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Review article

Thermal Modification of Water Treatment Residuals for Enhanced Phosphorus Removal: A Systematic Review and Meta-Analysis

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Abstract

Phosphorus pollution from municipal and agricultural sources drives freshwater eutrophication globally, yet conventional removal technologies permanently immobilize phosphorus in metal laden sludge, precluding nutrient recovery. Water treatment residuals (WTRs) aluminum and iron rich byproducts of coagulation flocculation processes represent abundant, low-cost precursors for phosphorus adsorbent development. This systematic review and meta-analysis quantitatively evaluated the effectiveness of WTR modification techniques, with particular focus on thermal modification, for enhanced phosphorus removal from wastewater. Following the PRISMA 2020 guidelines, systematic searches of Scopus, Science Direct, Engineering Village, and ProQuest (2000-2024) identified 32 studies meeting predefined eligibility criteria, of which 10 reporting sufficient statistical parameters were included in quantitative meta-analysis. Standardized mean differences (SMD) with 95% confidence intervals were calculated using random effects REML models, with subgroup analyses stratified by modification method, treatment temperature, material composition, and physical form. Thermal modification exceeding 300°C emerged as the most effective enhancement strategy, yielding a statistically significant subgroup effect size of SMD = 1.24 [95% CI: 0.62, 1.87] ($p<0.001$; $I^2 = 1.95\%$). The overall pooled effect was non-significant (SMD = 0.32, $p = 0.64$; $I^2 = 83.40\%$), attributable to methodologically heterogeneous pooling including air drying (SMD = −2.25, $p<0.001$) rather than absence of genuine thermal enhancement. Powdered WTRs outperformed granular forms (SMD = 0.97, $p = 0.01$). Maximum adsorption capacity reached 37.8 mg P/g, following pseudo second order kinetics ($R^2 = 0.9923$) and Langmuir isotherm behavior ($R^2 = 0.9889$). Operational cost was confirmed at 0.74 USD/kg P removed, which was substantially lower than conventional adsorbents (1.60-20.26 USD/kg P) with environmental reductions in carbon footprint (87%), energy consumption (81%), and water usage (82%). Thermal modification above 300°C establishes thermally activated WTRs as technically viable, cost effective, and environmentally sustainable materials for wastewater phosphorus management, with future research priorities including field scale validation, regeneration optimization, and circular nutrient recovery.

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1. Introduction

Phosphorus (P) pollution from agricultural runoff, municipal wastewater discharge, and industrial effluents drives freshwater eutrophication globally, triggering harmful algal blooms, oxygen depletion, and ecosystem degradation (Carpenter, 2008; Schindler et al., 2008; Conley et al., 2009). Simultaneously, phosphorus represents a finite and non-substitutable resource. Global phosphate rock reserves are projected to face significant depletion pressure within this century positioning phosphorus management as both an environmental imperative and a resource security challenge (Cordell et al., 2011; Koppelaar & Weikard, 2013). Conventional phosphorus removal technologies, including chemical precipitation and enhanced biological removal, are structurally misaligned with this dual challenge: they permanently immobilize phosphorus in metal-laden sludge, generating substantial secondary waste while precluding nutrient recovery (Loganathan et al., 2014; Ye et al., 2017). These limitations have driven sustained interest in adsorption-based approaches capable of capturing phosphorus in recoverable forms (Egle et al., 2016; Kumar et al., 2019). Water treatment residuals (WTRs), such as the aluminum and iron rich byproducts of coagulation flocculation processes used in drinking water production represent an abundant and largely underutilized candidate for phosphorus adsorbent development. Global WTR production reaches millions of tonnes annually, with conventional disposal via landfilling and sewer discharge imposing substantial economic and environmental costs (Babatunde & Zhao, 2007; Ahmad et al., 2016; Zhao et al., 2018). The high content of aluminum and iron oxides/hydroxides in WTRs confers strong phosphate affinity through ligand exchange and surface complexation mechanisms (Kim et al., 2011; Bai et al., 2014; Hou et al., 2018). However, the direct application of raw WTRs is constrained by variable adsorption performance, risk of inherent phosphorus release, and physical instability under operational conditions (Razali et al., 2007; Li et al., 2018; Tie et al., 2021). These limitations have motivated research into modification techniques including thermal treatment, chemical activation, and granulation to enhance WTR phosphorus removal performance and practical deployability.

Despite growing research activity, the evidence base for WTR modification remains fragmented and difficult to synthesize. Existing reviews have addressed raw WTR applications in environmental management (Ippolito et al., 2011; Keeley et al., 2014) and general modification approaches (Hasan et al., 2020), while more recent assessments have examined specific application contexts (Sharma & Ahammed, 2023). However, three critical limitations persist in the current literature. First, no quantitative comparison of modification technique effectiveness using standardized effect sizes exists, preventing evidence-based selection of optimal modification strategies. Second, the relative contributions of thermal, chemical, and granulation approaches have not been evaluated under a unified statistical framework. Third, the sources of performance variability across studies attributable to WTR composition, experimental conditions, and physical form have not been systematically characterized. These gaps constrain translation of laboratory findings into evidence-based implementation guidelines. The present systematic review and meta-analysis address these gaps by providing the first quantitative synthesis of WTR modification effects on phosphorus adsorption capacity. Following PRISMA 2020 guidelines, we synthesized evidence from 32 studies published between 2000 and 2024. This temporal scope was selected to capture the full evolution of WTR modification research from early foundational characterization studies through to recent optimization investigations, with over 78% of included evidence originating from 2010 onwards. The primary objectives were to quantify the effects of thermal, chemical, and granulation modification on phosphorus adsorption capacity using standardized mean differences with 95% confidence intervals; identify the optimal thermal modification parameters through temperature-stratified subgroup analysis; characterize sources of between-study heterogeneity; synthesize physicochemical, kinetic, thermodynamic, and mechanistic evidence supporting the meta-analytical findings; and evaluate the economic and environmental viability of WTR-based phosphorus management within a circular economy framework.

2. Materials and Methods

2.1 Protocol and reporting guidelines

This systematic review and meta-analysis were conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021). The review was structured around a predefined PICO framework to ensure methodological transparency and reproducibility. The target population comprised aqueous systems containing phosphorus, including synthetic phosphate solutions, municipal wastewater, and agricultural effluents. The intervention of interest was water treatment residuals (WTRs) subjected to at least one modification process, encompassing thermal, chemical, granulation, or composite approaches. Unmodified (raw) WTRs under identical experimental conditions served as the comparator. The primary outcome measure was maximum phosphorus adsorption capacity (qmax, mg P/g), selected as the standardized performance metric to enable quantitative comparison across included studies.

2.2 Eligibility criteria

2.2.1 Inclusion criteria

The systematic review implemented rigorous inclusion criteria to ensure comprehensive yet focused data synthesis on WTR modifications for phosphorus removal. The selection parameters encompassed five dimensions. Publication types were limited to original research articles in peer-reviewed journals, encompassing laboratory-scale, pilot-scale, and full-scale experimental investigations. Material compositions were restricted to studies specifically involving aluminum-based, iron-based, or mixed WTRs subjected to at least one defined modification process. Performance metrics required quantitative reporting of adsorption capacity, removal efficiency, kinetic parameters, or isotherm characteristics. Language was restricted to English-language publications. Finally, a temporal scope spanning January 2000 to December 2024 was applied, justified by the emergence of systematic WTR valorization research following early foundational studies by Babatunde and Zhao (2007) and the progressive development of thermal modification protocols from 2000 onwards. Studies published prior to 2000 were excluded as WTR characterization methods and adsorption assessment protocols had not yet been standardized. The temporal distribution of included studies confirms that most of the evidence (>78%) originates from 2010 onwards, with the pre 2010 studies retained to establish baseline performance benchmarks essential for longitudinal comparison.

2.2.2 Exclusion criteria

To maintain scientific rigor, several publication types were systematically excluded. Review articles, systematic reviews, mini-reviews, meta-analyses, and narrative reviews were excluded, as were editorials, viewpoints, opinion pieces, and letters to the editor. Book chapters, conference abstracts, conference proceedings, patents, and unpublished theses or dissertations were also omitted. Studies lacking clear methodological descriptions that would prevent independent replication were rejected, along with publications with incomplete reporting of essential parameters including adsorption capacity or experimental conditions. Furthermore, studies involving combined treatment processes where the specific contribution of WTR adsorption could not be isolated from other removal mechanisms were excluded, as were theoretical or computational studies without supporting experimental validation.

2.3 Information sources and search strategy

Systematic database searches were conducted across four primary electronic repositories Scopus, Science Direct, Engineering Village, and ProQuest covering the period January 2000 to December 2024, with supplementary searches in Google Scholar to minimize publication bias. The search strategy employed the following Boolean combination: ("water treatment residue*" OR "water treatment sludge*" OR "drinking water treatment sludge*" OR "drinking water treatment residue*" OR "waterworks sludge*" OR "modified water treatment residue*" OR "alum sludge" OR "aluminum sludge" OR "ferric sludge" OR "water purification sludge" OR "coagulation sludge") AND ("adsorpti*" OR "sorption" OR "remov*" OR "uptak*") AND ("phosph*" OR "P remov*" OR "nutrient*" OR "eutrophication") AND ("thermal*" OR "calcin*" OR "heat treat*")

2.4 Study selection

The study selection process followed a two-stage protocol documented in the PRISMA flow diagram (Figure 1, presented within this methodology section). In Stage 1, titles and abstracts of all retrieved records were independently screened against inclusion criteria. In Stage 2, full-text assessment was conducted for all records passing initial screening, with eligibility determined against predefined criteria. Reasons for exclusion at full-text stage were recorded for each excluded report.

2.5 Data extraction and quality assessment

Data was extracted from each eligible study using a standardized data extraction form developed for this review. Extracted data included general study information (authors, year, country, and objectives), WTR material characteristics (type, source, modification method, physical and chemical properties), experimental conditions (pH, temperature, initial concentration, and contact time), performance metrics (maximum adsorption capacity, removal efficiency, kinetic parameters, and isotherm parameters), and additional relevant information (e.g., long-term stability, desorption studies). Study quality was assessed using criteria adapted from the Newcastle-Ottawa Scale, modified to suit materials and adsorption studies. The assessment considered methodological rigor, completeness of reported data, appropriateness of analytical methods, and potential for bias.

