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Modified hydrogels against phosphorus pollution in aqueous environments: a meta-quantitative analysis of performance and key influencing factors

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ADMINISTRATIVE INFORMATION

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Conflicts of interest - None declared.

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Amendments - This protocol was registered with the International Platform of Registered Systematic Review and Meta-Analysis Protocols (INPLASY) on 12 August 2026 and was last updated on 12 August 2026.

INTRODUCTION

Review question / Objective Specifically, the research progress on the topic of modified hydrogels over the past decade was systematically summarized, with a focus on the key breakthroughs and technological applications of modified hydrogels for phosphorus pollution control. According to different components of reinforced active sites, various hydrogel modification systems were recorded, classified and subjected to quantitative analysis (such as inorganic, organic, bio-based, inorganic-organic, and inorganic-inorganic composite materials to enhance adsorption efficiency). Our primary objectives included: i) quantification of the overall dissolved P removal efficiency of the modified hydrogels; and ii) investigation of the influence of various factors (such as pH, initial P concentration, reinforced component, dosage, reaction time and temperature, etc.) on the P pollution removal performance of these materials. The outcomes of this study will provide further understanding of hydrogels that could serve as valuable references for researchers and engineering practitioners assisting in alternative means for control of P pollution, especially in its dissolved form.

Condition being studied Phosphorus pollution has become one of the most critical environmental issues facing river basins, posing severe challenges to water environment management and remediation. Modified hydrogels hold great promise for application for phosphorus pollution treatment. Nevertheless, the phosphorus removal efficiencies of modified hydrogels reported in the literature differ significantly, their practical application effects are still debated, and the influences of operating conditions remain unclear. These limit practical application of modified hydrogels and often lead to difficulties in determining appropriate dosage. To address this, our study conducted a systematic quantitative meta-analysis to integrate and compare existing data on the phosphorus removal performance of modified hydrogels.

METHODS

Search strategy This study was based on a systematic literature screening process, which consisted of four steps: i) initial literature search within a specific publication timeframe; ii) further screening based on titles' and abstracts' contents; iii) full-text review and assessment against certain criteria; and iv) identification of the final set of studies for analysis. This systematic literature search was conducted using the Web of Science database, using the keywords "hydrogel," "phosphate/phosphorus," and "removal." Eligible studies had to be published between January 2016 and December 2025 and address P removal using hydrogels. A total of 386 peer-reviewed articles were retrieved and screened against the above criteria.This systematic literature search was conducted using the Web of Science database, using the keywords "hydrogel," "phosphate/phosphorus," and"removal.".

Participant or population In the phosphate removal experiment, the experimental group monitored concentration variations with modified hydrogel, while the control group tracked concentration changes without modified hydrogel treatment.

Intervention In the phosphate removal experiment, the experimental group monitored concentration variations with modified hydrogel, while the control group tracked concentration changes without modified hydrogel treatment.

Comparator The research object of this experiment is the phosphate removal performance of various modified hydrogel materials.

Study designs to be included Differences in phosphate removal performance between the experimental groups and control groups will be explored under varied conditions, including different reinforcing materials, pH values, temperatures, coexisting ions, treatment durations and dosages. On this basis, the modified hydrogel material with optimal removal performance can be screened. Furthermore, the importance of each influencing factor will be evaluated according to the magnitude of heterogeneity.

Eligibility criteria • Titles and abstracts of the retrieved papers must relate to the topic of hydrogel-mediated P removal to ensure that the studies are relevant.
• Review articles were excluded.
• Selected papers must include data related to different water body types and any of the corresponding conditions/parameters: pH, temperature, reaction time, coexisting ions, dosage, and P removal efficiency.
• The data validity was then verified ensuring each study included an adequate number of samples and observations, as well as the mean and standard deviation for both the control and treatment assays.
• A rigorous sample data verification was performed to check the mathematical consistency of the reported results, screen for obvious outliers, and exclude studies with irreconcilable data errors or duplicated datasets. The latter accounts for the criteria that were assessed in the quantitative assessment of the modified hydrogels' effectiveness against phosphorus removal.

