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Pollutant Removal Performance of Ecological Floating Beds Treating Eutrophic Water: A Meta-analysis

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Abstract. Current studies on remediation of eutrophic water by ecological floating beds (EFBs) differ greatly in experimental scales and conditions, resulting in inconsistent purification effects and lacking unified quantitative evaluation criteria. This study conducted a meta-analysis on 104 Chinese and English papers published from 2001 to 2025, covering a total of 3,599 datasets, to quantitatively evaluate the removal efficiencies of EFBs on total nitrogen (TN), total phosphorus (TP) and chemical oxygen demand (COD). Subgroup analyses were performed based on plant functional types and EFB construction modes, and the effects of key environmental factors were systematically quantified. The results indicated that EFBs can steadily remove TN, TP and COD, with pollutant removal capacity ranked as TP > TN > COD; TN removal showed the highest stability. Floating plants achieved optimal nitrogen and phosphorus removal efficiency, emergent plants delivered stable and balanced purification performance, while terrestrial plants exhibited the poorest treatment effect. Composite EFBs equipped with fillers possessed the strongest overall treatment capacity, and mixed-plant EFBs performed better in removing organic pollutants. Operation duration and water temperature positively improved purification efficiency, and temperature exerted the most prominent promoting effect on COD degradation. Initial pollutant concentrations produced differential regulatory effects; elevated dissolved oxygen restrained purification performance, while pH exerted negligible influence. This study quantifies the performance discrepancies of EFBs under various conditions, provides reliable quantitative references for structural optimization and field application of EFBs in eutrophic water treatment, and enriches relevant theories of artificial ecological restoration.

Keywords: eutrophic water body, ecological floating bed, constructed wetland, meta-analysis

1. Introduction

The eutrophication of lakes and reservoirs worldwide has intensified year by year, becoming a critical problem to be urgently solved in watershed water environment governance [1]. With continuous advancement of domestic industrialization and large-scale expansion of agricultural planting, urban and rural domestic sewage, factory tailwater and farmland surface runoff continuously input nitrogen and phosphorus nutrients into natural water bodies, directly leading to excessive TN, TP, COD and chlorophyll-a in water, which can easily trigger large-scale

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cyanobacterial bloom disasters. Massive algal reproduction blocks underwater light and hinders normal photosynthesis of submerged plants; the decomposition process after algae death consumes a large amount of dissolved oxygen in water. The long-term anoxic environment causes massive death of aquatic organisms such as fish and shrimp, destroys the original food chain structure of water areas, continuously weakens the self-purification capacity of water bodies, and eventually evolves into malodorous black and odorous water bodies, exerting long-term adverse impacts on regional aquatic ecological security and living environment of surrounding residents [2].

Current treatment technologies for eutrophic water bodies are mainly divided into three categories: physical remediation, chemical remediation and biological-ecological remediation. Physical remediation includes sediment dredging, mechanical aeration and other methods. Although it can improve water quality in the short term, it only alleviates surface pollution and cannot fundamentally reduce internal nutrient salts; dredging construction disturbs sediment and destroys the original habitat of benthic organisms. Chemical remediation relies on dosing flocculants and phosphorus removal reagents to achieve emergency algae control, but long-term continuous dosing will form chemical sludge deposition and destroy the original ecological balance of water areas [3]. Compared with the former two types of technologies, ecological floating beds and constructed wetlands rely on symbiotic systems formed by aquatic plants, rhizosphere microorganisms and aquatic animals to complete in-situ water purification. They have the advantages of low construction cost, favorable landscape effect and long-term restoration capacity, and have become mainstream technical schemes for treating micro-polluted water in rivers and lakes [4, 5].

Sorting out existing published experimental results reveals that most experiments related to ecological floating beds are limited to laboratory static simulation or small-scale enclosure pilot tests. Experimental scales, continuous observation cycles and regional hydrological conditions vary greatly across different studies, the reported nitrogen and phosphorus removal rates fluctuate drastically in various literatures, and research conclusions show obvious divergences. A unified and universally applicable quantitative evaluation system has not been formed in the industry. Traditional qualitative reviews can only summarize existing research through textual description, and are difficult to excavate internal action rules behind massive fragmented data. Meta-analysis, as a quantitative data integration method, can combine multiple groups of independent experimental data and eliminate random errors brought by single experiments, making it suitable for systematically evaluating the comprehensive purification performance of ecological floating beds [6].

