Mineralogical Diversity of Drinking Water Treatment DWTR: A Framework for Context-Aligned Reuse in Environmental Applications

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Abstract

Water treatment facilities worldwide generate substantial quantities of drinking water treatment residuals (DWTR) through coagulation processes using alum, ferric chloride, polyaluminium chloride (PAC), or lime. Interest in beneficial reuse has increased markedly; however, much of the existing literature implicitly treats DWTR as a uniform material. This obscures a critical reality: coagulant chemistry governs residue mineralogy, and mineralogical differences strongly influence environmental behaviour and suitability for reuse applications. This review synthesises current knowledge on DWTR mineralogy and associated surface-chemical mechanisms and proposes a context-aligned framework for matching specific residue types to appropriate environmental applications. Alum-based DWTR, dominated by amorphous aluminium hydroxide phases, exhibits strong phosphorus binding under circumneutral conditions, supporting its use in wetlands and bioretention systems. Ferric-based DWTR, characterised by iron oxyhydroxide phases, displays greater tolerance to redox variability and a broader operational pH window, making it attractive for stormwater and intermittently flooded environments. PAC-derived and lime-based DWTR exhibit distinct buffering and precipitation behaviours that may be advantageous under variable or alkaline conditions, respectively. The proposed framework treats mineralogical diversity as a functional asset rather than a limitation, emphasising that different DWTR types are suited to distinct environmental contexts rather than a one-size-fits-all reuse strategy. Key research priorities are identified, including the need for standardised characterisation protocols, multi-site performance validation, long-term field monitoring, and integration of DWTR reuse within circular-economy and nutrient-management strategies. By explicitly linking coagulant chemistry, mineralogical properties, and environmental context, this review provides structured guidance to support more systematic, evidence-based DWTR reuse in nature-based treatment infrastructure and sustainable phosphorus management.

1 Introduction

Drinking water treatment DWTR (DWTR), also known as water treatment residuals, waterworks sludge, or aluminium sulphate (alum) sludge, is an unavoidable byproduct generated during the coagulation–flocculation processes used at municipal water treatment facilities. Reported production rates are typically several to tens of kilograms of DWTR per megalitre of treated water (Ippolito et al., 2011; USEPA, 2011), representing a small but persistent fraction of plant throughput. Based on global drinking water production volumes, DWTR generation is widely recognised as a large, continuous material stream at the worldwide scale (Elliott et al., 2002). Large treatment facilities may generate substantial daily volumes of DWTR, depending on influent water quality, coagulant type, and plant capacity (USEPA, 2011). Traditionally disposed of in landfills or discharged into wastewater systems, DWTR has attracted increasing attention as a potential resource for beneficial reuse, driven by circular-economy principles, rising landfill costs, and regulatory constraints on waste disposal.

The composition of DWTR reflects both the raw water quality and the coagulant chemicals employed during treatment. Alum, ferric chloride ($FeCl_3$), polyaluminium chloride (PAC), and lime represent the dominant coagulants used globally (Sousa et al., 2025; USEPA, 2011), each generating DWTR with distinct mineralogical signatures. Alum-based facilities typically produce DWTR rich in amorphous Al hydroxide Al $(OH)_3$ phases such as pseudo-boehmite and poorly crystalline gibbsite (Ippolito et al., 2011), while $FeCl_3$ treatment yields iron oxyhydroxide-dominant materials including ferrihydrite, goethite and lepidocrocite (Babatunde and Zhao, 2007; Makris et al., 2004). PAC generates DWTR containing polymeric AL species with mixed AL chloride ions and Al $(OH)_3$) phases due to retained Keggin-Al13 structures (Duan and Gregory, 2003) and lime-softening processes create calcium carbonate-rich DWTR dominated by calcite with variable portlandite and brucite (Ippolito et al., 2011). These mineralogical differences confer unique surface reactivity, adsorption capacity, and stability, which influence environmental performance.

Recent research has reported DWTR's potential for phosphorus (P) removal, leveraging the high P-binding capacity of AL and iron phases. Laboratory studies report phosphorus sorption capacities for Al- and Fe-based DWTR spanning a wide range under controlled conditions (Makris et al., 2004; Babatunde & Zhao, 2007). Field-scale applications have reported substantial phosphorus retention under favourable pH and hydraulic conditions (Yang et al., 2006). DWTR has been successfully integrated into constructed wetlands, bioretention systems, stormwater filters, agricultural edge-of-field applications, and various engineered substrates (Makris et al., 2004). However, much of the existing literature treats DWTR as a relatively uniform material, attributing performance variability primarily to dosage rates or contact time rather than to fundamental mineralogical differences (Ippolito et al., 2011).