Information sources This study was based on a systematic literature screening process, which consisted of four steps: i) initial literature search within a specific publication timeframe; ii) further screening based on titles' and abstracts' contents; iii) full-text review and assessment against certain criteria; and iv) identification of the final set of studies for analysis. This systematic literature search was conducted using the Web of Science database, using the keywords "hydrogel," "phosphate/phosphorus," and "removal." Eligible studies had to be published between January 2016 and December 2025 and address P removal using hydrogels. A total of 386 peer-reviewed articles were retrieved and screened against the above criteria.

Main outcome(s) The meta-analysis on selected hydrogel-based studies from over the past decade confirmed that P pollution reduction loads from water bodies using modified hydrogel technology is feasible and highly dependent on several environmental and operational conditions. Specifically, modification strategy is the key factor determining P pollution removal efficiency with inorganic-inorganic hydrogels that are maintained in a wet state exhibiting optimal performance. Competition mechanisms for active sites on the hydrogels, especially from HCO_3^- compounds, have been identified as the strongest P adsorption inhibitor of hydrogels. Furthermore, in descending order, based on influencing P removal from hydrogels, coexisting ions, pH, initial phosphorus concentration, hydrogel dosage, temperature, hydrogel morphology, and reaction time influence P fate in water bodies but are considered secondary factors with their contribution rates (R^2) ranging between 9.03% and 0.33%. Despite the promising prospects of hydrogels against P pollution in principle, this new environmental strategy also faces numerous challenges that need

to be highlighted. The stability of hydrogels under extreme temperature (both high and low) conditions, their degradation rate under varying conditions, the risk of metal leaching over time, and the durability of the reinforcement material are key factors that remain unknown, and currently decelerate the transition from Research & Development to practical applications.

Quality assessment / Risk of bias analysis Finally, to assess potential publication bias, funnel plots were generated and Egger's regression test was performed, with effect sizes weighted by the inverse of the variance. A p-value < 0.05 for Egger's test was considered indicative of statistically significant asymmetry. Notably, a markedly asymmetric funnel plot combined with Egger's test may suggest publication bias—i.e., statistically significant positive results are more likely to be submitted and published, whereas non-significant or negative studies are often delayed or omitted, leading the distribution of included effect sizes to deviate from the theoretical symmetric state.

Strategy of data synthesis Finally, to assess potential publication bias, funnel plots were generated and Egger's regression test was performed, with effect sizes weighted by the inverse of the variance. A p-value < 0.05 for Egger's test was considered indicative of statistically significant asymmetry. Notably, a markedly asymmetric funnel plot combined with Egger's test may suggest publication bias—i.e., statistically significant positive results are more likely to be submitted and published, whereas non-significant or negative studies are often delayed or omitted, leading the distribution of included effect sizes to deviate from the theoretical symmetric state.

Subgroup analysis We conducted subgroup analyses based on different modified hydrogels, diverse reinforcement systems, varied gel morphologies, and interference from different coexisting ions.

Sensitivity analysis We will conduct subgroup analyses based on the type of modified hydrogel, reinforcement system, gel morphology, and interference from coexisting ions. We will use meta-regression to quantitatively explore the continuous factors contributing to heterogeneity. We will also assess the risk of bias (publication bias). This review will not perform sensitivity analyses. We will comprehensively investigate the sources of heterogeneity solely through subgroup analyses and meta-regression.

Country(ies) involved The studies included in this review were conducted in China, South Korea, the United States, Brazil, Romania, New Zealand, Ethiopia, Algeria, Malaysia, India, Poland and Switzerland.

Keywords Modified hydrogel; Reinforced component; Phosphorus pollution removal; Meta-analysis.

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