improving nutrient removal from agricultural drainage water. These approaches not only address the pressing issue of agricultural water pollution but also promote sustainable agricultural practices and protect aquatic ecosystems. [21, 1, 47]



(a) Field measurements and model output comparison[24]

(b) The image shows two benzene rings connected by a methyl group.[27]

(c) Physical and biological site characteristics +1 standard error, n = 10 per site/habitat type.[6]

Figure 5: Examples of Mechanisms and Effectiveness

As shown in Figure 5, The example of "Catalysis for Nutrient Removal; Mechanisms and Effectiveness" is illustrated through a series of figures that collectively highlight various aspects of the mechanisms and their effectiveness in nutrient removal processes. The first figure presents a comparative analysis between field measurements and model outputs for different soil properties and climatic conditions, providing insights into how accurately models can predict real-world scenarios. This is followed by a depiction of two benzene rings connected by a methyl group, symbolizing the chemical structures involved in catalytic processes. The final figure showcases a detailed study of physical and biological site characteristics, emphasizing the variability and reliability of data through error bars. Together, these images offer a comprehensive overview of the scientific and practical considerations involved in catalysis for nutrient removal, underscoring the complexity and precision required in such environmental interventions. [**?**]meyer2019cover,ericsson2016involvinghighschoolstudents,bulmer2018elevated)

4.3 Innovative Approaches and Materials

Innovative approaches in catalysis for nutrient removal have increasingly focused on the development and application of advanced materials that enhance catalytic performance through unique structural and chemical properties. A notable advancement is the utilization of dual-atom catalysts (DACs), which leverage the synergistic effect of metal dimer coupling to significantly boost catalytic activity. This approach optimizes the interaction between the metal atoms, thereby enhancing the efficiency of nutrient removal processes [41].

The generation of diverse functional groups on catalyst surfaces represents another innovative strategy. The calcination of PMOB materials, for instance, enables the formation of functional groups such as carbonyls and carboxylic acids, which improve the interaction between catalysts and pollutants. This method enhances the catalytic properties of PMOB surfaces in water, offering a superior alternative to traditional approaches [42]. These functional groups facilitate the adsorption and breakdown of nutrients, contributing to more efficient removal processes.

The incorporation of these advanced materials and innovative approaches into catalytic systems underscores the potential for significant improvements in nutrient removal from agricultural drainage water. By improving the structural and chemical properties of catalysts, strategies that incorporate advanced carbon nanomaterials, such as carbon nanotubes and graphene oxides, hold significant potential for developing more effective and sustainable solutions to nutrient pollution. These materials can enhance the performance of environmental remediation efforts, particularly in addressing challenges like elevated turbidity and its detrimental effects on ecosystems, such as seagrass meadows, which play a crucial role in nutrient removal and overall marine health. [6, 11]

4.4 Recent Research Findings

Recent research in the field of catalysis for nutrient removal has yielded significant advancements, particularly in the development of novel catalysts that enhance the efficiency of electrochemical processes. A study by Shu et al. identifies FeMo@g-CN, CrMo@g-CN, and CrRu@g-CN as promising catalysts for electrochemical nitrate reduction. These catalysts exhibit high activity, selectivity, and stability, making them suitable candidates for efficient nutrient removal applications [41]. The incorporation of graphitic carbon nitride (g-CN) as a support material enhances the catalytic performance by providing a stable and conductive matrix that facilitates electron transfer and interaction with nitrate molecules.

Additionally, the calcination of PMOB materials has been shown to effectively generate functional groups such as carboxylic acids and phenols, which interact with amines in water. This process enhances the catalytic properties of PMOB surfaces, contributing to more efficient nutrient removal by improving the adsorption and breakdown of pollutants [42]. The generation of these functional groups is crucial for enhancing the interaction between the catalyst and target molecules, thereby increasing the overall effectiveness of the removal process.