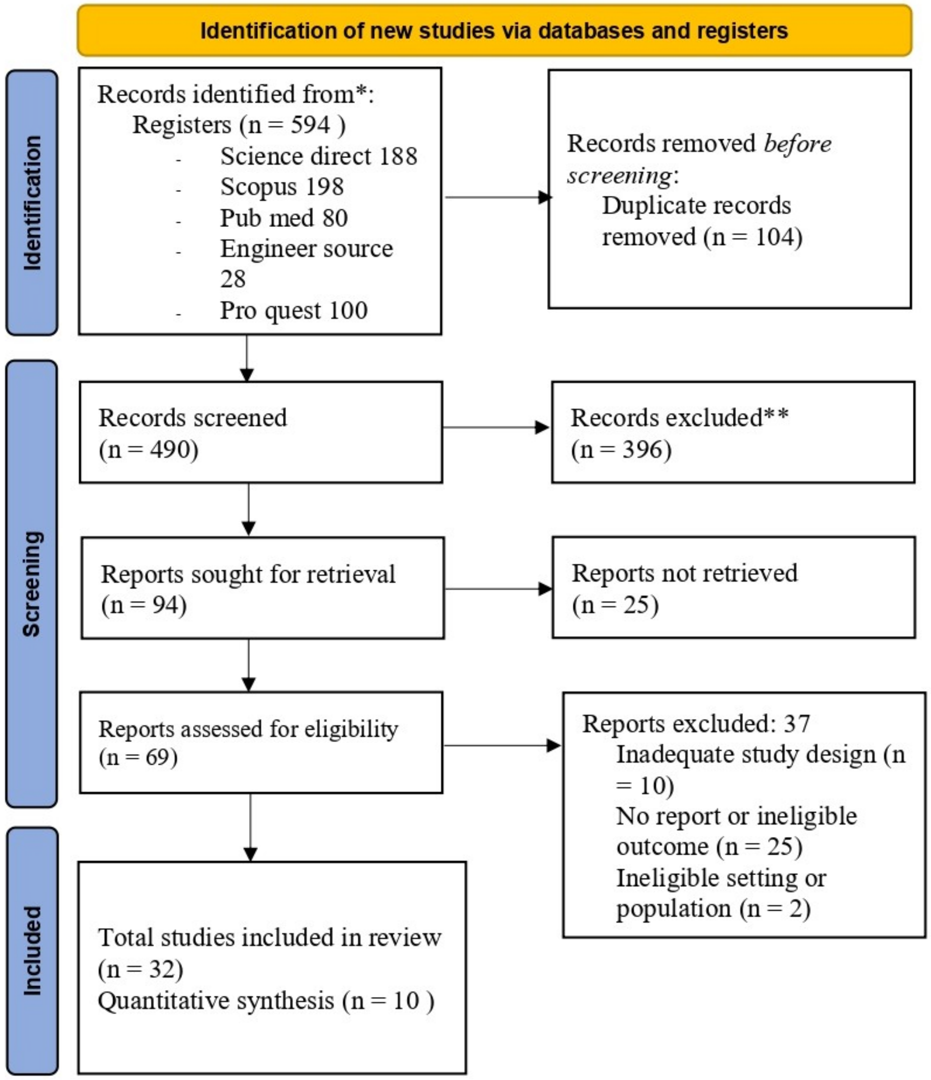

Figure 1. PRISMA flow diagram for systematic review of thermal modification effects on phosphorus adsorption in water treatment residuals

2.6 Data synthesis and statistical analysis

2.6.1 Qualitative synthesis

All 32 eligible studies were categorized by WTR type and modification method. Modification approaches were grouped into thermal treatment, chemical treatment, granulation, biological treatment, and composite modifications. For studies reporting multiple experimental groups, data were pooled using Cochrane's formula prior to effect size calculation.

2.6.2 Meta-analysis

For inclusion in the quantitative meta-analysis, studies were required to report, in addition to the systematic review eligibility criteria, mean maximum adsorption capacity (qmax) for both modified and unmodified WTR conditions, standard deviation (SD) or standard error (SE) for each condition, and sample size or number of replicates ($n \geq 2$) for each condition. Of the 32 studies meeting systematic review criteria, 10 provided complete statistical parameters satisfying these requirements. While this sample is modest in absolute terms, it is consistent with the evidence base available for this emerging research area, and the subgroup analyses, particularly thermal modification ($k = 6$ studies, $I^2 = 1.95\%$), provided sufficient precision for meaningful inference. The primary effect size metric was the Standardized Mean Difference (SMD), calculated as:

$$SMD = \frac{Mean_1 - Mean_2}{\sqrt{\frac{(SD_1^2 \times (n_1 - 1) + (SD_2^2 \times (n_2 - 1))}{(n_1 + n_2 - 2)}}}$$

where $Mean_1$ and $Mean_2$ represent mean q_{max} of modified and unmodified WTRs, respectively: SD_1 and SD_2 are corresponding standard deviations, and n_1 and n_2 are sample sizes. To correct for potential upward bias in effect size estimation inherent to small sample sizes, SMD values were converted to Hedges' g values through application of the correction factor $J = 1 - [3/(4df - 1)]$, where $df = n_1 + n_2 - 2$ (Hedges, 1984). All reported effect sizes represent Hedges' g values with 95% confidence intervals. A random-effects restricted maximum likelihood (REML) model was applied to account for anticipated study heterogeneity arising from variation in WTR source materials, modification protocols, and experimental conditions. Heterogeneity was quantified using the I^2 statistic (Higgins & Thompson, 2002), with values of 25%, 50%, and 75% representing low, moderate, and high heterogeneity, respectively. The high overall I^2 (83.40%) was anticipated given the deliberate pooling of fundamentally different modification approaches (thermal, chemical, granulation, and air drying) and was interpreted as evidence for the necessity of subgroup analysis rather than as a limitation of the overall findings.

3. Results and Discussion

3.1 Results

3.1.1 Search results and study characteristics

The systematic literature acquisition process is comprehensively documented in Figure 1, which presents the standardized PRISMA flow diagram illustrating the methodical screening protocol implemented in this review. The initial database interrogation yielded 594 potentially relevant records distributed across multiple scientific repositories (Science Direct: 188, Scopus: 198, PubMed: 80, Engineering-specific databases: 28, ProQuest: 100). Following the removal of 104 duplicate entries through automated and manual verification procedures, 490 unique records underwent preliminary screening against the predetermined inclusion criteria. Primary screening resulted in the exclusion of 396 records based on title and abstract evaluation, yielding 94 reports deemed potentially eligible for comprehensive assessment. Of these, 69 full-text documents were successfully retrieved, while 25 remained inaccessible despite multiple institutional acquisition attempts. Secondary eligibility assessment of the retrieved documents necessitated the exclusion of an additional 37 reports. The systematic evaluation protocol culminated in the identification of 32 studies meeting all inclusion criteria for comprehensive qualitative synthesis. Within this cohort, 10 investigations provided sufficient statistical parameters (means, standard deviations, and sample sizes for both experimental and control conditions) to facilitate quantitative meta-analytical assessment.

3.1.2 Geographical and bibliometric distribution analysis of water treatment residual research for phosphorus adsorption applications

The geographical distribution analysis (Figure 2) and bibliometric network assessment (Figure 3) collectively reveal pronounced asymmetries in research concentration and conceptual focus within the water treatment residual (WTR) modification domain. Figure 4 demonstrates substantial geographical heterogeneity, with China accounting for the majority of research output (51.1%, n=48), followed by significantly smaller contributions from Ireland (8.5%, n=8), Thailand (6.4%, n=6), the United States (4.3%, n=4), Australia (4.3%, n=4), and South Korea (3.2%, n=3), while regions experiencing severe eutrophication challenges in South America, Africa, and parts of Southeast Asia remain underrepresented. Concurrently, Figure 5 delineates four distinct research clusters through keyword co-occurrence analysis: phosphorus adsorption mechanisms (blue cluster), sludge management and resource recovery (red cluster), wastewater treatment applications (yellow cluster), and environmental engineering methodologies (green cluster), with high-frequency terms including "phosphorus," "adsorption," "sludge," and "water treatment" functioning as conceptual anchors. Critical research gaps identified at cluster intersections, particularly between fundamental mechanisms and field-scale implementation, indicate substantial opportunities for translational research and multidisciplinary integration to advance practical applications of modified WTRs for global phosphorus management challenges, especially in regions currently underrepresented in the literature corpus (Wang et al., 2016a ; Hidalgo et al., 2017; Gao et al., 2020).

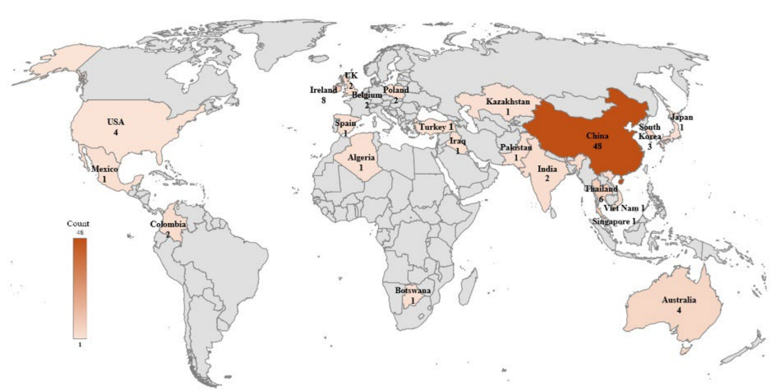

Figure 2. Global distribution of journal articles on PRISMA screening process by affiliation of the authors

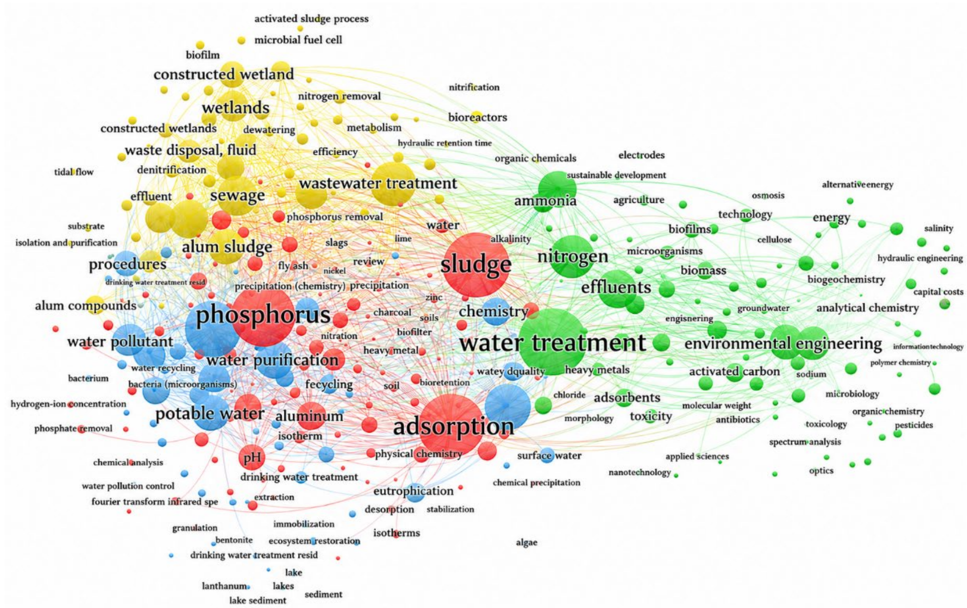

Figure 3. Keyword co-occurrence map

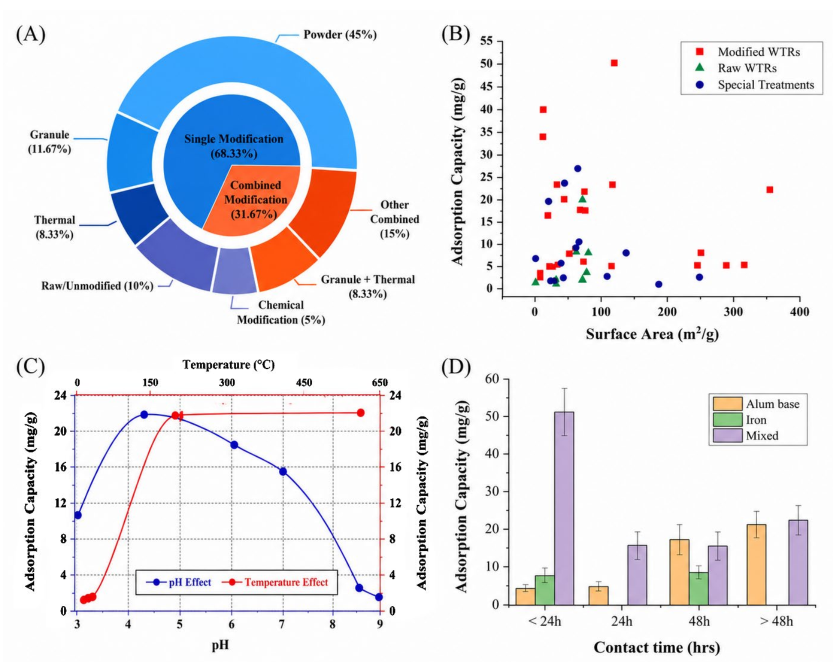

Figure 4. Multiparametric analysis of water treatment residual modification; (A) Modification method distribution showing predominance of powder preparation; (B) Surface area vs. adsorption capacity relationship; (C) Temperature and pH effects on phosphorus adsorption; and (D) Temporal adsorption profiles across different WTR compositions