This paper quantitatively calculates the reduction levels of nitrogen, phosphorus and organic matter in water by ecological floating beds through meta-analysis. The relevant research results can improve the theoretical framework of artificial ecological restoration, provide quantitative reference data for plant screening, system structure optimization and daily operation maintenance of floating beds in engineering sites, and promote the transformation of ecological floating beds from experience-based construction to data-supported precise management. It possesses certain theoretical research value and on-site engineering guiding significance [7].

2. Data and methods

2.1. Data sources

All literature materials of this study were retrieved from two databases: China National Knowledge Infrastructure (CNKI) and Web of Science Core Collection, with the retrieval time span set from 2001 to 2025. The combined Chinese retrieval keywords were set as "ecological floating bed" and

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"constructed wetland", and corresponding subject terms were matched synchronously for English retrieval. To ensure the representativeness of included data and reliability of statistical results, clear inclusion and exclusion criteria for literature were formulated. Inclusion criteria: The experimental carrier is ecological floating beds deployed in field sites; concentration values of TN, TP and COD before and after experiments are completely recorded; blank control experimental groups are set synchronously. After preliminary retrieval, the first round of rough screening was carried out by titles and abstracts, then the full texts were read to recheck the integrity of experimental designs, and duplicate publications and literature with non-standard experimental designs were eliminated. After multiple rounds of screening and verification, 104 valid papers were finally included, and 3,599 groups of valid experimental data were sorted out.

The literature samples after screening were grouped and counted from multiple dimensions. According to plant growth habits, four groups were divided: emergent plants, floating plants, submerged plants and terrestrial plants, to distinguish the differential effects of different plant root morphologies, aeration tissue structures and physiological metabolic characteristics on absorption and transformation of nutrients in water bodies. According to the construction modes of floating bed systems, four categories were classified: single-species plant floating beds, mixed multi-species plant floating beds, coupled floating beds combining plants and aquatic animals, and enhanced floating beds combining plants and artificial fillers. Meanwhile, experimental parameters recorded in the literature such as initial pollutant concentration, water pH, dissolved oxygen (DO), water temperature and system operation duration were extracted for quantitative analysis of the influence degree of various environmental conditions on the purification effect of floating beds.

2.2. Meta-analysis

Referring to the research of Tian et al. [8], response ratio (RR) was adopted to characterize the relative change of pollutant concentration before and after treatment by artificial ecological systems, and the calculation formula is shown in Formula (1). X represents the average pollutant concentrations of the control group and treatment group (influent and effluent) respectively. The lower the value of ln(RR), the higher the pollutant removal efficiency. Due to large differences in water pollution types, treatment processes, plant species and planting densities, logarithmic response ratios were used to avoid interference from extreme values [9]. The calculation method of experimental data weight is shown in Formula (2), where N is the number of experimental replicates; higher replicate numbers correspond to stronger data reliability.

$$\ln(\mathrm{RR}) = \ln(\mathrm{X}_{\mathrm{treatment}}/\mathrm{X}_{\mathrm{control}}) \tag{1}$$

$$W_t = \frac{\mathrm{N}_{\mathrm{treatment}} \times \mathrm{N}_{\mathrm{control}}}{\mathrm{N}_{\mathrm{treatment}} + \mathrm{N}_{\mathrm{control}}} \tag{2}$$

Mixed-effects models were constructed with the lme4 package on the R Studio platform to process multi-group observation data. Mixed-effects models integrate fixed effects and random effects, serving as mainstream analytical tools for meta-analysis [10]. Fixed effects assume that all experiments share a unified true effect value, and observation differences only derive from sampling

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errors; random effects hold that effect values of each study have natural differences, and the analysis target is the overall mean effect.

3. Results

3.1. Overall analysis

A negative lnRR value indicates that the floating bed system can remove pollutants, and a larger absolute value corresponds to better purification effect; standard deviation reflects the dispersion degree of effect values in each group, directly representing result stability, while sample size determines the credibility of statistical conclusions. Statistical results of all data show that the weighted effect values of the three pollutants TN, TP and COD are all negative, proving that ecological floating beds can stably remove the three types of pollutants in water (Figure 1).

TP achieves the optimal overall removal effect, with a weighted effect value of -0.57±0.11 and 3,266 groups of valid samples, the largest sample size, which endows the conclusion stronger universality. The moderate standard deviation indicates slight fluctuations in TP removal effects under different experimental scenarios. TN removal ranks second, with a weighted effect value of -0.52±0.08 and 3,062 groups of samples. Its standard deviation is the lowest among the three pollutants, meaning that the denitrification effect of ecological floating beds has a small dispersion degree, high consistency of experimental conclusions and strong statistical credibility. COD removal presents the weakest performance, with a weighted effect value of only -0.49±0.14 and the minimum sample size of 2,107 groups. Meanwhile, its standard deviation reaches the maximum, illustrating that COD removal effects show obvious inter-group differences and poor purification stability.