These findings highlight the critical role of innovative catalyst design and the strategic incorporation of functional groups in enhancing the efficiency of nutrient removal processes, particularly in the context of advanced wastewater treatment systems, such as those analyzed in the Agtrup dataset. This dataset provides comprehensive insights into the operational dynamics of phosphorus removal through both chemical and biological methods, supporting the development of sophisticated predictive models and optimization strategies. Additionally, recent assessments of exchange-correlation functionals for heterogeneous catalysis underscore the importance of selecting appropriate computational methods to accurately evaluate the interactions and efficiencies of nitrogen-containing compounds, which is essential for improving the sustainability and effectiveness of nutrient removal technologies. [34, 44]. By leveraging the unique properties of advanced materials and optimizing catalytic mechanisms, recent research continues to push the boundaries of what is possible in the field of environmental remediation.

5 Phytoremediation Strategies

Addressing the global issue of nutrient pollution has led to the development of phytoremediation strategies, with vegetation in wetland buffer zones emerging as a key solution. This approach not only facilitates nutrient removal but also enhances ecosystem health. This section explores the importance of vegetation harvesting in wetland buffer zones, highlighting its role in nutrient management and sustainable agriculture.

5.1 Vegetation Harvesting in Wetland Buffer Zones

Vegetation harvesting in wetland buffer zones is crucial for nutrient management, offering a sustainable method to reduce nutrient pollution in agricultural runoff. These zones function as natural filters, intercepting nutrients before they reach larger water bodies, thus mitigating eutrophication and improving aquatic health [21]. Strategic harvesting enhances nutrient uptake and biomass quality, with potential applications in bioenergy.

Mixed culture planting, involving diverse plant species, has shown superior nutrient removal efficiency over monocultures, while lowering contamination risks [48]. This diversity increases wetland resilience, allowing adaptation to varying environmental conditions. Studies on organic-mineral interactions provide insights into nutrient cycling dynamics, informing effective management of wetland buffer zones [12].

Incorporating vegetation harvesting into nutrient management strategies significantly improves nitrogen (N) and phosphorus (P) removal from agricultural runoff. Research shows that harvested wetland buffer zones can achieve up to 92

5.2 Microalgae Systems for Nutrient Removal

Microalgae systems offer a promising solution for nutrient removal, leveraging algae's natural metabolic processes to assimilate pollutants. Research on microalgae in photobioreactors has advanced these systems' optimization for various wastewater sources. Full-scale semi-closed horizontal tubular photobioreactors have demonstrated microalgae's efficacy in nutrient removal from agricultural runoff and treated domestic wastewater, indicating potential for large-scale applications [43].

Combining freshwater and marine algal species in mixed cultures enhances adaptability and resilience in saline wastewater treatment, improving nutrient removal efficiency while minimizing contamination risks [48]. Additionally, microalgae cultures in photobioreactors are used for CO2 capture from flue gases, offering dual benefits of carbon capture and nutrient removal [7]. Studies show that mixed-culture microalgae dominated by Parachlorella can effectively remove ammonia nitrogen under anaerobic conditions, highlighting the importance of optimizing environmental conditions [49].

Research on specific algal species, such as Coelastrum morus, identifies factors influencing nutrient removal efficiency, emphasizing optimal conditions for nutrient uptake [16]. These insights confirm microalgae systems' potential as sustainable solutions for nutrient pollution, offering versatile and effective water treatment methods.

5.3 Diatom-Based Approaches for Silica and Nutrient Removal

Diatom-based approaches offer an innovative strategy for removing silica and nutrients, particularly in agricultural drainage systems. Diatoms, with their siliceous cell walls, are effective biological agents for silica removal, making them suitable for high-silica waters like agricultural drainage and reverse osmosis concentrate [50].