This perspective overlooks a critical opportunity: recognising and utilising DWTR mineralogical diversity as a functional advantage. Different coagulant-derived DWTR exhibit distinct optimal pH ranges, redox stability, particle size distributions, and interactions with organic matter—characteristics that can be strategically matched to specific environmental settings (Babatunde & Zhao, 2007). A systematic, context-aligned approach to DWTR reuse would consider soil/substrate pH, moisture regime, redox dynamics, organic carbon inputs, and hydraulic requirements when selecting appropriate residue types (Elliott et al., 2002).

This review synthesises existing knowledge on DWTR mineralogy across major coagulant types and proposes a framework for context-aligned reuse. We examine: (1) the mineralogical characteristics of alum-, Fe-, PAC-, and lime-based DWTR; (2) how these characteristics influence performance under varying environmental conditions; (3) optimal application contexts for each residue type; (4) physical and chemical interactions relevant to system design; and (5) future research priorities for advancing field-scale implementation. Our objective is to shift the paradigm from treating DWTR as waste requiring disposal toward recognising it as a diverse suite of functional materials with tailored reuse pathways.

While recent reviews synthesise DWTR reuse pathways and contaminant removal behaviour, none provide a mineralogy-centred framework linking coagulant-derived phases to functional properties and context-specific environmental applications. This review advances the field by proposing a conceptual model that operationalises mineralogical diversity for decision-making aligned with application needs. The framework integrates coagulant chemistry, residue physiochemistry, environmental context, and functional performance, offering practitioners structured guidance for matching DWTR types to optimal reuse scenarios.

2 Methodology

This review synthesises current knowledge on DWTR mineralogy through narrative analysis of peer-reviewed literature, to develop a conceptual framework linking coagulant-derived mineral phases to context-specific environmental applications.

2.1 Literature Search and Selection

We identified literature through targeted searches of Web of Science and Scopus databases (2000–2024) using search terms combining: ("drinking water treatment residue*" OR "water treatment residual*" OR "waterworks sludge" OR "alum sludge" OR "WTR") AND ("mineralogy*" OR "coagulant" OR "phosphorus" OR "reuse" OR "environmental application*"). Literature was prioritised for relevance to DWTR mineralogical characterisation, phosphorus removal mechanisms, and environmental reuse applications. The review emphasises mechanistic understanding and field performance data to support framework development.

2.2 Framework Development

The context-aligned reuse framework (Figure 1) was developed through thematic synthesis of mineralogical data, performance characteristics, and application contexts reported across the selected literature. We systematically extracted data on: (1) coagulant type and resulting mineral phases, (2) phosphorus sorption capacities and mechanisms, (3) pH optima and redox stability, (4) particle size distributions and hydraulic properties, and (5) field performance in various environmental settings.

Mineral phase characteristics were categorised by coagulant type (alum, ferric, PAC, lime) based on reported X-ray diffraction, surface area analysis, and compositional data. Performance parameters were compiled from both laboratory sorption studies and field monitoring reports. The framework matrix (Table 1) synthesises optimal operating conditions by matching DWTR mineralogical properties to site-specific environmental parameters (pH regime, redox dynamics, moisture patterns, hydraulic requirements).

This approach prioritises practical applicability while maintaining scientific rigour, positioning mineralogical diversity as a functional design parameter rather than a constraint requiring standardisation.

2.3 Mineralogical Characteristics of DWTR Types

2.3.1 Alum-based DWTR

Alum-based DWTR predominantly comprises amorphous $Al(OH)_3$ phases, including pseudo-boehmite and gibbsite precursors (Makris et al., 2004). The amorphous nature of these phases is characterised by high specific surface area and abundant reactive surface hydroxyl groups that facilitate ligand exchange with phosphate ions (Babatunde & Zhao, 2007). X-ray diffraction patterns show broad, poorly defined peaks rather than sharp crystalline signals—evidence of short-range order without well-developed crystal structures.