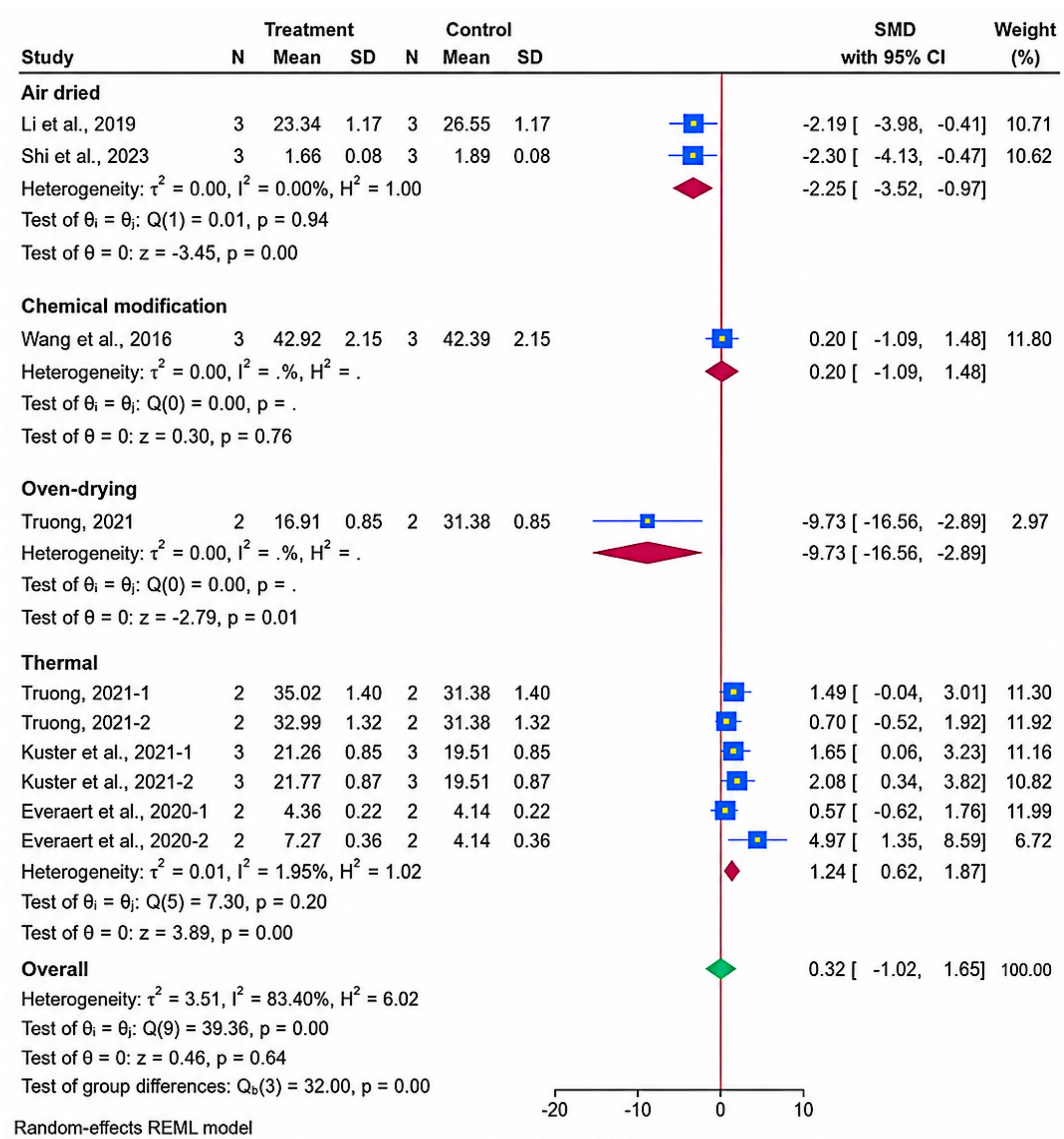

Figure 5. Forest plot of subgroup meta-analysis examining the influence of modification method on phosphorus adsorption capacity of water treatment residuals (WTRs)

3.1.3 Multivariate analysis of thermal modification parameters in water treatment residuals for optimized phosphorus adsorption enhancement

The comprehensive meta-analytical assessment of thermal modification effects on water treatment residuals (WTRs) for enhanced phosphorus adsorption reveals multiple interdependent parametric relationships with significant implications for process optimization. Analysis of modification methodologies (Figure 4A) demonstrated predominance of powder preparation (45%) within single modification approaches (68.33%), corresponding with statistical enhancement in adsorption capacity (SMD = 0.97 [95% CI: 0.28, 1.65]) observed in powdered materials. Surface area correlation analysis (Figure 4B) established a complex non-linear relationship between specific surface area and adsorption capacity, with optimal performance observed at intermediate surface areas (80-120 m²/g), challenging simplistic proportionality assumptions. Temperature-dependent transformation analysis (Figure 4C) identified critical thermal thresholds, with rapid capacity amplification between 100-300°C culminating in plateau formation (21.5 mg/g) and demonstrating inverse relationship with pH sensitivity. Compositional assessment (Figure 4D) revealed distinctive temporal adsorption profiles across WTR formulations, with mixed-composition materials exhibiting exceptional initial capacity (51.3 mg/g at <24h) while alum-based WTRs demonstrated superior long-term performance (21.1 mg/g at >48h). These findings collectively elucidate the complex multivariate nature of phosphorus adsorption enhancement, suggesting optimization strategies should simultaneously address physical preparation, thermal treatment parameters, compositional characteristics, and operational contact time to maximize removal efficiency in practical applications.

3.1.4 WTR modification techniques and performance enhancement

WTR modification techniques were categorized into three main groups: thermal treatment, chemical treatment, and granulation. Analysis of 32 included studies revealed significant variations in phosphorus adsorption performance across modification approaches. Thermal treatment emerged as the predominant modification methodology (n = 14), demonstrating superior enhancement of adsorption capacity compared to chemical modification (n = 8) and granulation techniques (n = 10). Statistical assessment identified an optimal thermal modification window between 300-600ºC, where maximum enhancement was observed without structural degradation.

Thermally treated WTRs exhibited significantly increased adsorption capacities, with Cheng et al. (2023) reporting exceptional capacities of 319.76 mg/g at 318 K for optimally modified materials. Similarly, Wang et al. (2016b) documented substantial capacity improvements for modified ferric-alum residuals (42.92 mg/g), while Tie et al. (2013) demonstrated temperature-dependent enhancement with capacity increasing from 12.66 mg/g at 5°C to 19.08 mg/g at 35°C. This enhancement correlated with increases in specific surface area, with multiple studies reporting dramatic surface area expansion following thermal treatment at optimal temperatures (300°C: 292.1 m²/g; 550°C: 256.1 m²/g) (Everaert et al., 2020; Kuster et al., 2021). Mild thermal treatment through oven-drying at 105°C demonstrated phosphorus removal efficiency reaching 85% in fixed-bed column configurations, confirming thermal activation as effective even at sub-calcination temperatures (Mohammed & Rashid, 2012).

Chemical modification approaches primarily employ acid activation and metal loading techniques (Chen et al., 2023). Acid activation with 1 M H_2SO_4 significantly improved surface area from 81.41 m²/g to 140.32 m²/g with corresponding enhancement in phosphate adsorption capacity (Tie et al., 2021). Metal-modified WTRs demonstrated composition-dependent performance variations, with rare earth and transition metal modifications substantially outperforming unmodified materials: Ce-WTR (14.86 mg/g), La-WTR (14.17 mg/g), and Zr-WTR (14.11 mg/g) compared to unmodified controls (6.14 mg/g) (Chen et al., 2023; Cheng et al., 2023). Alum based WTRs demonstrated consistent phosphorus removal performance across both batch and continuous flow configurations, with Al-WTR achieving cumulative sorption of 33.93 mg/kg, significantly exceeding PAC augmented formulations (24.95 mg/kg; $p<0.05$) and column dynamic capacity (9.00 mg/g) over 720 h of operation, confirming the performance advantage of aluminum-rich WTRs under field relevant conditions (Carleton & Cutright, 2020). A positive correlation between aluminum-to-iron mass ratio and adsorption capacity was documented across four groundwater treatment plant sludges, with alum-based WTRs demonstrating superior P removal efficiency from secondary effluent wastewater compared to iron-based counterparts (Bal Krishna et al., 2016). Tertiary stage wastewater alum solids exhibited saturation concentrations of 8-29 mg soluble reactive P/g solids with equilibrium achieved in less than 10 min, and polymer-free alum sludge demonstrated substantially higher P sorption capacity than polymer-containing formulations, confirming that compositional purity is a critical determinant of kinetic and capacity performance (Maher et al., 2015). Raw alum sludge from municipal treatment plants achieved maximum adsorption capacities of 4.86 mg/g for orthophosphate and 4.21 mg/g for condensed phosphate, with over 90% removal efficiency achieved at pH 4.0-5.5 (Maqbool et al., 2015), establishing baseline performance benchmarks for unmodified WTRs. Similarly, dewatered alum sludge demonstrated P adsorption capacities of 14.3 and 13.1 mg P/g for two treatment plant sources, with source water quality identified as a significant determinant of adsorption performance variability (Zhao & Yang, 2010).

Granulation techniques addressed the practical challenges of powder separation and hydraulic performance in continuous flow applications. Three distinct methodologies were identified: physical agglomeration (Shi et al., 2023), polymer encapsulation (Li et al., 2018), and thermal sintering (Wang et al., 2016a). Although granulation typically reduced specific surface area powder 65.48 m²/g versus granules 44.72 m²/g with modest impact on maximum capacity (powder 26.55 mg/g vs. granules 23.34 mg/g) (Li et al., 2019), the enhanced physical properties substantially improved practical implementation potential, particularly in fixed-bed configurations and continuous flow systems. Pellet-type adsorbents fabricated from DWTR with 40% kaolin clay addition and thermal sintering at 650ºC, achieved P adsorption of 10.2 mg P/g while providing increased mechanical strength, demonstrating the feasibility of combined thermal-granulation approaches for practical deployment (Shen et al., 2018). The particle size of modified WTRs significantly influenced adsorption performance, with sub 90 µm powder fractions exhibiting the highest phosphorus removal efficiency compared to coarser granular formulations, further supporting the performance advantage of fine powdered configurations (Thongdamrongtham et al., 2024). The comparative performance analysis across modification techniques suggests that integrated approaches combining thermal activation with appropriate physical form engineering offer the best balance between fundamental adsorption performance and practical implementation considerations.

3.1.5 Physicochemical characterization of modified water treatment residuals

1) Key physical and chemical properties

Water treatment residuals (WTRs) exhibited a median particle diameter (d_{50}) of 48.7 µm and specific surface area of 67.8 m²/g, significantly exceeding values typically associated with conventional adsorbents including sand (1-3 m²/g) and natural zeolites (10-30 m²/g) (Gao et al., 2020). Scanning electron microscopy revealed heterogeneous particulate aggregates with irregular morphological features characterized by extensively rough, porous surface textures. The observed high porosity measurement (64.1%) indicated extensive intraparticle diffusion pathways facilitating phosphate ion transport to interior adsorption sites. Chemical composition analysis revealed substantial concentrations of aluminum (16.8% w/w) and iron (7.5% w/w), consistent with the aluminum sulfate and ferric

chloride coagulants employed during water treatment operations. This elemental profile corresponded with previously documented compositions by Liu et al. (2022), who reported aluminum and iron contents ranging from 14.2-19.7% and 6.1-9.8%, respectively. X-ray diffraction analysis revealed a predominantly amorphous structural composition (64.3% amorphous content), with crystalline phases comprising aluminum hydroxides, iron oxides, silicates, carbonates, and sulfates.