Synthesizing all data characteristics, the pollutant removal capacity order of ecological floating beds is TP > TN > COD, and the purification stability order is TN > TP > COD. Overall, ecological floating beds deliver favorable and stable purification effects on nitrogen and phosphorus nutrients in water bodies, while their capacity to reduce organic pollutant COD is limited, with wider fluctuations of purification effects under different scenarios.

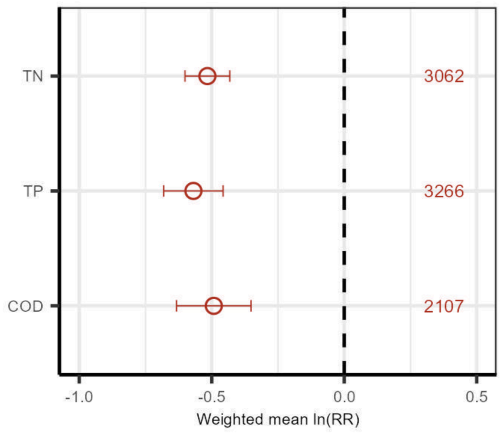

Figure 1. Overall analysis. Circles represent weighted mean effects and their 95% confidence intervals (CIs). Numbers on the right denote sample sizes. An effect value is significant if its 95% confidence interval does not intersect zero

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3.2. Subgroup analysis

Statistical results grouped by plant growth habits are shown in Figure 2. Floating plant floating beds exhibit the optimal comprehensive pollutant removal performance, with TN removal effect of -0.66±0.11 and TP removal effect of -0.73±0.15, representing the highest nitrogen and phosphorus removal levels among the four plant categories; however, floating plants only achieve a COD removal effect of -0.41±0.17 with merely 189 groups of valid samples, presenting weak capacity to degrade organic pollutants. Emergent plant floating beds deliver balanced purification levels for all types of pollutants, with TN, TP and COD removal effects of -0.63±0.10, -0.66±0.13 and -0.49±0.15 respectively. The removal effects of all three indicators fall within the medium-upper range, and the large sample sizes of 992 to 998 groups guarantee stable and reliable statistical results. Submerged plant floating beds show weak overall pollutant removal capacity, with sequential TN, TP and COD effect values of -0.37±0.13, -0.48±0.16 and -0.31±0.18, corresponding to low comprehensive purification levels. Terrestrial plant floating beds deliver the poorest pollutant removal effects among the four categories, with TN, TP and COD removal effects only reaching -0.38±0.20, -0.37±0.19 and -0.32±0.18. The standard deviation values of each group are relatively large, indicating high data dispersion within groups and drastic fluctuations in purification effects.

Obvious inter-group differences exist in data after grouping by floating bed construction modes (Figure 2). Single-plant floating beds possess the largest sample sizes (TN=1981, TP=2039, COD=1347) and the highest statistical credibility, with TN, TP and COD removal effects of -0.56±0.09, -0.60±0.12 and -0.44±0.14 respectively. They realize stable and reliable nitrogen and phosphorus purification with medium organic matter removal effects. Mixed multi-plant floating beds display differentiated purification characteristics: their TN and TP removal effects are relatively weak, with effect values of -0.37±0.13 and -0.40±0.15, while the COD removal effect reaches -0.53±0.17, ranking the highest in all single plant configuration modes. This reflects the unique advantage of multi-species collocation in degrading organic pollutants in water bodies.

All composite enhanced floating beds deliver markedly better overall pollutant removal performance than single-plant floating beds. Coupled floating beds combining plants and aquatic animals achieve balanced removal levels for the three pollutants, with TN, TP and COD effect values of -0.52±0.17, -0.56±0.23 and -0.52±0.20 respectively, without obvious weak points. Nevertheless, the standard deviations of each group are generally high, indicating that the plant-animal symbiotic system is highly susceptible to external environmental interference and generates volatile purification effects. Enhanced floating beds combining plants and artificial fillers possess the strongest comprehensive pollutant removal capacity among all configuration modes, with sequential TN, TP and COD removal effect values of -0.52±0.14, -0.63±0.17 and -0.61±0.16. Particularly, their COD removal effect is obviously superior to other groups, which verifies that artificial fillers can compensate for the insufficient organic pollutant removal capacity of traditional single-plant floating beds.