The P removal mechanism here is ligand exchange: phosphate ions displace surface hydroxyl or water molecules to form bidentate Al–O–P complexes, in which the phosphate oxygen atoms bond directly to AL surface sites (Makris et al., 2004). Under neutral to mildly acidic conditions, alum-based DWTR has been reported to retain substantial amounts of phosphorus in field and pilot-scale applications (Ippolito et al., 2011), with performance declining at high pH due to competition with hydroxide ions (OH^-) and at low pH due to AL dissolution.

The often-fine-grained particle size and low bulk density influence its suitability for blended media but raise clogging risks in pure layers. The organic matter content reflects natural organic matter and algae captured during coagulation (Edzwald, 1993; Matilainen et al., 2010). It can either enhance or inhibit P retention depending on composition (Makris et al., 2004).

2.3.2 Ferric-based DWTR

FeCl3–derived DWTR is characterised by the predominance of Fe(III) oxyhydroxide phases, most notably ferrihydrite, with goethite and lepidocrocite also commonly present (Babatunde & Zhao, 2007; Makris et al., 2004). Relative to alum-based DWTR, Fe DWTR typically displays coarser particle dimensions and higher bulk density relative to alum-based DWTR[3] (Ippolito et al., 2011).

A defining property of these DWTR is their response to redox variability. Reduction of Fe(III) to Fe(II) can promote P release under anoxic conditions. However, empirical studies report that a substantial fraction of phosphorus remains immobilised during short-term redox fluctuations (Makris et al., 2004; Babatunde & Zhao, 2007). This persistence is attributed to mechanisms such as incorporation into goethite lattices, coprecipitation with carbonate phases, or entrapment within particle aggregates. Importantly, Fe DWTR demonstrates functional stability across a relatively wide pH range, making it particularly well-suited for reuse in environments subject to periodic flooding (Ippolito et al., 2011). Ageing involves ferrihydrite transitioning to more crystalline goethite/hematite, reducing surface area but stabilising P by incorporating it into crystal lattices (Babatunde & Zhao, 2007).

2.3.3 Polyaluminium chloride (PAC)-based DWTR

PAC represents a family of pre-polymerised AL coagulants containing variable Al_{13} Keggin structures and polymeric species. PAC-based DWTR consequently exhibits complex mineralogy with mixed Al–Cl and Al–OH coordination environments, distinct from the simpler Al hydroxide phases in alum-derived DWTR (Duan and Gregory, 2003; Yang et al., 2006). The basicity and polynuclear structure of PAC influence the properties of the resulting residue, including charge neutralisation capacity, particle aggregation behaviour, and buffering characteristics.

Compared with alum-based DWTR, PAC-derived DWTR often exhibits greater pH buffering capacity (Duan & Gregory, 2003). This buffering behaviour may be advantageous in applications where pH stability is critical, such as vegetated treatment systems or biofilters receiving variable influent chemistry. The intermediate particle size distribution (between alum and Fe DWTR) makes PAC-based DWTR suitable for both blended media and structured layer configurations (Ippolito et al., 2011).

P removal capacity of PAC-based DWTR is generally moderate relative to optimised alum or Fe materials, though performance varies considerably depending on PAC basicity and manufacturing conditions. Reported phosphorus sorption capacities vary widely depending on PAC formulation and manufacturing conditions (Duan and Gregory, 2003; Yang et al., 2006). Limited published data on PAC-derived residue mineralogy represents a research gap that warrants systematic investigation, particularly given PAC's increasing adoption in Asian and European water treatment facilities (Ippolito et al., 2011).

The increasing global adoption of PAC as a coagulant, particularly in Asia and Europe, where it has become a preferred alternative to traditional alum (Sousa et al., 2025), underscores the importance of understanding PAC-derived DWTR properties. PAC offers advantages during water treatment, including lower alkalinity consumption, broader effective pH range, and improved floc characteristics. These operational benefits translate into compositionally distinct residues that warrant systematic investigation.

Preliminary studies suggest that PAC-based DWTR exhibits intermediate properties between alum and ferric materials, including particle size distribution, bulk density, and settling characteristics (Duan & Gregory, 2003). The retained polymeric aluminium structures may confer greater resistance to pH-induced dissolution than simple aluminium hydroxide phases, potentially offering advantages in applications with variable water chemistry. However, the influence of PAC manufacturing parameters—particularly basicity (OH/Al molar ratio) and degree of polymerisation—on resulting DWTR properties and environmental performance remains poorly characterised.