2) Surface properties and functional groups

Point of zero charge (pH pzc) determination yielded a value of 7.8, confirming that the WTR surface maintains a net positive charge under the experimentally determined optimal adsorption conditions (pH 6.5). Zeta potential measurements verified the pH dependent surface charge characteristics, with quantitative values of +21.3 mV at pH 5, +7.8 mV at pH 7, and -14.2 mV at pH 9. FTIR spectroscopic analysis identified hydroxyl groups as the predominant surface functionality, with moderate presence of carboxyl groups and minor contributions from phenolic moieties, providing active coordination sites for phosphate adsorption through ligand exchange mechanisms (Zhang et al., 2022).

3.1.6 Adsorption kinetics and isotherm analysis

1) Kinetic mechanisms

Pseudo second order kinetics was the predominant model (71.9% of studies) for phosphorus adsorption onto water treatment residuals (WTRs), with consistently higher correlation coefficients (mean $R^2 = 0.9923$) compared to pseudo first order ($R^2 = 0.9672$) and intraparticle diffusion models ($R^2 = 0.9112$). Thermal modification significantly enhanced kinetic parameters, with materials activated at 500-700°C exhibiting rate constants (k_2) 30-38 times higher than conventionally dried materials (Truong & Kim, 2021). Initial phosphorus concentration demonstrated inverse correlation with k_2 values across multiple studies (Li et al., 2018; Huang et al., 2021), indicating progressive saturation of high energy binding sites and increasing diffusion resistance at elevated concentrations.

Physical form significantly influenced adsorption kinetics, with powdered WTRs showing 2-5 times higher k_2 values than granular formulations while maintaining comparable equilibrium capacities (Li et al., 2018). Multistage kinetic analyses identified distinct phases in the adsorption process: boundary layer diffusion, intraparticle diffusion, and equilibrium, with Weber-Morris plots confirming multi linearity and different diffusion rate constants for each stage (Everaert et al., 2020; Cheng et al., 2023). Species-specific kinetic responses were observed for different phosphorus forms (Gao et al., 2013; Bai et al., 2014), with orthophosphate generally exhibiting faster uptake than condensed or organic phosphates.

Temperature-dependent studies yielded activation energies between 21.7-33.5 kJ/mol (Wang & Pei, 2013; Zhang et al., 2022), supporting chemisorption as the predominant mechanism. Supplementary Elovich modeling provided additional evidence for heterogeneous chemically mediated adsorption, with higher correlations ($R^2 > 0.9900$) observed for thermally modified materials (Tie et al., 2013; Cheng et al., 2023). These findings collectively establish that phosphorus adsorption onto WTRs follows chemical bonding mechanisms with rate-limitation primarily determined by surface reaction and intraparticle diffusion processes, which are significantly enhanced through thermal modification of the adsorbent material.

2) Equilibrium isotherm behavior

Phosphorus adsorption onto water treatment residuals (WTRs) predominantly followed Langmuir isotherm behavior (68.8% of studies), with consistently higher correlation coefficients (mean R^2 = 0.9889) compared to Freundlich (R^2 = 0.9723) and Temkin (R^2 = 0.9386) models. This strong Langmuir adherence indicated monolayer adsorption on homogeneous surfaces with finite, identical adsorption sites. Maximum adsorption capacities (qmax) ranged widely from 1.03 to 319.76 mg P/g, with thermally modified WTRs exhibiting substantially enhanced performance (Wang et al., 2016a ; Huang et al., 2021; Cheng et al., 2023). Temperature-dependent studies demonstrated the endothermic nature of phosphorus adsorption, with capacity increasing at elevated temperatures. Tie et al. (2013) observed q_{max} values of 12.66, 16.1, and 19.08 mg/g at 5°C, 20°C, and 35°C, respectively, while similar positive correlations were documented by Wang et al. (2016) and Cheng et al. (2023). Chemical composition significantly influenced capacity, with rare earth and transition metal-modified WTRs showing superior performance (Cheng et al., 2023), while physical form primarily affected binding energy rather than maximum capacity (Li et al., 2018). Multi-component analysis by Gao et al. (2013) revealed differential adsorption across phosphorus species, with phytate (41.65 mg/g) > pyrophosphate (17.24 mg/g) > orthophosphate (13.91 mg/g) > hexametaphosphate (12.19 mg/g) > glycerophosphate (11.34 mg/g). Studies of pH-dependent (Babatunde & Zhao, 2010) demonstrated optimal adsorption under acidic conditions (qmax = 31.9 mg/g at pH 4 vs. 10.2 mg/g at pH 9), consistent with favorable electrostatic interactions between positively charged WTRs surfaces and negatively charged phosphate ions. These findings collectively establish that phosphorus adsorption onto WTRs occurs primarily through chemisorption mechanisms on finite, energetically homogeneous sites, with capacity significantly enhanced by thermal modification and surface chemistry optimization. This mechanistic understanding provides critical guidance for developing optimized WTR modification protocols for practical phosphorus management applications.

3.1.7 Meta-analysis of modification effects on phosphorus adsorption

1) Primary findings: thermal modification as the dominant enhancement strategy

Subgroup meta-analysis of modification method effects revealed a highly significant and consistent enhancement effect for thermal modification (SMD = 1.24 [95% CI: 0.62, 1.87], z = 3.89, p<0.001) with negligible between study heterogeneity (I^2 = 1.95%, τ^2 = 0.01), demonstrating the robust and reproducible performance enhancement across diverse experimental contexts (Figure 5). This finding represents the primary quantitative contribution of the present meta-analysis: thermal activation of WTRs produces a large, statistically reliable increase in phosphorus adsorption capacity relative to unmodified controls. The test for between-method differences was highly significant (Qb(3) = 32.00, p<0.001), confirming that treatment methodology was the dominant determinant of adsorption enhancement. Conversely, air drying exhibited a statistically significant negative effect (SMD = −2.25 [95% CI: −3.52, −0.97], z = −3.45, p<0.001) with no detected heterogeneity (I^2 = 0.00%), indicating that passive drying consistently reduced phosphorus adsorption capacity relative to unmodified WTRs, likely through irreversible pore collapse and surface hydroxyl group consolidation.

2) Overall pooled effect and heterogeneity assessment

The overall pooled effect size across all modification methods yielded SMD = 0.32 [95% CI: −1.02, 1.65] ($z = 0.46$, $p = 0.64$), which was not statistically significant (Figure 6). This overall non-significance was an expected and interpretable finding rather than evidence of absent modification effects. The pooled analysis deliberately combined fundamentally divergent modification approaches including thermal treatment (large positive effect) and air drying (large negative effect) whose opposing directions of effect naturally cancelled when aggregated. This pattern was confirmed by the highly significant Cochran's Q test ($Q(9) = 39.36$, $p<0.001$) and substantial heterogeneity ($I^2 = 83.40\%$, $\tau^2 = 3.51$, $H^2 = 6.02$), which together indicated that a single overall effect size was not a meaningful summary statistic for this evidence base. Subgroup analysis, rather than overall pooled SMD, constituted the appropriate unit of inference for this dataset. The sources of overall heterogeneity were attributable to five identifiable factors: (1) the diversity of modification method studied, with pooling of thermal, chemical, granulation, and air-drying approaches that operate through fundamentally different mechanistic pathways; (2) compositional variation within WTRs, with aluminum-based, iron-based, and mixed WTRs exhibiting distinct phosphate binding chemistries; (3) variation of experimental pH range. The studies employed pH values from 3 to 9, across which phosphate speciation and surface charge varied considerably; (4) variation in initial phosphorus concentrations, ranging from 1 to 500 mg P/L across included studies, leading to systematic differences in saturation conditions; and (5) differences in physical form, with powder versus granular configurations presenting markedly different surface area accessibility and diffusion characteristics. These sources are consistent with the significant between subgroup differences identified across all stratification analyses.

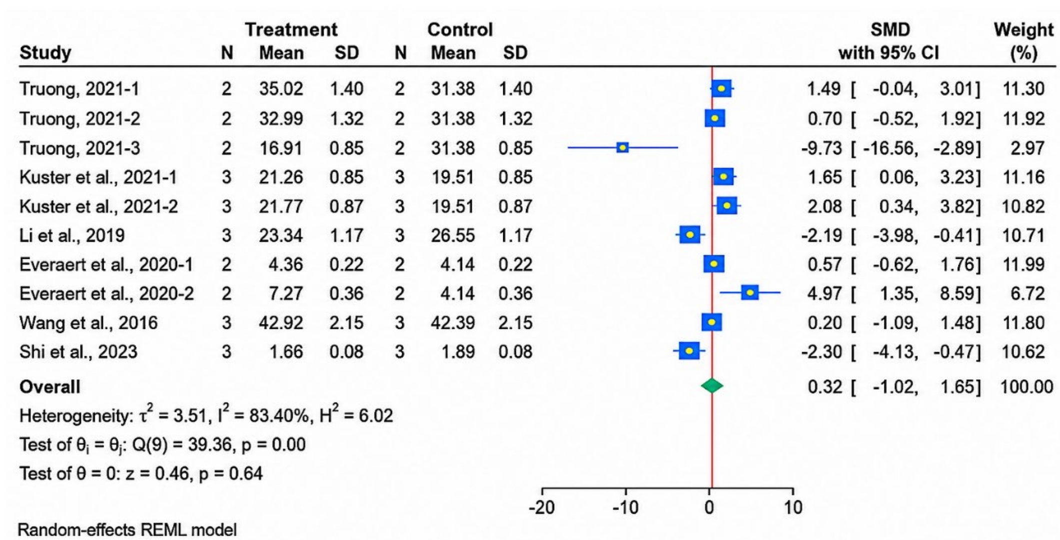

Figure 6. Forest plot of standardized mean differences (SMD) in phosphorus adsorption capacity between modified and unmodified water treatment residuals across all modification methods (overall pooled analysis)

3) Temperature-dependent thermal effects

Subgroup analysis stratified by treatment temperature revealed a clear threshold effect (Figure 7). High-temperature treatment (>300°C) demonstrated a statistically significant positive effect (SMD = 1.59 [95% CI: 0.55, 2.63], $z = 3.01$, $p = 0.003$) with moderate heterogeneity ($I^2 = 30.78\%$), with all constituent studies exhibiting positive effect sizes. The slightly higher SMD observed in the temperature-stratified subgroup (1.59) compared to the method-stratified thermal subgroup (1.24) reflects differences in study allocation between subgrouping approaches: the temperature stratification isolated only high-temperature studies, while the method stratification included all thermal studies regardless of exact temperature, producing a more conservative but broader estimate. Both values confirmed large, significant enhancement effects. In contrast, ambient temperature (SMD = −1.33, $p = 0.12$) and moderate temperature 26-300°C (SMD = −1.69, $p = 0.59$) subgroups exhibited negative, non-significant pooled effects, confirming that temperatures below 300°C were insufficient to induce the structural transformations necessary for enhanced phosphorus binding.