Summary of rules derived from subgroup data: Among single plant systems, floating plants present the best nitrogen and phosphorus removal effects, emergent plants realize stable and balanced purification of all pollutants, while terrestrial plants are poorly adapted to eutrophic water restoration scenarios. In terms of configuration modes, filler-composite enhanced floating beds deliver optimal comprehensive pollutant removal capacity, mixed multi-plant floating beds are more suitable for treating organically polluted water bodies, and single-plant floating beds feature wide applicable scenarios and stable operation effects. All lnRR calculation results of each group are negative, confirming that all types of ecological floating beds possess pollutant removal capacity for

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water bodies, with only obvious distinctions in purification intensity and effect stability among different groups.

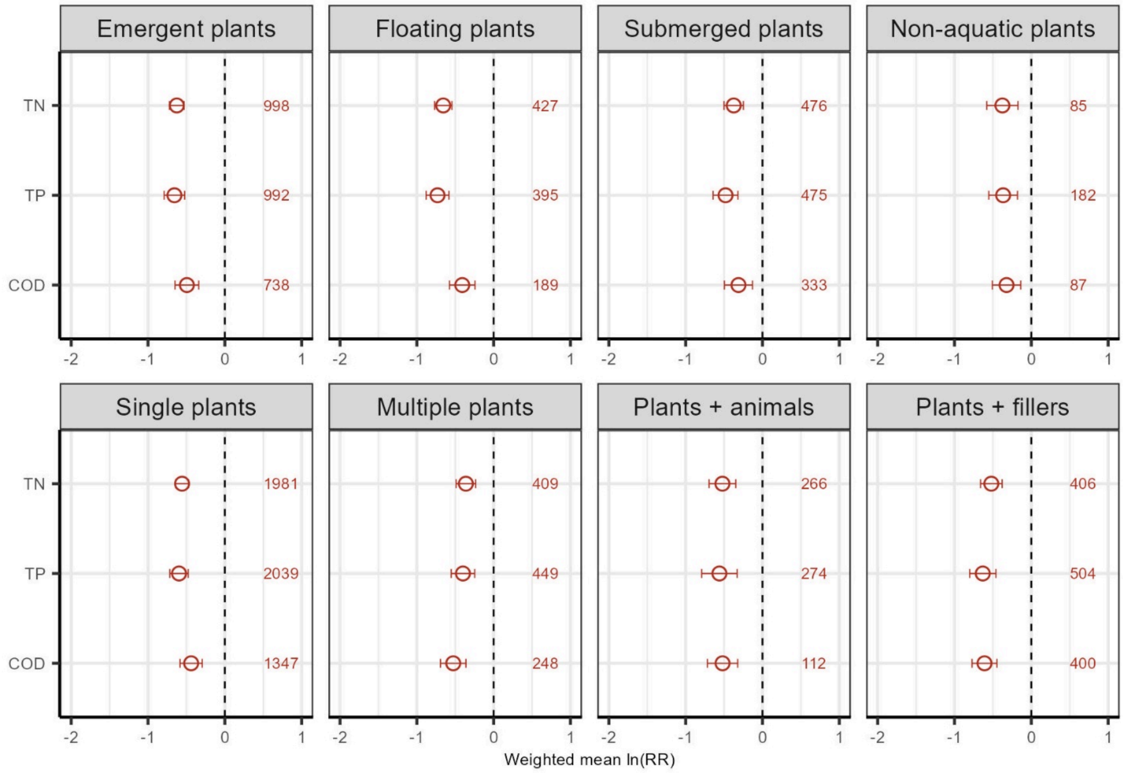

Figure 2. Subgroup analysis. Circles represent weighted mean effects and their 95% confidence intervals (CIs). Numbers on the right denote sample sizes. An effect value is significant if its 95% confidence interval does not intersect zero, otherwise it is insignificant

3.3. Analysis of influencing factors

Weighted slopes of various environmental factors are mainly negative, which illustrates that different environmental conditions exert differentiated regulatory effects on the purification performance of ecological floating beds, and also explains the internal causes of fluctuating pollutant removal effects of floating beds under various field scenarios (Figure 3).