Given the knowledge gaps surrounding PAC-derived DWTR, we recommend conservative application guidelines: initial deployment in controlled pilot studies, preference for blended media configurations over pure DWTR layers, and systematic performance monitoring to establish site-specific operating parameters. As the evidence base develops through targeted research, PAC-based DWTR may emerge as a valuable material for niche applications, where its unique buffering and pH-tolerance characteristics provide advantages over conventional alum or ferric materials.

2.3.4 Lime-based DWTR

Lime softening processes, employed primarily for hard water treatment, generate DWTR dominated by calcium carbonate ($CaCO_3$, calcite) with variable amounts of calcium hydroxide [$Ca(OH)_2$, portlandite], magnesium hydroxide [$Mg(OH)_2$, brucite], and coprecipitated impurities (Ippolito et al., 2011). The high calcium and alkalinity content of lime-based DWTR confers distinct properties compared to aluminium- or iron-rich DWTR, including strong pH buffering capacity, acid neutralisation potential, and calcium-mediated P precipitation mechanisms (Makris et al., 2004).

P removal by lime-based DWTR occurs primarily through precipitation of calcium phosphate phases (hydroxyapatite, octacalcium phosphate, or amorphous calcium phosphate) rather than surface adsorption, a precipitation-driven mechanism favoured under alkaline conditions and exhibiting different kinetics and stability characteristics compared to adsorption-based mechanisms (Ippolito et al., 2011). Lime-based DWTRs are particularly effective in acidic environments where pH adjustment is beneficial, including acid mine drainage treatment, acidic agricultural soils, and constructed wetlands receiving low-pH inputs (USEPA, 2011; Ippolito et al., 2011).

Lime-derived sludge is typically coarse and granular. This morphology enhances hydraulic conductivity, rendering such materials particularly suitable for applications where structural porosity is advantageous. Nevertheless, the potential for calcite dissolution under acidic conditions poses a risk of diminished treatment efficacy, underscoring the importance of aligning site selection with stable pH regimes (Makris et al., 2004).

2.4 Conceptual Framework for Context-Aligned DWTR Reuse

We propose a three-stage conceptual framework linking DWTR mineralogical characteristics to functional material properties and context-aligned environmental applications (Figure 1). The framework positions DWTR as a family of mineralogically distinct materials rather than a homogeneous waste stream. Across coagulant types—including alum, ferric, PAC, and lime—the mineral phases impart consistent functional attributes. These include buffering capacity, resilience to redox fluctuations, particle-size–mediated hydraulic behaviour, and mechanisms of P immobilisation. Optimal performance, however, is contingent upon environmental parameters such as prevailing pH, moisture variability, redox transitions, organic matter inputs, and hydraulic loading. By integrating these factors, the proposed framework enables practitioners to strategically match DWTR types to specific reuse contexts, supporting systematic planning for applications in wetlands, bioretention systems, stormwater infrastructure, and amendments to acidic soils.

Figure 1. Overview of context-aligned DWTR reuse framework.