Cultivating diatoms with other microalgae species, such as Chlorella vulgaris and Scenedesmus obliquus, boosts biomass productivity and nutrient removal in saline wastewater [48]. Diatoms assimilate essential nutrients like nitrogen and phosphorus, critical for their growth. Mixed microalgal cultures can achieve over 90

Diatom-based systems show significant potential for enhancing nutrient and silica removal, particularly in challenging contexts like agricultural drainage. Research indicates that naturally occurring diatoms can achieve over 95

5.4 Constructed Wetlands for Phosphorus Retention

Constructed wetlands are engineered ecosystems that mimic natural processes, providing effective phosphorus retention solutions in agricultural drainage systems. These systems utilize soil, plants, and microorganisms to capture and transform phosphorus, reducing its concentration in water bodies and mitigating eutrophication risks. Studies show that constructed wetlands can remove up to 63

Integrating mixed microalgae cultivation within constructed wetlands enhances nutrient removal efficiency and biomass production. This approach is economically viable, as mixed microalgae cultures achieve high nutrient removal rates, making them a sustainable strategy for nutrient pollution management [48]. Additionally, incorporating diatom-based processes improves nutrient cycling, as diatoms effectively assimilate silica and other nutrients, achieving over 95

Constructed wetlands are crucial for phosphorus retention in tile-drained agricultural catchments, where excess phosphorus from fertilizers and manure can lead to eutrophication. By treating drainage discharge, these systems significantly reduce dissolved and particulate phosphorus forms, achieving removal efficiencies of 17

5.5 Innovative Techniques Combining Biochemical Methods and DHS Systems

Innovative techniques integrating biochemical methods with Downflow Hanging Sponge (DHS) systems have shown promise in enhancing nutrient removal from agricultural drainage water. These approaches leverage the synergy of biological processes and advanced treatment systems to achieve superior pollutant reduction. The integration of microalgae systems within the DHS framework exemplifies this synergy, as microalgae assimilate and degrade nutrients while contributing to biomass production [16]. Optimizing operational parameters, such as light intensity and nutrient concentrations, is crucial for maximizing microalgae system efficiency [43].

Incorporating mixed algal cultures within DHS systems enhances nutrient uptake and resilience under fluctuating conditions [48]. Exploring alternative algal species and optimizing growth conditions are essential for improving mixed cultures' performance, leading to more effective nutrient removal and biomass utilization. pH control strategies within DHS systems are vital for maintaining optimal conditions for microalgae growth and nutrient assimilation, necessitating cost-effective pH management methods for large-scale applications [49].

The combination of biochemical remediation techniques with DHS systems has significantly improved the reduction of potentially toxic elements (PTEs) compared to conventional methods [8]. This integrated approach enhances nutrient removal efficiency and contributes to the sustainability of wastewater treatment processes. Large-scale pilot testing and economic feasibility studies are necessary to assess these innovative techniques' practicality, while advancements in biomass harvesting technologies will support their implementation [7].

Integrating biochemical methods with Distributed Health Systems (DHS) offers an opportunity to enhance nutrient removal technologies in wastewater treatment. This approach utilizes advanced datasets, such as those from Denmark's Agtrup wastewater treatment plant, to optimize chemical and biological phosphorus removal processes. By employing machine learning techniques and developing predictive models, researchers can improve nutrient management efficiency and address challenges posed by agricultural runoff and wastewater pollution. This methodology aims to enhance treatment sustainability while supporting digital twins for improved system performance under varying conditions [34, 43, 1, 48]. By combining biological processes with advanced treatment systems, these innovative techniques provide a comprehensive solution for mitigating nutrient pollution in agricultural drainage water, with potential applications across diverse environmental contexts.

6 Ion Exchange Processes

6.1 Principles of Ion Exchange in Nutrient Removal

Ion exchange processes are crucial for nutrient removal, relying on ion hydration and electrostatic interactions to selectively replace undesirable ions. The efficiency of these processes is determined by ion distribution at interfaces, where electrostatic interactions influence adsorption energies and capacities [51]. Clay minerals, with their layered structures and surface charge properties, exemplify high ionic adsorption capacities and selectivity [26]. The mineralogical composition and exchangeable cations in clays can be optimized for nutrient removal from agricultural drainage. Agglomeration of ions at interfaces can lead to reversed fractionation, necessitating precise ion concentration measurements to optimize adsorption energies [22]. Techniques like electrocoagulation, where positively charged ions neutralize pollutants, further enhance the process. Advanced modeling, including numerical simulations of ion transport and adsorption, optimizes removal processes by improving ion dynamics understanding and supporting predictive model development [19, 36, 34, 47, 21]. These principles can refine ion exchange processes to combat nutrient pollution in agricultural settings effectively.