System operation duration acts as the most stable and credible positive factor regulating floating bed purification performance, supported by thousands of groups of large samples for all three pollutants with slight data fluctuations. Statistical results show that the weighted slopes of operation duration on TN, TP and COD removal are -0.26±0.03, -0.24±0.03 and -0.17±0.03 respectively, corresponding to sample sizes of 3,062, 3,266 and 2,107 groups. The regulatory slopes of the three indicators are stably negative, meaning that as the system operation cycle extends, the capacity of ecological floating beds to purify nitrogen, phosphorus and organic matter continuously improves. From the perspective of quantitative differences, the promotion amplitudes of operation duration on TN and TP removal are roughly equal and significantly higher than that on COD, indicating that cumulative purification effects brought by long-term operation are more suitable for adsorption, interception and microbial degradation processes of nitrogen and phosphorus in water bodies. Meanwhile, the standard deviations of the three datasets of this factor are all at low levels. Combined with support from large sample data, it can be confirmed that the positive regulatory rule

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of operation duration on floating bed purification performance boasts strong universality and low dispersion, serving as a key condition to guarantee long-term stable operation of floating beds.

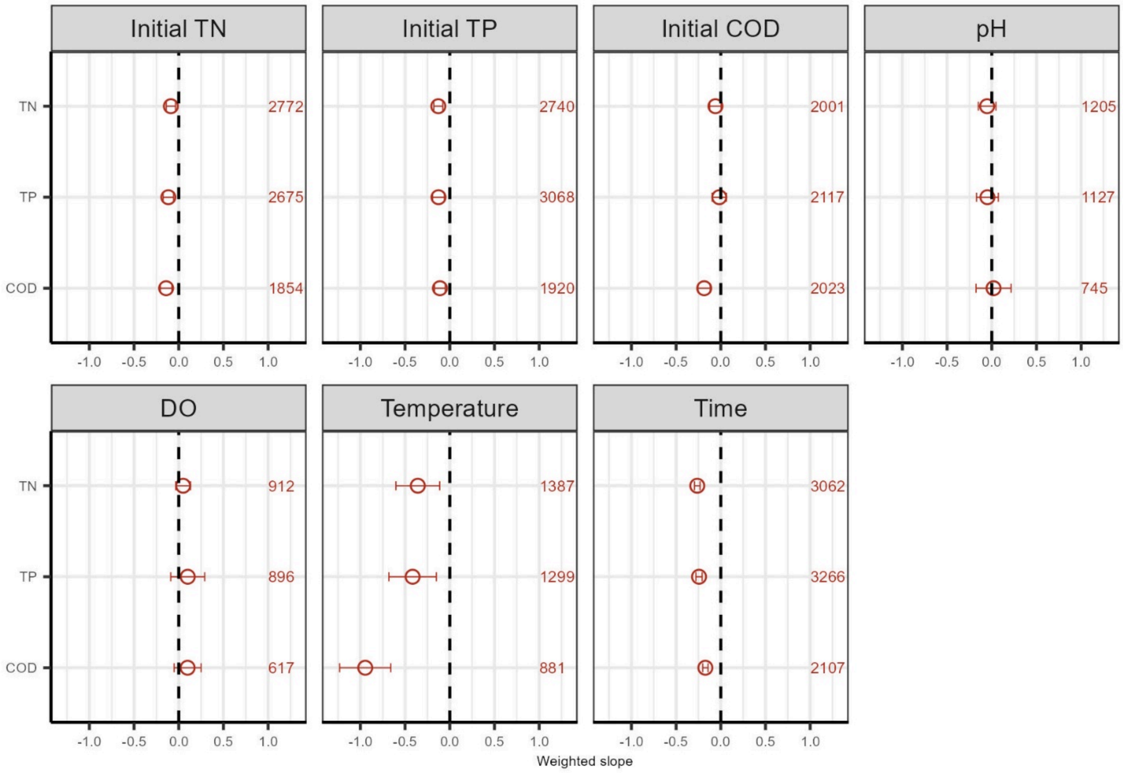

Figure 3. Analysis of influencing factors. Circles represent weighted slopes and their 95% confidence intervals (CIs). Numbers on the right denote sample sizes. An effect value is significant if its 95% confidence interval does not intersect zero, otherwise it is insignificant