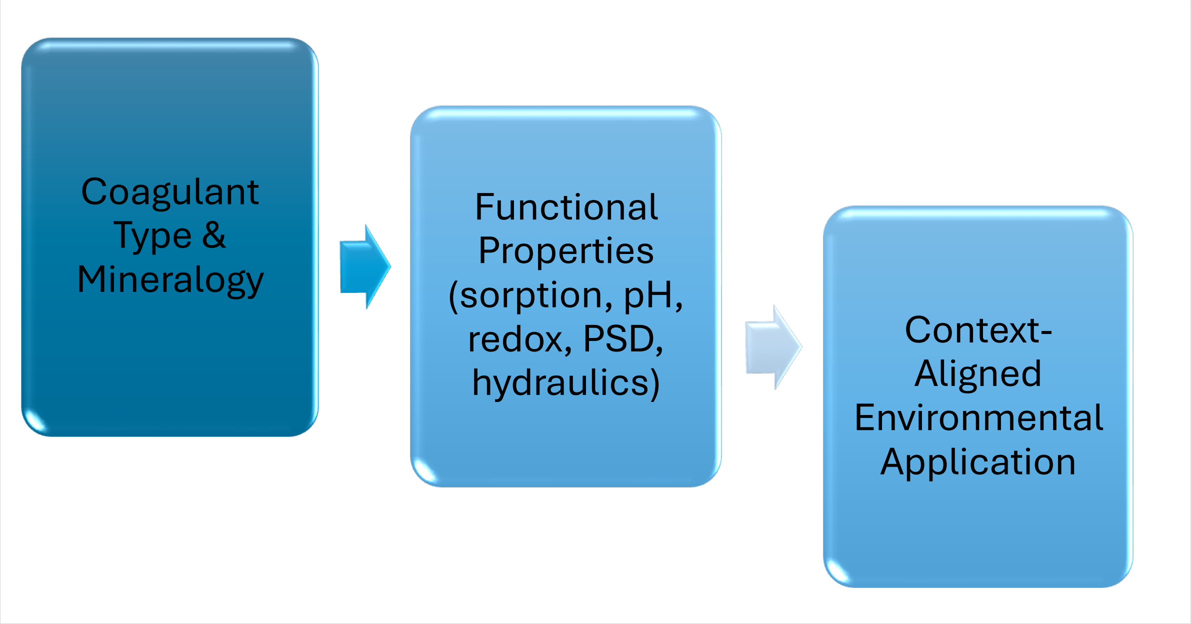

Figure 1 is the three-stage framework for mineralogy-driven DWTR application selection. Coagulant chemistry determines mineralogical characteristics, which confer functional properties (P sorption, pH tolerance, redox stability, particle size, hydraulics) that enable context-aligned deployment in appropriate environmental settings.

Collectively, these analyses demonstrate that the mineralogical behaviour of DWTR can be anticipated and used as a basis for residue selection across diverse applications, including constructed wetlands, bioretention systems, stormwater filtration units, floating treatment wetlands, and amendments for acidic soils. When residue type is systematically aligned with site-specific environmental conditions, practitioners can optimise P immobilisation, sustain hydraulic performance, and promote long-term functional stability.

3 Context-Aligned Reuse Framework

Effective DWTR reuse requires systematic matching of material properties to site-specific environmental conditions. We propose a context-aligned framework (Figure 1) that considers four key domains: (1) mineralogical characterisation of available DWTR, (2) environmental condition assessment at the proposed application site, (3) matching material properties to site requirements, and (4) performance monitoring with adaptive management.