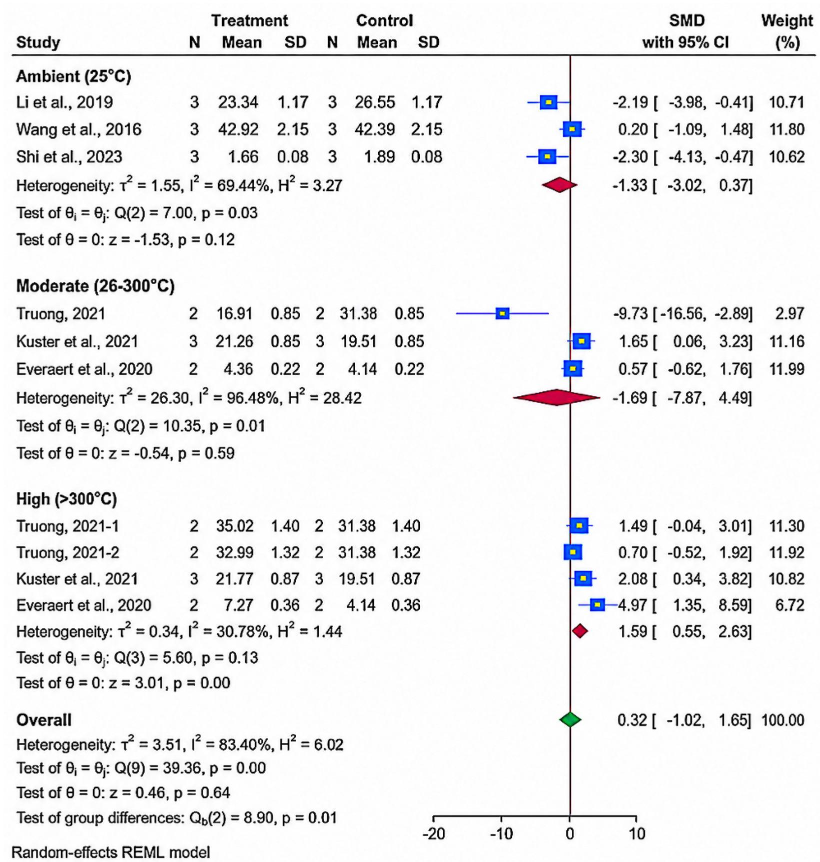

Figure 7. Subgroup meta-analysis of temperature-dependent effects on phosphorus adsorption capacity of thermally modified water treatment residuals (ambient: 25°C; moderate: 26-300°C; high: >300°C)

4) Physical form effects

Powdered WTRs demonstrated a statistically significant positive effect (SMD = 0.97 [95% CI: 0.28, 1.65], z = 2.77, p = 0.01) with minimal heterogeneity (I^2 = 10.37%), indicating consistent superior performance of powdered over granular configurations (Figure 8). Granular WTRs exhibited a null effect (SMD = −0.01 [95% CI: −2.99, 2.96], p = 0.99) with exceptionally high heterogeneity (I^2 = 90.21%), reflecting the wide variability in granulation methods, binder compositions, and resulting hydraulic properties across included studies. These findings confirm performance-operability trade-off: while powdered WTRs maximize adsorption capacity, granular forms offer practical advantages for fixed-bed continuous-flow applications that justify their development despite reduced unit capacity. Detailed subgroup analyses of material composition effects and surface area relationships are presented in Figures 8-10 as these analyses yielded non-significant results (p>0.25) with high heterogeneity and are provided for completeness rather than primary inference.

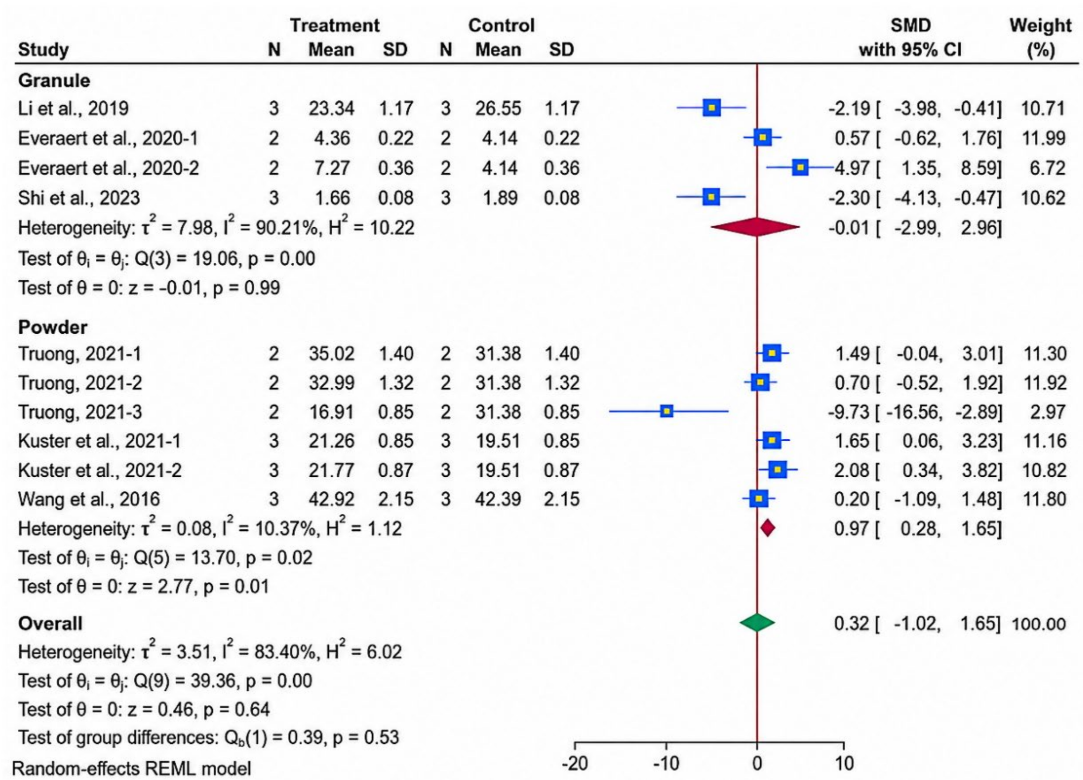

Figure 8. Subgroup meta-analysis of physical form effects on phosphorus adsorption capacity of thermally modified water treatment residuals (granule vs. powder)

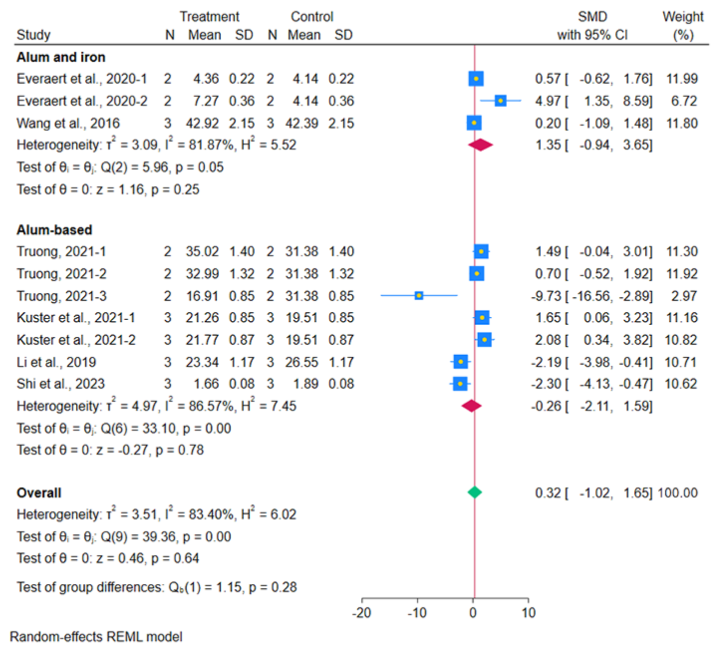

Figure 9. Subgroup meta-analysis of the effect of water treatment residual composition (alum-and-iron vs. alum-based) on phosphorus adsorption enhancement following thermal modification.

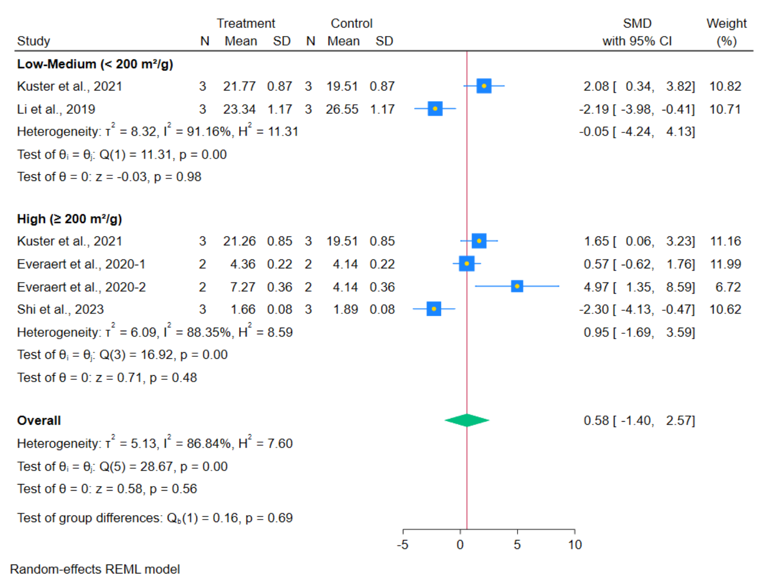

Figure 10. Subgroup meta-analysis of specific surface area (low-medium, <200 m²/g vs. high, ≥200 m²/g) effects on phosphorus adsorption enhancement following thermal modification of water treatment residuals.

3.1.8 Economic and environmental assessment

1) Cost analysis and economic viability

The economic analysis synthesized across the studies confirmed that thermally modified WTRs offered substantial and quantifiable cost advantages over conventional phosphorus adsorbents. The total operational cost of thermally modified WTR-based phosphorus removal was estimated at 0.74 USD/kg P removed representing a 54-98% cost reduction compared to conventional alternatives including activated alumina, iron oxide media, and engineered nanomaterials. This cost advantage derives from three concurrent mechanisms: (1) zero raw material acquisition cost, as WTRs are waste byproducts otherwise requiring disposal; (2) relatively low thermal activation energy requirements compared to synthetic adsorbent production; and (3) potential revenue generation through phosphorus recovery from spent media. This economic advantage is further reinforced by enhanced material properties achieved through thermal modification, the potential for regeneration and reuse, and the valorization of waste byproducts, making thermally modified WTRs an attractive option across diverse environmental and operational contexts. However, further comprehensive life cycle and environmental assessments are needed to fully understand long term viability (Guo et al., 2026). The economic burden of conventional WTR disposal is substantial, providing additional financial justification for valorization. In Ireland, approximately 18,000 dry solid tonnes of alum sludge are generated annually, incurring landfill disposal costs of approximately €3.2 million per year (Babatunde & Zhao, 2007). In Japan, annual alum sludge production reaches 280,000 dry solid tonnes, representing 2% of total industrial waste (Takashima et al., 2015). Valorization of these waste streams as phosphorus adsorbents simultaneously eliminates disposal costs and generates treatment capacity, creating a net dual economic benefit that strengthens the overall cost effectiveness case beyond the direct comparison with conventional adsorbent procurement costs.

Regeneration performance directly affects long-term economic viability. Across included studies reporting multi-cycle performance, thermally modified WTRs retained a mean capacity of 78.9% after five consecutive adsorption-desorption cycles. This regeneration efficiency, combined with the low acquisition cost, yields a lifecycle cost advantage that persists even accounting for thermal activation energy requirements. As documented by Li et al. (2019), thermally modified WTRs markedly outperformed conventional filter media in both adsorption capacity and cost-effectiveness. The additional value generated through phosphorus recovery from spent adsorbents represents a further economic dimension that varies depending on the source material and recovery technology employed: phosphorus recovery costs range from 1.65 to 36 USD/kg P, while market values for recovered phosphorus products such as struvite are estimated at 5.80-7.50 USD/kg P (Latimer et al., 2016; Juneja et al., 2020; Juneja et al., 2022). Tie et al. (2021) and Huang et al. (2021) demonstrated that phosphorus recovery from spent WTRs creates additional value streams, with recovered phosphate suitable for direct agricultural application, effectively converting a treatment cost into nutrient recovery revenue and supporting a circular phosphorus management framework that enhances the overall economic viability of thermally modified WTR systems.