Initial pollutant concentrations in water bodies exhibit obvious specificity in regulating floating bed purification performance, and the promotion amplitudes of different initial pollution indicators on removal of the three pollutants are significantly differentiated. Initial TN concentration exerts broad-spectrum positive effects on overall pollutant removal, with weighted slopes of -0.09±0.05, -0.12±0.06 and -0.14±0.07 on TN, TP and COD removal respectively, corresponding to sample sizes of 2,772, 2,675 and 1,854 groups. Higher initial nitrogen concentrations in water slightly elevate the removal effects of floating beds on all three pollutants, with a relatively prominent gain in COD degradation. The regulatory rule of initial TP concentration is balanced and stable, with sequential slopes of -0.13±0.05, -0.13±0.07 and -0.11±0.06 on TN, TP and COD removal, corresponding to sample sizes of 2,740, 3,068 and 1,920 groups. It delivers mild positive promotion effects on all three pollutants without obvious preference, and low standard deviations guarantee stable regulatory effects. Initial COD concentration displays extremely strong regulatory specificity: it only significantly elevates the removal level of COD itself, with a weighted slope of -0.19±0.07 (2,023 groups of samples); its promotion amplitude on TN removal is weak (-0.06±0.06, 2,001 groups); it barely regulates TP removal effects (-0.02±0.08, 2,117 groups). This proves that initial organic carbon in water can only specifically strengthen COD degradation and exerts no obvious auxiliary effect on nitrogen and phosphorus purification.

Water pH and dissolved oxygen (DO) deliver weak overall regulatory intensity with high data dispersion. Among them, DO inhibits floating bed purification performance, while slight fluctuations of pH barely alter overall pollutant removal levels. Water pH generates weak positive promotion effects on TN and TP removal, with weighted slopes of -0.05±0.10 and -0.05±0.12 respectively, corresponding to sample sizes of 1,205 and 1,127 groups. Nevertheless, the standard deviation values of both groups are relatively high with large inter-group data differences, meaning that the regulatory effects of pH on nitrogen and phosphorus purification are highly susceptible to interference from experimental scenarios. Meanwhile, pH presents slight inhibitory effects on COD removal with a slope of 0.02±0.20 (745 groups), completely losing positive promotion capacity. This indicates that minor fluctuations of conventional water pH cannot effectively regulate the organic pollutant degradation capacity of floating beds. DO uniformly exerts negative regulatory effects on removal of all three pollutants, with sequential slopes of 0.05±0.08, 0.10±0.19 and 0.10±0.15, corresponding to sample sizes of 912, 896 and 617 groups. Higher dissolved oxygen levels in water weaken the pollutant removal effects of floating beds, and the standard deviations corresponding to TP and COD rise sharply, demonstrating that the inhibitory intensity brought by DO varies drastically across regions and scenarios, acting as a secondary limiting factor causing inconsistent floating bed purification effects in different water areas.

Water temperature is the positive regulatory indicator with the strongest regulatory intensity, most obvious inter-group differences and highest sensitivity among all observed factors, directly determining the overall pollutant removal capacity of ecological floating beds. The weighted slopes of water temperature on TN, TP and COD removal are -0.36±0.25, -0.42±0.27 and -0.95±0.29 respectively, corresponding to sample sizes of 1,387, 1,299 and 881 groups. All slopes present strong negative values, with regulatory amplitudes far exceeding other factors such as operation duration and initial pollutant concentrations. Quantitative data reveal that water temperature delivers the most prominent promotion effect on COD degradation, serving as the core environmental condition driving mineralization and decomposition of organic matter; its promotion amplitude on TP removal ranks second, and its regulatory intensity on TN removal is relatively weak but still classified as a strong positive effect. It should be noted that the standard deviations of the three water temperature indicators rank high among all datasets, representing extremely strong inter-group heterogeneity of temperature regulatory effects. Seasonal and regional temperature fluctuations directly trigger drastic variations in floating bed purification effects in field sites, which are core inducements for unstable on-site purification performance.

Synthesizing statistical rules of all environmental factors: Operation duration and water temperature act as core positive regulatory indicators that can significantly improve floating bed pollutant removal capacity; dissolved oxygen serves as a major negative limiting factor; initial pollutant concentrations produce differentiated fine-tuning effects; water pH delivers weak overall regulatory intensity and barely exerts obvious influences on floating bed pollutant removal efficiency.

4. Discussion

By integrating large-sample datasets, this study quantitatively reveals the discrepancies in removal efficiency of TN, TP and COD in water by different types of ecological floating beds as well as their key regulating environmental factors based on lnRR effect values and weighted slopes. Quantitative results clearly elaborate the overall pollutant removal effects, subgroup differentiation characteristics and environmental response rules of ecological floating beds, providing data support for technical selection, parameter optimization and scenario adaptation of ecological restoration technologies for eutrophic water bodies.