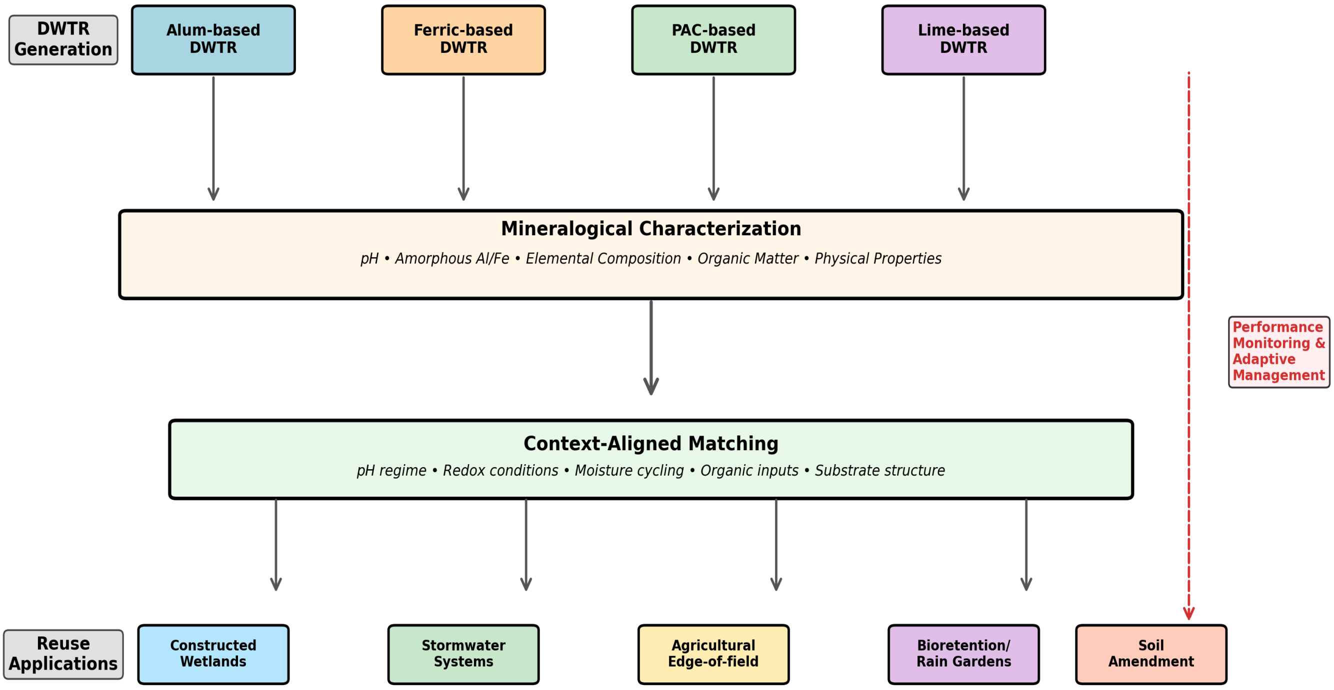

Figure 2. Decision pathway for DWTR characterisation and application matching.

Figure 2. depicts that the workflow begins with four major DWTR types generated from different coagulation processes, proceeds through systematic mineralogical characterization (pH, extractable Al/Fe, composition, organic content, physical properties), evaluates site-specific context factors (pH regime, redox dynamics, moisture patterns, organic matter inputs, substrate requirements), and concludes with application selection across five environmental domains (range applications, constructed wetlands, stormwater systems, agricultural amendments, bioretention/biofilters, soil amendments). Feedback loops (red dashed arrow) enable adaptive management based on performance monitoring.

Table 1 presents a synthesis of optimal conditions for each primary DWTR type based on mineralogical characteristics and documented performance in field and laboratory studies. This matrix provides practical guidance for matching available DWTR to prospective applications, recognising that site-specific validation remains essential.

Table 1. Comparative *context-aligned environmental application matrix for major DWTR types*

DWTR Type	Optimal pH Range	P Binding Capacity*	Typical Amendment %	Optimal Applications
Alum-based	6.0-7.5	20-50 g P/kg	5-15% (v/v)	Constructed wetlands (neutral pH) Bioretention cells Stable moisture systems
Ferric-based	5.0-8.5	15-40 g P/kg	10-25% (v/v)	Stormwater systems Wet-dry cycling sites Variable redox conditions
PAC-based	6.0-8.5	10-35 g P/kg	5-20% (v/v)	Variable pH systems Biofilters Systems requiring pH buffering
Lime-based	7.5-9.0	8-25 g P/kg	15-30% (v/v)	Acidic soils/waters Acid mine drainage High hydraulic flow systems

Note: pH ranges and P binding capacities are approximate and vary with source water quality, organic matter content, and treatment conditions. Optimal applications should be validated through site-specific testing. AL-aluminium, $Al(OH)_3$-aluminium hydroxide, Al–Cl–aluminium chloride, Al–Al-OH-aluminium hydroxide, CA-calcium, DOC-dissolved organic carbon, PSD-particle size distribution

3.1 Constructed Wetlands

Constructed wetlands represent a prime opportunity for DWTR reuse, with DWTR serving as substrate amendments to enhance P retention. Applications of alum-derived DWTR in wetland systems are well documented, particularly in free-water-surface and horizontal subsurface-flow designs where DWTR is commonly incorporated as a blended amendment with sand or soil at modest volumetric proportions (Babatunde & Zhao, 2007; Makris et al., 2004). Multi-year field and mesocosm studies report sustained phosphorus retention over operational timescales, with retention mechanisms shifting from early-stage surface adsorption toward more occluded and residual fractions as substrates age (Ament et al., 2022; Makris et al., 2004)