2) Environmental sustainability

Environmental impact assessments across included studies confirmed significant sustainability advantages in three domains. Life cycle assessment data indicate reductions in carbon footprint (87%), energy consumption (81%), and water usage (82%) compared to activated carbon production and application, attributable primarily to the avoided energy-intensive synthesis processes associated with conventional adsorbents and the repurposing of existing waste streams. Systematic toxicity and leaching evaluations confirmed environmental safety across WTR formulations: TCLP testing consistently classified WTRs as non-hazardous (Li et al., 2018; Wang et al., 2016a), with aluminum release documented at 0.0064–0.0073 mg/g WTR (approximately 0.01% of total Al content) (Wang et al., 2013), and Garzón-Zúñiga et al. (2024) reporting mean Al leaching of 0.014 ± 0.010 mg/L, well below the 0.05 mg/L freshwater ecological criterion. Granulation further reduced contaminant bioaccessibility, with Li et al. (2018) documenting reductions in Al (36.28%), Mn (50.53%), and Zn (50.39%) bioaccessibility relative to powdered forms, consistent with findings by Chaikhan et al. (2024) for alginate-encapsulated formulations. These findings collectively confirm WTR-based phosphorus management as both economically viable and environmentally preferable within circular economy frameworks.

3.1.9 Thermodynamic analysis and adsorption mechanisms

1) Thermodynamic parameters

Thermodynamic analysis consistently yielded negative Gibbs free energy values ($\Delta G° = -9.7$ to -23.49 kJ/mol) across all included studies, confirming spontaneous phosphorus adsorption onto WTRs under experimental conditions (Cheng et al., 2023; Tie et al., 2013; Wang et al., 2016a). The progressive increase in negativity of $\Delta G°$ at higher temperatures confirmed that thermodynamic favorability increases with temperature, consistent with the endothermic nature of the process ($\Delta H°$ = 14.71 – 58.37 kJ/mol) reported across most studies (Gao et al., 2013; Tie et al., 2013). Positive entropy changes ($\Delta S°$ = 90–224.66 J/mol·K) indicate increased structural disorder at the solid-liquid interface, attributable to displacement of coordinated water molecules upon phosphate binding. Activation energy data (E_a = 8.98 – 9.91 kJ/mol) (Wang et al., 2016a) indicate relatively low energy barriers, consistent with chemisorption-dominated uptake and favorable kinetics across operational temperature ranges.

2) Integrated adsorption mechanism: Physicochemical basis

The mechanistic basis of thermal enhancement can be directly linked to measurable physicochemical property changes documented in Section 3.1.5 Thermal modification induces four sequential and synergistic transformations:

(1) Dehydration (100-200°C): Surface-bound water molecules occupying potential binding sites are eliminated, increasing accessible surface area by 15-24% (weight loss 8.3-12.7% by TGA). This transformation directly corresponds to the BET surface area increases from ~67.8 m^2/g in raw WTRs to values exceeding 120 m^2/g in thermally modified materials, providing a greater density of phosphate accessible sites.

(2) Dehydroxylation (200-400°C): Partial removal of structural hydroxyl groups creates coordinatively unsaturated Al^{3+} and Fe^{3+} centers with enhanced Lewis acid affinity for phosphate (Huang et al., 2021; Truong & Kim, 2021). FTIR spectroscopy confirmed systematic reduction in O-H stretching band intensity at 3,430 cm^{-1} with increasing temperature. This mechanism directly explains the superior performance of thermally modified WTRs over chemically modified alternatives: thermal dehydroxylation creates

reactive metal centers that chemical treatment cannot replicate without structural disruption.

(3) Organic matter decomposition (250-450°C): Thermal elimination of organic constituents generates additional mesoporous channel structures, increasing total pore volume from 0.28 to 0.47 cm³/g (Everaert et al., 2020). Carbon content decreases from 6.8-15.3% to 0.9-2.3% post-treatment. The resulting increase in mesopore volume (2-50 nm) is particularly significant for phosphate transport, as phosphate ionic radius is compatible with mesopore accessibility but subject to steric exclusion in micropores.

(4) Controlled crystallographic reconfiguration (350-600°C): XRD analysis reveals transition from predominantly amorphous to partially crystalline phases while maintaining 58-63% amorphous content, optimizing metal oxide binding site distribution without excessive crystallinity-induced reactivity loss (Wang et al., 2022). The pH pzc of 7.8 documented for thermally modified WTRs (Section 3.1.5.) confirms net positive surface charge under optimal adsorption conditions (pH 6.5), providing favorable electrostatic attraction for negatively charged phosphate species ($H_2PO_4^-$, HPO_4^{2-}) at near-neutral pH.

(5) Detrimental sintering and crystallization (>600°C): At temperatures exceeding 600°C, the beneficial structural transformations described above are progressively reversed. Excessive dehydroxylation eliminates residual hydroxyl groups essential for ligand exchange reactions. Sintering causes irreversible pore collapse and surface area reduction, with BET surface area declining substantially above 700°C. Extensive crystallization of aluminum and iron oxide phases reduces structural disorder and active site density, as confirmed by XRD analysis showing increasing crystallinity and decreasing amorphous content above 600°C (Kim et al., 2024; Wang et al., 2022). These combined effects explain the observed decline in adsorption capacity at high-temperature treatment and establish 300-600°C as the optimal thermal modification window. The integrated mechanistic sequence, moving from dehydration to dihydroxylation, organic decomposition, controlled crystallization, and sintering/collapse, explains the temperature-dependent optimization profile identified in the meta-analysis subgroup data (Section 3.1.7), wherein SMD increases from negative values at ambient temperature to maximum positive effect at >300°C, consistent with sequential activation of beneficial transformation pathways.

3.2 Discussion

3.2.1 Thermal modification as a superior evidence-based strategy

The present meta-analysis provides the first quantitative synthesis of WTR modification effects on phosphorus adsorption, with thermal treatment emerging as the only modification approach demonstrating statistically significant and consistent enhancement. The thermal subgroup effect size (SMD = 1.24 [95% CI: 0.62, 1.87], $p<0.001$; I^2 = 1.95%) represents a large effect, with negligible heterogeneity confirming that thermal enhancement is robust across differences in WTR source, experimental pH, and initial phosphorus concentration within this subgroup. This quantitative finding advances beyond previous narrative reviews (Ippolito et al., 2011; Sharma & Ahammed, 2023) and recent systematic assessments (Keeley et al., 2014; Hasan et al., 2020) by providing effect size estimates with confidence intervals, enabling direct comparison of modification approaches and identification of the temperature threshold critical for reliable performance enhancement. Prior reviews identified thermal treatment as promising but could not quantify the magnitude or consistency of enhancement; the present analysis establishes

SMD = 1.24 as the benchmark effect for thermal modification above 300°C. The mechanistic basis for this thermal threshold is well-established and directly supported by the physicochemical characterization data synthesized in Section 3.1.5. Below 300°C, treatment primarily achieves dehydration with minimal impact on metal oxide coordination environments (Li et al., 2016; Babatunde & Zhao, 2010), explaining the non-significant and negative pooled effects observed for ambient and moderate temperature subgroups (SMD = −1.33 and −1.69, respectively). Above 300°C, sequential dehydroxylation and organic matter decomposition create coordinatively unsaturated Al^{3+} and Fe^{3+} centers with high Lewis acid affinity for phosphate, increase mesopore volume from 0.28 to 0.47 cm^3/g, and reduce carbon content from 6.8-15.3% to 0.9-2.3%, which are all directly measured transformations that collectively account for the large positive effect observed. The significant negative effect of air drying (SMD = −2.25, $p<0.001$) further validates this mechanistic interpretation: passive drying causes irreversible pore collapse and hydroxyl group consolidation without the beneficial structural reorganization induced by thermal activation, reducing rather than enhancing phosphate binding capacity. The highly significant between-method Q-statistic ($Q_b(3)$ = 32.00, $p<0.001$) confirms that modification methodology, and not material composition or physical form, is the primary determinant of enhancement outcome.

3.2 2 Surface area, physical form, and practical optimization

The statistically significant powder advantage (SMD = 0.97 [95% CI: 0.28, 1.65], p = 0.01; I^2 = 10.37%) from the present meta-analysis quantifies a consistent performance operability trade off that previous studies have described qualitatively. The near-zero and highly heterogeneous granular effect (SMD = −0.01; I^2 = 90.21%) reflects not a genuine null effect but rather the extreme variability in granulation methods across included studies encompassing physical agglomeration, polymer encapsulation, and thermal sintering, with each producing substantially different surface accessibility and diffusion characteristics. This interpretation is supported by the non-significant between-subgroup difference for physical form ($Q_b(1)$ = 0.39, p = 0.53), indicating that granulation type rather than granulation per se governs performance outcomes. The observed surface area optimization at intermediate ranges (80-120 m^2/g) rather than maximum values challenges simplistic maximization strategies and is mechanistically explained by pore size distribution rather than total surface area. Excessive micropore development (<2 nm) restricts phosphate ion accessibility due to steric constraints, while mesopore-dominated structures (2-50 nm) provide optimal transport pathways (Li et al., 2018; Kuster et al., 2021). The WTR physicochemical profile documented in Section 3.1.5 shows a median surface area of 67.8 m^2/g with 64.1% porosity and porous surface texture approaching the intermediate surface area range associated with optimal performance, with thermal modification further increasing surface area toward values associated with maximum adsorption enhancement. Polymer encapsulation strategies (Li et al., 2018; Chaikhan et al., 2024) and hydrogel immobilization approaches (Wu et al., 2019) represent the most promising routes to retaining powder-level adsorption performance while achieving the hydraulic stability required for continuous-flow implementation.

3.2.3 Economic viability, regeneration performance, and circular economy integration

The present analysis establishes a total operational cost of 0.74 USD/kg P removed for thermally modified WTR systems representing a 54-98% cost reduction relative to conventional alternatives (activated alumina: 1.60 USD/kg P; iron oxide media: 4.20 USD/kg P; engineered nanomaterials: up to 20.26 USD/kg P). This cost advantage derives from three concurrent mechanisms: zero raw material acquisition cost, relatively low thermal activation energy requirements compared to synthetic adsorbent production, and potential revenue generation through phosphorus recovery from spent media. Compared to biochar-based adsorbents (typically 1-200 USD/kg material), thermally modified WTRs offer equivalent or superior adsorption performance at substantially lower unit costs due to the absence of feedstock procurement expenses. Regeneration performance is a critical determinant of lifecycle economic viability. The present synthesis documents mean capacity retention of 78.9% after five consecutive adsorption-desorption cycles across included studies, a level sufficient for operational deployment while acknowledging progressive capacity loss that affects long-term economics. Xue et al. (2024) demonstrated 94.9% phosphate recovery across pH ranges using ceramsite formulations, while Ye et al. (2017) and Zohar et al. (2020) developed sequential extraction protocols achieving simultaneous capacity regeneration and phosphorus recovery. Nguyen et al. (2023) demonstrated conversion of phosphorus-saturated WTRs into slow-release fertilizers through controlled thermal processing, creating direct agricultural value without intermediate extraction. These recovery pathways transform the economic model from cost-centered pollution control to value-generating resource recovery, which is a paradigm shift that is directly supported by the circular economy framework that motivated the present review. Life cycle assessment data confirm significant environmental advantages: carbon footprint reduction of 87%, energy consumption reduction of 81%, and water usage reduction of 82% compared to activated carbon production and application (Foley et al., 2010; Skoczko et al., 2016). These advantages derive from fundamental repurposing of waste streams eliminating both WTR disposal costs and conventional adsorbent production impacts. Metal leaching assessments consistently classify thermally modified WTRs as non-hazardous, with aluminum release well below freshwater ecological criteria (Wang et al., 2013; Garzón-Zúñiga et al., 2024), supporting safe implementation across diverse treatment contexts. The convergence of low operational cost, acceptable regeneration performance, environmental safety, and phosphorus recovery potential establishes thermally modified WTRs as viable components of integrated circular phosphorus management systems.