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4.1. Pollutant removal mechanisms and effect discrepancies of ecological floating beds

Overall effect statistical results confirm that all types of ecological floating beds can stably reduce TN, TP and COD in water bodies, with pollutant removal capacity ordered TP > TN > COD and purification stability ordered TN > TP > COD. Subgroup analysis results demonstrate that plant species selection and floating bed construction modes are two core factors for artificially regulating purification performance. Plant roots can fix nitrogen and phosphorus in plant tissues through biological assimilation to complete physical interception of nutrients in water. Water denitrification mainly relies on three pathways: denitrification, sediment interception and plant absorption, among which denitrification contributes nearly 80% of total nitrogen removal. Phosphorus removal is realized through filler adsorption, water sedimentation and complexation reactions; microorganisms can convert organic phosphorus in water into inorganic phosphorus, which is then fixed and removed via assimilation by plants and microorganisms. As an indicator characterizing organic pollution in water, COD degradation mainly depends on aerobic metabolism of microorganisms and is directly correlated with variations of dissolved oxygen content in water.

Statistical results grouped by plant growth habits show that floating plants deliver optimal capacity to remove nitrogen and phosphorus in water, while emergent plants achieve balanced and stable purification levels for all pollutants. Both plant types are more suitable for conventional restoration of eutrophic rivers and lakes. Submerged and terrestrial plants exhibit obviously low overall pollutant removal capacity. Emergent plants can promote phosphorus activation and absorption through regulation of rhizosphere microenvironment, yet most plant biomass is exposed above the water surface, resulting in limited contact area with dissolved phosphorus in water bodies. Submerged plants are fully submerged underwater but are highly susceptible to water turbidity and insufficient underwater light, making it difficult to maintain stable growth in heavily eutrophic water bodies. Terrestrial plants lack adaptive capacity to long-term waterlogging, and their roots tend to rot after prolonged immersion, failing to exert stable purification functions [11].

Although floating plants deliver outstanding phosphorus removal performance, independent deployment also brings obvious drawbacks. Floating plants present low removal efficiency of nitrate nitrogen (NO_3^--N), and large-area surface coverage hinders atmospheric reoxygenation of water bodies and inhibits activity of aerobic microorganisms. Most current studies recommend constructing three-dimensional composite floating beds combining floating and emergent plants, which integrate the advantages of high-efficiency phosphorus removal by floating plants and stable nitrogen removal by emergent plants to realize functional complementarity [11]. Three-dimensional configuration can not only fully utilize the vertical space of water bodies, but also enrich types of root exudates, promote proliferation of heterotrophic microbial communities, and further elevate mineralization efficiency of degradable organic matter.

From the perspective of floating bed construction modes, single-plant and composite enhanced floating beds possess distinct functional divisions. Single-plant floating beds feature wide applicable scenarios and stable operation effects, suitable for large-scale conventional river and lake treatment projects. Mixed multi-species collocation systems can significantly improve COD removal capacity, compensating for the insufficient organic matter degradation capacity of single plants through functional complementarity among species. Among them, enhanced floating beds combining plants and artificial fillers deliver optimal comprehensive pollutant removal capacity with the most prominent promotion amplitude of COD removal, which verifies that artificial fillers such as ceramsite, biochar and sponge iron can optimize the internal structure of floating beds, increase microbial attachment carriers and strengthen filtration and adsorption effects of water bodies,

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serving as effective reconstruction means to make up for the insufficient organic pollutant removal capacity of traditional floating beds. Coupled systems combining plants and aquatic animals (snails, mussels, filter-feeding fish) theoretically possess complete producer-consumer-decomposer food chains capable of realizing synergistic purification through material circulation, yet data fluctuate drastically in actual experiments. Such instability originates from high sensitivity of aquatic animals to environmental changes: temperature fluctuations directly alter animal metabolic rates and feeding intensity, and water quality deterioration easily triggers mass mortality; undegraded animal excreta may transform into internal pollution and instead aggravate nutrient loads in water bodies.

4.2. Analysis of factors influencing purification performance of ecological floating beds

System operation duration acts as a low-heterogeneity, high-stability positive regulatory factor. With continuous extension of restoration cycles, plant growth tends to mature and stabilize, rhizosphere microbial community structures improve, and pollutants in water bodies are continuously adsorbed and degraded, leading to steady elevation of nitrogen and phosphorus removal effects. The cumulative promotion effects of operation duration on nitrogen and phosphorus are obviously superior to those on COD, which also explains the technical characteristic that long-term operated floating beds are more suitable for treating nitrogen-phosphorus eutrophic water bodies. Nevertheless, the observation cycles of most pilot tests in existing research only last 1 to 2 months. Although short-term experiments can confirm the rapid pollutant removal capacity of floating beds, sufficient data support is still lacking for long-term evolution rules of field operation, requiring subsequent long-term in-situ monitoring.