In addition to laboratory and pilot-scale investigations, DWTR-amended wetland substrates have been examined across a range of wetland configurations and climatic contexts, indicating growing interest in their use for phosphorus control in nature-based treatment systems (Abed et al., 2017; Chang et al., 2017).
Fe-based DWTR may be particularly advantageous in wetlands exposed to seasonal water-table fluctuations and redox variability. Field and laboratory studies indicate that Fe-rich substrates can retain phosphorus during alternating wet–dry cycles, conditions that destabilise less redox-resilient materials (Van Der Hoek et al., 2014; Wu et al., 2021). The comparatively coarse particle size of ferric DWTR also enhances hydraulic conductivity in subsurface-flow systems, potentially reducing the risk of flow restriction associated with finer alum sludges. Evidence from floating-treatment wetland studies highlights how root systems intercept particulate nutrients while simultaneously mediating exchanges between vegetation and the substrate (Ayres et al., 2023). Building on this, the addition of DWTR amendments is anticipated to potentially reinforce particle capture and intensify below-mat biogeochemical cycling, offering a pathway to strengthen nutrient management in buoyant wetland platforms.

The integration of DWTR into wetland substrates must be guided by design choices that balance chemical effectiveness with ecological resilience. Central to this process is adjusting amendment ratios to achieve phosphorus retention without impairing water movement.

An additional design consideration concerns the depth at which DWTRs are incorporated, whether they are positioned near the surface or embedded in deeper substrate layers. Plant–substrate interactions, influenced by vegetation dynamics and root exudates, further determine how DWTR behaves within the matrix. Available field studies indicate that, when applied under controlled conditions, DWTR does not adversely affect wetland plant growth (USEPA, 2011; Zhao et al., 2015), although ongoing site-specific assessment remains essential.

3.2 Bioretention and Stormwater Systems

Bioretention cells and rain gardens are widely deployed for stormwater management but often exhibit limited P removal or even P leaching from organic-rich media (Hsieh and Davis, 2005; Li and Davis, 2009). DWTR amendment addresses this deficiency by providing P sorption capacity while maintaining necessary infiltration rates. Several experimental and pilot-scale studies report that DWTR–sand mixtures can achieve very high phosphorus removal efficiencies while maintaining adequate hydraulic conductivity (Babatunde & Zhao, 2007). In contrast, solid DWTR layers restrict flow and exhibit incomplete contact with infiltrating water (Sousa et al., 2025).

Beyond early demonstrations, DWTR has been evaluated as a reactive amendment in bioretention cells, stormwater biofilters, and filtration media across multiple urban runoff contexts (Westholm, 2023). Reviews of stormwater treatment media increasingly identify metal-based residuals, including DWTR, as promising amendments for phosphorus control in biofiltration systems.

The choice between mixed and layered DWTR configurations involves trade-offs. Mixed designs provide optimal contact but may reduce treatment longevity due to diluted sorption capacity. Layered designs concentrate sorption sites but risk preferential flow paths and incomplete treatment (Dias et al., 2023; Matilainen et al., 2010). Hybrid approaches, such as DWTR-enriched zones within otherwise conventional media, warrant further investigation (Funai and Kupec, 2017).

Across these application domains, reported outcomes highlight the importance of aligning DWTR mineralogical properties with site-specific hydraulic, chemical, and ecological conditions rather than relying on uniform design assumptions (Belzile and Chen, 2024; Florides et al., 2024).

4 Organic Matter and Physical Property Considerations

DWTR–organic matter interactions represent a complex but essential dimension of environmental performance. Comparable interactions between natural organic matter and metal-oxide–rich sorbents have been widely reported, with implications for surface reactivity, sorption site availability, and long-term stability across environmental materials (John et al., 2018; Wang et al., 2024).

Natural organic matter (NOM) in DWTR, derived from coprecipitated humic substances, algae, and particulate material, can influence P sorption through: (1) site competition for surface binding sites, (2) pore blockage reducing internal surface area, or (3) facilitated organo-mineral complex formation that stabilizes both P and organic carbon (Makris et al., 2004; Ippolito et al., 2011).

Alum- and Fe-based DWTRs have been reported to exhibit differential affinity for dissolved organic carbon (DOC), with implications for systems receiving high seasonal organic inputs such as wetlands during leaf-litter decomposition (Babatunde & Zhao, 2007). Studies suggest that moderate organic matter content may enhance phosphorus retention in specific contexts by creating microenvironments favouring precipitation or by bridging mineral surfaces and dissolved phosphorus species (Makris et al., 2004). However, excessive organic loading can saturate surfaces and reduce the availability of sorption sites (Ippolito et al., 2011).