6.2 Types of Ion Exchange Materials

The selection of ion exchange materials is vital for optimizing nutrient removal, with various materials offering unique advantages in selectivity, capacity, and environmental compatibility. Natural materials like zeolites and clay minerals are favored for their high cation exchange capacities and abundance. Zeolites, with their open framework structure, effectively remove ammonium and other nutrients from wastewater [33]. Synthetic ion exchange resins, composed of organic polymers, provide customizable capacities and enhanced mechanical stability, functionalized for selective ion removal [51]. Emerging materials, such as nanocomposites and hybrid structures, are explored for superior ion exchange properties. Incorporating nanoparticles enhances surface area and reactivity, improving efficiency. For instance, iron oxide nanoparticles in composites have demonstrated enhanced phosphate ion removal [32]. By leveraging the distinct characteristics of natural, synthetic, and advanced materials, ion exchange systems can be optimized for nutrient management in agricultural settings, particularly in tile-drained catchments where phosphorus is transported in dissolved and particulate forms. Implementing targeted edge-of-field technologies, like constructed wetlands and vegetated buffer strips, can significantly enhance phosphorus retention and promote sustainable agricultural practices [10, 47].

6.3 Recent Developments and Innovations

Recent advancements in ion exchange technology focus on improving efficiency and applicability for nutrient removal in agricultural drainage. Electrically polarized 3D-printed spacers, such as the E-GRP spacer, have shown over 50% higher water flux compared to conventional spacers, mitigating gypsum scaling [52]. Nanocomposites, particularly those with iron oxide nanoparticles, enhance ion exchange by increasing surface area and reactivity, especially for phosphate removal [32]. Future research should optimize synthesis processes and examine varying carbon contents, alongside real wastewater testing. Modeling advancements, such as new clay system models, elucidate complex interactions in ion exchange [26]. These models enhance understanding of ion hydration and electrostatic interactions, vital for optimizing capacities and selectivity. Future research should explore complex geometries and material properties to improve model accuracy and applicability across diverse capacitive deionization (CDI) systems [19]. Challenges persist, including large-scale production of carbon nanotubes (CNTs) and graphene oxide (GO), and environmental concerns [11]. Addressing these challenges is essential for advancing ion exchange technology and ensuring sustainability and effectiveness in nutrient removal. Recent developments underscore the potential for significant enhancements in nutrient removal through advanced materials, innovative design strategies, and improved modeling techniques. Innovations in agricultural water management, like electrocoagulation, present substantial opportunities for refining ion exchange systems to mitigate nutrient pollution. Implementing integrated water quality management strategies involving diverse stakeholders and best management practices can address environmental and health challenges posed by agricultural runoff, contributing to sustainable practices and improved water quality [53, 1, 47].

7 Nanomaterials in Nutrient Removal

7.1 Catalytic Properties of Nanomaterials

Nanomaterials enhance nutrient removal due to their high surface area, electronic properties, and reactivity, which facilitate pollutant degradation in water. Silicene nanosheets, for instance, demonstrate environmental application potential by effectively adsorbing volatile organic compounds (VOCs) [54]. Graphene oxide's adsorption capabilities are improved by structural changes from UV irradiation, optimizing its pollutant interaction [23]. Nanoceria's enzyme-like activities, influenced by surface area and $Ce3+$ fraction, enhance complex pollutant breakdown [14]. These properties establish nanomaterials as valuable for water treatment technologies.