Initial pollutant concentrations present positive correlations with removal effects: higher initial nutrient concentrations in water bodies correspond to higher unit-time pollutant removal quantities of floating beds. Water pH exerts weak regulatory intensity on overall floating bed purification performance, and minor fluctuations of acid-base conditions will not significantly alter pollutant removal levels, proving that this technology can adapt to various natural water bodies with wide pH ranges. Elevated dissolved oxygen inhibits floating bed purification capacity, mainly because high dissolved oxygen environments destroy anaerobic and anoxic microhabitats in floating bed root zones, significantly hindering denitrification and anaerobic degradation of organic matter. Water temperature acts as the positive environmental factor with the strongest regulatory intensity and highest heterogeneity. High temperatures accelerate microbial metabolic rates, promote plant growth and reproduction, and elevate pollutant degradation speeds, with the most prominent promotion effect on COD degradation. However, annual and seasonal temperature fluctuations are substantial, directly causing significant spatial-temporal variations in purification effects of field projects, serving as core inducements for unstable on-site purification performance during operation and maintenance.

Synthesizing all quantitative data, ecological floating beds represent high-efficiency ecological technologies for treating nitrogen and phosphorus eutrophication in water bodies. Single-plant modes are suitable for restoration of conventional small and medium-sized water bodies, while composite floating beds equipped with artificial fillers can simultaneously and efficiently remove nitrogen, phosphorus and organic pollutants. Extending system operation duration and regulating water temperature can effectively improve purification levels, and excessively high dissolved oxygen in water bodies restrains pollutant removal capacity of floating beds. During practical engineering design stages, composite floating beds constructed with floating plants, emergent plants and artificial fillers can be prioritized, and the purification potential of ecological floating beds can

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be maximized by reasonably extending restoration cycles and synchronously controlling dissolved oxygen levels in water bodies.

4.3. Limitations and future research perspectives

The dataset integrated in this study suffers from partial missing indicators and incomplete supporting experimental background information, and such data defects will increase uncertainties in merged meta-analysis results to a certain extent. In addition, this paper only completes comparative grouping by plant life forms without analyzing discrepancies in removal efficiency of single plant species. The core reason for such research design lies in the wide variety of suitable plants applicable to ecological floating bed engineering, as well as significant differences in planting densities and deployment scales of the same plant across various literatures. Direct horizontal comparison at the single species level lacks unified reference standards; further subdivision into single-species groups will drastically aggravate data missing and insufficient sample sizes within subgroups. Subsequent research needs to expand field in-situ monitoring samples, improve records of full-dimensional experimental background indicators, and conduct control variable experiments to unify plant planting conditions, realizing quantitative differentiation of water purification capacity of different single species.

5. Conclusions and prospects

This study integrated 3,599 groups of samples from 104 papers via meta-analysis, quantitatively clarifying that ecological floating beds deliver significant purification effects on TN, TP and COD in eutrophic water bodies, with overall pollutant removal capacity ordered TP > TN > COD and optimal stability of denitrification effects. Purification efficiency varies significantly among different aquatic plants and floating bed configuration modes: single floating plants present prominent advantages in nitrogen and phosphorus removal, emergent plants realize stable and balanced comprehensive purification, filler-composite enhanced floating beds can simultaneously and efficiently remove nitrogen, phosphorus and organic pollutants, mixed multi-plant systems deliver prominent gains in COD degradation, while terrestrial plants and plant-aquatic animal coupled systems generate poor pollutant removal effects with drastic fluctuations. Operation duration and water temperature serve as core positive factors improving floating bed pollutant removal capacity, initial pollutant concentrations produce differentiated regulatory characteristics, elevated dissolved oxygen in water bodies inhibits system purification performance, and conventional pH variations exert no obvious influences on floating bed pollutant removal efficiency. Comprehensive quantitative results indicate that ecological floating beds represent high-efficiency ecological technologies for treating nitrogen and phosphorus eutrophication in water bodies. In engineering practice, composite floating beds constructed with floating plants, emergent plants and artificial fillers can be prioritized, and purification efficiency can be maximized by extending restoration cycles and controlling dissolved oxygen levels in water bodies. Most experiments in existing literature are short-term small-scale simulations, and the coupling effects of long-term field operation rules, seasonal temperature differences, internal sediment pollution and emerging pollutants on floating bed purification performance remain unclear. Subsequent research needs to carry out long-term in-situ field monitoring to further improve precise regulation theories and engineering application systems of ecological floating beds under multi-environment coupling conditions.

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