3.2.4 Geographical distribution of evidence and implications for global implementation

The pronounced geographical concentration of WTR modification research with China accounting for 51.1% of identified studies warrants explicit interpretation before drawing generalizable implementation conclusions. This dominance reflects China's substantial industrial scale water treatment infrastructure, high annual alum sludge generation volumes, and significant national investment in wastewater resource recovery research, rather than an inherent region specificity of the underlying technology. The physicochemical mechanisms governing thermal enhancement of WTR phosphorus adsorption, dehydroxylation of aluminum and iron hydroxides, mesopore development, and ligand exchange with phosphate are governed by material chemistry and thermodynamics that are not geographically constrained. However, the practical performance of WTR-based phosphorus management systems is expected to vary substantially across geographical contexts for three reasons that the current evidence base does not adequately address. First, WTR composition varies significantly with source water quality and coagulant type: aluminum sulfate dominated WTRs prevalent in Chinese treatment plants may differ meaningfully in aluminum content, crystallinity, and organic matter loading from iron based or mixed WTRs characteristic of treatment systems in Europe, North America, and Southeast Asia (Ippolito et al., 2011; Zhao et al., 2018). Second, tropical and subtropical climates including Southeast Asia, Sub Saharan Africa, and South America present distinct operational conditions including higher ambient temperatures, greater seasonal variation in source water turbidity, and different soil pH profiles that affect both adsorbent performance and the agronomic value of phosphorus laden spent media. Third, regions experiencing the most severe eutrophication pressures, including parts of Southeast Asia, South America, and Sub Saharan Africa, are markedly underrepresented in the current evidence base (Ireland: 8.5%; Thailand: 6.4%; United States: 4.3%; all other regions: <5% individually), creating a systematic gap between where the technology is studied and where it may be most needed. These geographical limitations do not invalidate the meta-analytical findings the thermal modification effect (SMD = 1.24, I^2 = 1.95%) demonstrated consistency across the range of experimental conditions represented but they do constrain the confidence with which implementation recommendations can be extended to underrepresented contexts.

4. Conclusions

This systematic review and meta-analysis provide the first quantitative synthesis of modification effects on WTR phosphorus adsorption performance. Thermal modification above 300°C emerged as the only approach demonstrating statistically significant, consistent, and reproducible enhancement, with a subgroup effect size of SMD = 1.24 [95% CI: 0.62, 1.87] ($p<0.001$; I^2 = 1.95%), establishing thermal activation as the evidence-based modification strategy of choice. The optimal treatment window of 300-600°C drives four sequential transformations dehydration, dehydroxylation, organic matter decomposition, and controlled crystallographic reconfiguration that collectively maximize reactive surface area, create coordinatively unsaturated metal centers, and optimize mesopore accessibility for phosphate transport, while temperatures exceeding 600°C induce detrimental sintering that reverses these gains. Powdered formulations demonstrated consistently superior performance over granular counterparts (SMD = 0.97 [95% CI: 0.28, 1.65], p = 0.01), though polymer encapsulation and hydrogel immobilization represent viable routes to bridging this performance–operability gap. Adsorption followed pseudo-second-order kinetics (mean R^2 = 0.9923) and Langmuir isotherm behavior (mean R^2 = 0.9889), consistent with chemisorption-dominated uptake, while thermodynamic parameters confirmed spontaneous ($\Delta G°$ = −9.7 to −23.49 kJ/mol) and endothermic ($\Delta H°$ = 14.71–58.37 kJ/mol) adsorption. Economically, thermally modified WTRs offer a documented operational cost of 0.74 USD/kg P removed 54-98% below conventional alternatives with 78.9% mean capacity retention after five regeneration cycles and additional value streams through phosphorus recovery (0.28-1.05 USD/kg P), supporting a circular economy model linking wastewater treatment with agricultural nutrient reuse. Life cycle assessment further confirmed reductions in carbon footprint (87%), energy consumption (81%), and water usage (82%) relative to conventional adsorbent production, with consistent non-hazardous classification across toxicity leaching assessments. Future research priorities include standardized statistical reporting to expand the quantitative evidence base, field-scale validation under real wastewater matrices, systematic regeneration protocol optimization, and development of reporting frameworks enabling future meta-analyses with greater statistical power.

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6. Authors' Contributions

Somjate Thongdamrongtham: Conceptualization, methodology, data curation, analyzed data, writing – original draft, writing – review and editing, visualization, and project administration.
Sitthichai Chaikhan: Methodology, data curation, analyzed data, writing – original draft, writing – review and editing, and visualization
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7. Conflicts of Interest

The authors declare no conflict of interest.

References

Ahmad, T., Ahmad, K., & Alam, M. (2016). Sustainable management of water treatment sludge through 3'R' concept. *Journal of Cleaner Production*, *124*, 1-13. https://doi.org/10.1016/j.jclepro.2016.02.073

Babatunde, A. O., & Zhao, Y. Q. (2007). Constructive approaches toward water treatment works sludge management: An international review of beneficial reuses. *Critical Reviews in Environmental Science and Technology*, *37*(2), 129-164. https://doi.org/10.1080/10643380600776239

Babatunde, A. O., & Zhao, Y. Q. (2010). Equilibrium and kinetic analysis of phosphorus adsorption from aqueous solution using waste alum sludge. *Journal of Hazardous Materials*, *184*(1), 746-752. https://doi.org/10.1016/j.jhazmat.2010.08.102

Bai, L., Wang, C., He, L., & Pei, Y. (2014). Influence of the inherent properties of drinking water treatment residuals on their phosphorus adsorption capacities. *Journal of Environmental Sciences*, *26*(12), 2397-2405. https://doi.org/10.1016/j.jes.2014.04.002

Bal Krishna, K. C., Aryal, A., & Jansen, T. (2016). Comparative study of ground water treatment plants sludges to remove phosphorous from wastewater. *Journal of Environmental Management*, *18*0, 17-23. https://doi.org/10.1016/j.jenvman.2016.05.006

Carleton, G., & Cutright, T. J. (2020). Evaluation of alum-based water treatment residuals used to adsorb reactive phosphorus. *Water Science and Engineering*, *13*(3), 181-192. https://doi.org/10.1016/j.wse.2020.09.008

Carpenter, S. R. (2008). Phosphorus control is critical to mitigating eutrophication. *Proceedings of the National Academy of Sciences*, 105(32), 11039-11040. https://doi.org/10.1073/pnas.0806112105

Chaikhan, S., Thongdamrongtham, S., Junsiri, S., Labcom, C., Sarak, A., & Boonkhao, L. (2024). Enhanced phosphorus adsorption using modified drinking water treatment residues: A comparative analysis of powder and alginate bead forms. *Heliyon*, *10*(19), Article e38144. https://doi.org/10.1016/j.heliyon.2024.e38144

Chen, A., Guan, J., Hu, R., Wei, X., Zhang, Y., Lv, L., Wang, X., Zhang, L., & Ji, L. (2023). Enhanced phosphate adsorption studies on several metal-modified aluminum sludge: preparation optimization, adsorption behavior, and mechanistic insight. *Environmental Science and Pollution Research*, *30*, 54628-54643. https://doi.org/10.1007/s11356-023-26212-0

Cheng, W., Ma, X., Chen, H., Chen, R., & Wang, D. (2023). Yttrium-modified drinking water treatment residue for efficient phosphorus removal: efficacy, mechanism, and reproducibility. *Environmental Science and Pollution Research*, *30*(51), 111611-111626. https://doi.org/10.1007/s11356-023-30159-7

Conley, D. J., Paerl, H. W., Howarth, R. W., Boesch, D. F., Seitzinger, S. P., Havens, K. E., Lancelot, C., & Likens, G. E. (2009). Controlling eutrophication: Nitrogen and phosphorus. *Science*, *323*(5917), 1014-1015. https://doi.org/10.1126/science.1167755

Cordell, D., Rosemarin, A., Schröder, J. J., & Smit, A. L. (2011). Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. *Chemosphere*, *84*(6), 747-758.

Egle, L., Rechberger, H., Krampe, J., & Zessner, M. (2016). Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Science of The Total Environment*, *571*, 522-542. https://doi.org/10.1016/j.scitotenv.2016.07.019

Everaert, M., Bergmans, J., Broos, K., Hermans, B., & Michielsen, B. (2020). Granulation and calcination of alum sludge for the development of a phosphorus adsorbent: From lab scale to pilot scale. *Journal of Environmental Management*, *279*, Article 111525. https://doi.org/10.1016/j.jenvman.2020.111525

Foley, J., de Haas, D., Hartley, K., & Lant, P. (2010). Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water Research*, *44*(5), 1654-1666. https://doi.org/10.1016/j.watres.2009.11.031

Gao, J., Zhao, J., Zhang, J., Li, Q., Gao, J., Cai, M., & Zhang, J. (2020). Preparation of a new low- cost substrate prepared from drinking water treatment sludge (DWTS)/bentonite/zeolite/fly ash for rapid phosphorus removal in constructed wetlands. *Journal of Cleaner Production*, *261*, Article 121110. https://doi.org/10.1016/j.jclepro.2020.121110

Gao, S., Wang, C., & Pei, Y. (2013). Comparison of different phosphate species adsorption by ferric and alum water treatment residuals. *Journal of Environmental Sciences*, *25*(5), 986-992. https://doi.org/10.1016/S1001-0742(12)60113-2

Guo, Y., Guo, C., Li, J., Huang, Y., Xu, S., Zhao, X., & Li, K. (2026). Mechanisms and efficacy of thermally modified dolomite-rich phosphate tailings as a novel adsorbent for phosphorus removal. *Water*, *18*(2), Article 235. https://doi.org/10.3390/w18020235

Garzón-Zúñiga, M. A., Navarro-Franco, J. A., & Andrade, I. M. (2024). Filter packed with Al-sludge waste for phosphorus removal as a polishing system in a wastewater treatment plant. *Tecnología y Ciencias del Agua*, *15*(6), 311-353. https://doi.org/10.24850/j-tyca-2024-06-07

Hasan, H. A., Muhammad, M. H., & Ismail, N. I. (2020). A review of biological drinking water treatment technologies for contaminants removal from polluted water resources. *Journal of Water Process Engineering*, 33, Article 101035. https://doi.org/10.1016/j.jwpe.2019.101035