7.2 Nanocomposites and Hybrid Structures

Nanocomposites and hybrid structures, integrating nanoparticles with polymers or inorganic matrices, are pivotal in nutrient removal. Iron oxide nanoparticle composites significantly enhance phosphate ion removal, highlighting nanotechnology's role [32]. Electrically polarized 3D-printed spacers improve water flux and reduce scaling, emphasizing advanced materials in nutrient removal [52]. Hybrid structures, like graphene oxide composites, enhance electronic properties and adsorption capabilities for pollutant capture [23]. These innovations offer tailored approaches for specific contaminants, advancing water pollution solutions.

7.3 Innovative Nanomaterial Applications

Nanomaterials advance nutrient removal by leveraging high surface area, reactivity, and tunable electronic characteristics. Electrically polarized 3D-printed spacers, such as the E-GRP spacer, improve water flux and gypsum scaling prevention [52]. Iron oxide nanoparticles enhance phosphate removal, underscoring nanocomposites' significance [32]. Graphene oxide's structural adaptability under UV irradiation optimizes adsorption capabilities [23]. Nanoceria's enzyme-like catalytic activities facilitate complex pollutant breakdown [14]. These applications transform environmental remediation strategies, improving water quality management and supporting sustainable agriculture [11, 1, 55].

7.4 Future Prospects and Research Directions

The future of nanomaterials in nutrient removal is promising, focusing on enhancing efficiency and sustainability. Research targets advanced nanocomposites and hybrid structures leveraging diverse material synergies to improve removal capabilities [32]. Optimizing synthesis and functionalization tailors properties for specific applications, with computational modeling guiding design [23, 26]. Assessing environmental impact and scalability ensures sustainable application [11]. Interdisciplinary collaborations enhance innovative solutions for complex environmental challenges [27, 11, 1, 35]. Future developments aim to improve performance and sustainability, expanding applicability in wastewater treatment through advanced materials and predictive models [11, 34, 1, 6, 35].

8 Conclusion

This survey underscores the multifaceted strategies essential for addressing nutrient pollution in agricultural drainage water, focusing on adsorption, catalysis, phytoremediation, ion exchange, and nanomaterials. Each method contributes uniquely to nutrient removal, forming an integrated approach to this environmental issue. Adsorption, employing both natural and engineered materials like kokopit and poly(triazine imide) (PTI), shows significant promise in pollutant capture, with kokopit notably effective in reducing nutrient levels. Catalysis, especially through single atom catalysts (SACs), offers enhanced degradation capabilities, highlighting the need for further optimization of SACs and exploration of diverse transition metals for improved outcomes.

Phytoremediation, utilizing wetland buffer zones and microalgae, harnesses natural processes for nutrient absorption and breakdown, presenting environmentally sustainable solutions. The use of edge-of-field technologies for phosphorus capture emphasizes the necessity for innovative, cost-effective materials, warranting additional investigation. Ion exchange and nanomaterial applications provide novel avenues for boosting nutrient removal efficiency, with advanced materials like heteropolymer gels showing significant potential for enhanced adsorption through engineering advancements. The catalytic properties of nanomaterials, such as nanoceria, further illustrate their promise in environmental remediation, offering effective solutions for nutrient management.

Future research should focus on optimizing bioremediation techniques across various agricultural environments to improve safety and sustainability. Refining adsorption models by incorporating diverse components and assessing environmental factors influencing pollutant sorption dynamics is critical. Exploring periodic polarization methods and the application of E-GRP to tackle different fouling types, including organic and biofouling, is a promising area for future research. Additionally, examining the impacts of pH and temperature variations on adsorption dynamics will enhance broader nutrient removal strategies. Expanding methodologies to explore interactions in larger clay particle assemblies will elucidate nanoscale clay-water retention mechanisms. Interdisciplinary research combining materials science, environmental engineering, and computational modeling is vital for advancing nutrient removal technologies. By addressing challenges related to scalability, environmental impact, and long-term stability, these innovations can significantly improve sustainable water management practices and mitigate nutrient pollution in agricultural settings.

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