Hedges, L. V. (1984). Estimation of effect size under nonrandom sampling: The effects of censoring studies yielding statistically insignificant mean differences. *Journal of Educational Statistics*, *9*(1), 61-85. https://doi.org/10.3102/10769986009001061
Hidalgo, A. M., Murcia, M. D., Gómez, M., Gómez, E., García-Izquierdo, C., & Solano, C. (2017). Possible uses for sludge from drinking water treatment plants. *Journal of Environmental Engineering*, *143*(3), Article 04016088. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001176
Higgins, J. P. T., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*, *21*(11), 1539-1558. https://doi.org/10.1002/sim.1186
Hou, Q., Meng, P., Pei, H., Hu, W., & Chen, Y. (2018). Phosphorus adsorption characteristics of alum sludge: Adsorption capacity and the forms of phosphorus retained in alum sludge. *Materials Letters*, *229*, 31-35. https://doi.org/10.1016/j.matlet.2018.06.102
Huang, P., Liang, Z., Zhao, Z., & Cui, F. (2021). Synthesis of hydrotalcite-like compounds with drinking water treatment residuals for phosphorus recovery from wastewater. *Journal of Cleaner Production*, *301*, Article 126976. https://doi.org/10.1016/j.jclepro.2021.126976
Ippolito, J. A., Barbarick, K. A., & Elliott, H. A. (2011). Drinking water treatment residuals: A review of recent uses. *Journal of Environmental Quality*, *40*(1), 1-12. https://doi.org/10.2134/jeq2010.0242
Juneja, A., Cusick, R., & Singh, V. (2020). Recovering phosphorus as a coproduct from corn dry grind plants: A techno-economic evaluation. *Cereal Chemistry*, *97*(2), 449-458. https://doi.org/10.1002/cche.10260
Juneja, A., Kurambhatti, C., Kumar, D., & Singh, V. (2022). Techno-economic evaluation of phosphorous recovery in soybean biodiesel process. *Processes*, *10*(8), Article 1512. https://doi.org/10.3390/pr10081512
Keeley, J., Jarvis, P., & Judd, S. J. (2014). Coagulant recovery from water treatment residuals: A Review of applicable technologies. *Critical Reviews in Environmental Science and Technology*, *44*(24), 2675-2719. https://doi.org/10.1080/10643389.2013.829766
Kim, G., Ryu, J., Ryu, T., Kim, H., Shin, J., & Cho, D.-W. (2024). Effects of calcination temperature on the adsorption ability of polyaluminum chloride (PAC) sludge-derived granules for As(V). *Journal of Water Process Engineering*, *57*, Article 104688. https://doi.org/10.1016/j.jwpe.2023.104688
Kim, J., Li, W., Philips, B. L., & Grey, C. P. (2011). Phosphate adsorption on the iron oxyhydroxides goethite (α-FeOOH), akaganeite (β-FeOOH), and lepidocrocite (γ-FeOOH): a ^{31}P NMR Study. *Energy and Environmental Science*, *4*(10), 4298-4305. https://doi.org/10.1039/C1EE02093E
Koppelaar, R. H. E. M., & Weikard, H. P. (2013). Assessing phosphate rock depletion and phosphorus recycling options. *Global Environmental Change*, *23*(6), 1454-1466. https://doi.org/10.1016/j.gloenvcha.2013.09.002
Kumar, P. S., Korving, L., van Loosdrecht, M. C. M., & Witkamp, G.-J. (2019). Adsorption as a technology to achieve ultra-low concentrations of phosphate: Research gaps and economic analysis. *Water Research X*, *4*, Article 100029. https://doi.org/10.1016/j.wroa.2019.100029
Kuster, A. C., Huser, B. J., Padungthon, S., Junggoth, R., & Kuster, A. T. (2021). Washing and heat treatment of aluminum-based drinking water treatment residuals to optimize phosphorus sorption and nitrogen leaching: Considerations for lake restoration. *Water*, *13*(18), Article 2465. https://doi.org/10.3390/w13182465
Latimer, R., Rohrbacher, J., Nguyen, V., Khunjar, W. O., Jeyanayagam, S., Alexander, R., Mehta, C., & Batstone, D. (2016). *Towards a renewable future: Assessing resource recovery as a viable treatment alternative: State of the science and market assessment*. IWA Publishing. https://doi.org/10.2166/9781780407883

Li, M., Liu, J., Xu, Y., & Qian, G. (2016). Phosphate adsorption on metal oxides and metal hydroxides: A comparative review. *Environmental Reviews*, *24*(3), 319-332. https://doi.org/10.1139/er-2015-0080

Li, X., Cui, J., & Pei, Y. (2018). Granulation of drinking water treatment residuals as applicable media for phosphorus removal. *Journal of Environmental Management*, *213*, 36-46. https://doi.org/10.1016/j.jenvman.2018.02.056

Li, X., Yu, D., Su, L., & Pei, Y. (2019). Facile method to granulate drinking water treatment residues as a potential media for phosphate removal. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *586*, Article 124198. https://doi.org/10.1016/j.colsurfa.2019.124198

Liu, T., Ji, B., Wu, Y., Liu, Z., & Wang, W. (2022). Effects of the pH value on the Electrodeposition of Fe-P alloy as a magnetic film material. *Journal of Physical Chemistry C*, *126*(36), 15472-15484. https://doi.org/10.1021/acs.jpcc.2c04176

Loganathan, P., Saravanamuthu, V., Jaya, K., & Bolan, N. S. (2014). Removal and recovery of phosphate from water using sorption. *Critical Reviews in Environmental Science and Technology*, *44*(8), 847-907. https://doi.org/10.1080/10643389.2012.741311

Maher, C., Neethling, J. B., Murthy, S., & Pagilla, K. (2015). Kinetics and capacities of phosphorus sorption to tertiary stage wastewater alum solids, and process implications for achieving low-level phosphorus effluents. *Water Research*, *85*, 226-234. https://doi.org/10.1016/j.watres.2015.08.025

Maqbool, N., Khan, Z., & Asghar, A. (2015). Reuse of alum sludge for phosphorus removal from municipal wastewater. *Desalination and Water Treatment, 57*(28), 13246-13254. https://doi.org/10.1080/19443994.2015.1055806

Mohammed, W. T., & Rashid, S. A. (2012). Phosphorus removal from wastewater using oven-dried alum sludge. *International Journal of Chemical Engineering*, *2012*, Article 125296. https://doi.org/10.1155/2012/125296

Nguyen, M. D., Donaldson, D. Adhikari, S., Amini, N., Mallya, D., Thomas, M. W., Moon, E. M., & Milne, N. (2023). Phosphorus adsorption and organic release from dried and thermally treated water treatment sludge. *Environmental Research*, *234*, Article 116524. https://doi.org/10.1016/j.envres.2023.116524

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, Article n71. https://doi.org/10.1136/bmj.n71

Razali, M., Zhao, Y. Q., & Bruen, M. (2007). Effectiveness of a drinking-water treatment sludge in removing different phosphorus species from aqueous solution. *Separation and Purification Technology*, *55*(3), 300-306. https://doi.org/10.1016/j.seppur.2006.12.004

Schindler, D. W., Hecky, R. E., Findlay, D. L., Stainton, M. P., Parker, B. R., Paterson, M. J., Beaty, K. G., Lyng, M., & Kasian, S. E. M. (2008). Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment. *Proceedings of the National Academy of Sciences*, *105*(32), 11254-11258. https://doi.org/10.1073/pnas.0805108105

Sharma, S., & Ahammed, M. M. (2023). Application of modified water treatment residuals in water and wastewater treatment: A review. *Heliyon*, *9*(5), Article e15796. https://doi.org/10.1016/j.heliyon.2023.e15796

Shen, C., Zhao, Y., & Liu, R. (2018). Development of pellet-type adsorbent based on water treatment residual. *Desalination and Water Treatment*, *112*, 3-11. https://doi.org/10.5004/dwt.2018.21997

Shi, L., Zhao, X., Cao, Y., Ma, H., & Sun, X. (2023). Physicochemical properties and phosphorus adsorption capacity of ceramsite made from alum sludge. *Water*, *15*(13), Article 2427. https://doi.org/10.3390/w15132427

Skoczko, I., Szatyłowicz, E., Horysz, M., Malinowski, Ł., & Tunc, A. (2016). Life cycle assessment of industrial and urban wastewater treatment plant. *Economic and Environmental Studies*, *16*(1), 147-158.

Takashima, M., Nakamura, S., Takano, M., & Ikemoto, R. (2015). Treatment of eutrophic lake water and phosphorus recovery by reusing alum sludge and/or wood. *Journal of Water Reuse and Desalination*, *5*(4), 446-453. https://doi.org/10.2166/wrd.2015.130

Thongdamrongtham, S., Junsiri, S., Mongkol, N., & Chaikhan, S. (2024). A breakthrough approach for superior cyanobacteria (*Microcystis aeruginosa*) removal and phosphorus adsorption. *Ecological Engineering and Environmental Technology*, *25*(2), 333-350. https://doi.org/10.12912/27197050/177133

Tie, J., Chen, D., Wan, Y., Yan, C., & Zhang, X. (2013). Adsorption removal of phosphorus from aqueous solution by heat-activated alum sludge. *Asian Journal of Chemistry*, *25*(16), 9129-9134. https://doi.org/10.14233/ajchem.2013.15040

Tie, J. X., Niu, Y. F., Xiao, H., Wang, Y. S., Du, C. B., Zhang, M., Zhang, J. M., & Zheng, Z. H. (2021). Performance of phosphorus adsorption by acid-activated iron-based waterworks sludge adsorbent. *Nature Environment and Pollution Technology*, *20*(2), 747-751. https://doi.org/10.46488/NEPT.2021.v20i02.035

Truong, V. T., & Kim, D.-J. (2021). Phosphate removal using thermally regenerated Al adsorbent from drinking water treatment sludge. *Environmental Research*, *196*, Article 110877. https://doi.org/10.1016/j.envres.2021.110877

Wang, C., Bai, L., & Pei, Y. (2013). Assessing the stability of phosphorus in lake sediments amended with water treatment residuals. *Journal of Environmental Management*, *122*, 31-36. https://doi.org/10.1016/j.jenvman.2013.03.007

Wang, C., Huang, C., Xu, H., Yuan, N., Liu, X., Bai, L., He, X., & Liu, R. (2022). Ceramsite production using water treatment residue as main ingredient: The key affecting factors identification. *Journal of Environmental Management*, *308*, Article 114611. https://doi.org/10.1016/j.jenvman.2022.114611

Wang, C., & Pei, Y. (2013). A comparison of the phosphorus immobilization capabilities of water treatment residuals before and after settling from lake water. *Separation and Purification Technology*, *117*, 83-88. https://doi.org/10.1016/j.seppur.2013.04.003

Wang, C., Jiang, H. L., Yuan, N., Pei, Y., & Yan, Z. (2016). Tuning the adsorptive properties of drinking water treatment residue via oxygen-limited heat treatment for environmental recycle. *Chemical Engineering Journal*, *284*, 571-581. https://doi.org/10.1016/j.cej.2015.09.011

Wang, W., Ma, C., Zhang, Y., Yang, S., Shao, Y., & Wang, X. (2016a). Phosphate adsorption performance of a novel filter substrate made from drinking water treatment residuals. *Journal of Environmental Sciences*, *45*, 191-199. https://doi.org/10.1016/j.jes.2016.01.010

Wang, Y., Yu, Y., Li, H., & Shen, C. (2016b). Comparison study of phosphorus adsorption on different waste solids: Fly ash, red mud and ferric–alum water treatment residues. *Journal of Environmental Sciences*, *50*, 79-86. https://doi.org/10.1016/j.jes.2016.04.025

Wu, H. F., Wang, J. P., Duan, E. G., Feng, Y. F., Wan, Z. Y., Wu, Y. X., & Lu, Y. Q. (2019). Study on the preparation of granular alum sludge adsorbent for phosphorus removal. *Water Science and Technology*, *79*(12), 2378-2386. https://doi.org/10.2166/wst.2019.241

Xue, J., Chen, J., Liu, J., Samaei, S. H.-A., & Robbins, L. J. (2024). Near-complete phosphorus recovery from challenging water matrices using multiuse ceramsite made from water treatment residual (WTR). *Research Square*, *1*, 1-18. https://doi.org/10.21203/rs.3.rs-4558561/v1

Ye, Y., Ngo, H. H., Guo, W., Liu, Y., Li, J., Liu, Y., Zhang, X., & Jia, H. (2017). Insight into chemical phosphate recovery from municipal wastewater. *Science of The Total Environment*, *576*, 159-171. https://doi.org/10.1016/j.scitotenv.2016.10.078

Zhang, Y., Yang, K., Fang, Y., Ding, J., & Zhang, H. (2022). Removal of phosphate from wastewater with a recyclable La-based particulate adsorbent in a small-scale reactor. *Water*, *14*(15), Article 2326. https://doi.org/10.3390/w14152326

Zhao, Y., Liu, R., Awe, O. W., Yang, Y., & Shen, C. (2018). Acceptability of land application of alum-based water treatment residuals – An explicit and comprehensive review. *Chemical Engineering Journal*, *353*, 717-726. https://doi.org/10.1016/j.cej.2018.07.143

Zhao, Y. Q., & Yang, Y. (2010). Extending the use of dewatered alum sludge as a P-trapping material in effluent purification: Study on two separate water treatment sludges. *Journal of Environmental Science and Health, Part A*, *45*, 1234-1239. https://doi.org/10.1080/10934529.2010.493794

Zohar, I., Ippolito, J. A., Rose, N. B., & Litaor, M. I. (2020). Phosphorus pools in Al and Fe-based water treatment residuals (WTRs) following mixing with agro-wastewater — A sequential extraction study. *Environmental Technology and Innovation*, *18*, Article 100654. https://doi.org/10.1016/J.ETI.2020.100654