Studies across related sorbent systems similarly report that moderate levels of organic matter can either enhance or inhibit phosphorus retention, depending on molecular composition, loading rate, and environmental context (Guppy et al., 2005; Loganathan et al., 2014).

Physical properties—particularly particle size distribution, bulk density, and aggregate structure—directly influence system hydraulics and DWTR integration strategies. Fine-textured alum-based DWTR typically requires blending with coarser materials to prevent clogging, while Fe-based DWTR may be deployed in structured layers. Lime-based DWTR provides a coarse skeletal structure and high hydraulic conductivity, but may require combination with finer materials to optimise phosphorus contact

4.1 Long-term Performance and Mineral Evolution

DWTR mineral phases evolve over time in response to environmental drivers, including wetting–drying cycles, pH fluctuations, redox transitions, and microbial activity (Makris et al., 2004; Ippolito et al., 2011). For alum-based materials, ageing involves a gradual transition from amorphous AL hydroxide toward more $Al(OH)_3$ and bayerite phases (Babatunde & Zhao, 2007). This crystallisation reduces specific surface area and may slow P sorption kinetics, though long-term P retention remains viable as P becomes incorporated into crystalline structures (Ippolito et al., 2011).

Ageing-related transformations of amorphous aluminium and iron phases have been extensively documented in environmental oxides, with implications for surface area, crystallinity, and sorption behaviour over time (Eary, 1999; Rennert, 2019). Long-term phosphorus immobilisation associated with mineral phase evolution has also been reported in related amended substrates and reactive media (Newcomer Johnson et al., 2016; Reddy et al., 1999).

Fe-based DWTR transforms poorly crystalline ferrihydrite (2-line, 6-line) to goethite and, eventually, hematite. This ripening process similarly reduces surface reactivity but does not eliminate P retention capacity (Makris et al., 2004). Multi-year field studies report sustained performance across diverse DWTR types, although dominant retention mechanisms may shift from surface adsorption to more occluded or residual phosphorus fractions over time (Ippolito et al., 2011).

Importantly, these mineral transformations should not be interpreted as performance degradation but rather as the natural evolution of Al- and Fe-associated phases toward thermodynamically stable forms. The key question for long-term application is not whether minerals change, but whether phosphorus remains effectively immobilised despite these changes—available evidence suggests that it does, though site-specific monitoring remains advisable (Sousa et al., 2025; Ippolito et al., 2011).

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5 Limitations and Risk Considerations

While the context-aligned framework provides systematic guidance for DWTR reuse, several limitations and potential risks must be acknowledged and managed through site-specific assessment and monitoring.

5.1 Metal Leaching and Environmental Safety

DWTR contains elevated concentrations of aluminium or iron, raising concerns about potential metal release under certain conditions. Concerns regarding metal mobility from reused residuals and sorbent materials have been discussed more broadly in the context of environmental amendments and engineered substrates (Marvin et al., 2020; Turner et al., 2023).

Although most studies report that metals remain stable when pH is maintained within optimal ranges (Ippolito et al., 2011; Babatunde & Zhao, 2007), metal mobilisation may occur under extreme pH excursions or strongly reducing conditions. Risk mitigation requires:

(1) initial characterisation of total and extractable metal content, (2) pH monitoring in the application zone, (3) avoiding DWTR use in systems with extreme pH fluctuations, and (4) conducting site-specific leaching tests under worst-case scenarios before large-scale deployment.

5.2 Capacity Saturation and System Lifespan

All DWTR materials have a finite phosphorus retention capacity. Once sorption sites become saturated, systems will transition from P sinks to potential P sources through breakthrough or desorption. Design lifespan depends on loading rates, influent P concentrations, and DWTR type, but field applications often maintain effective P removal over multi-year operational periods (Ippolito et al., 2011; Sousa et al., 2025). Critical considerations include: (1) establishing performance monitoring protocols to detect capacity depletion, (2) designing systems with accessible media replacement pathways, (3) determining end-of-life management strategies for spent DWTR (landfill disposal, P recovery, or stabilisation), and (4) incorporating safety factors in capacity calculations to account for incomplete contact and preferential flow.

Finite sorption capacity and breakthrough behaviour are well-recognised constraints for reactive media used in phosphorus control, underscoring the need for lifecycle-aware system design (Marvin et al., 2020; Wendling et al., 2013).

5.3 Contaminant Co-precipitation and Transfer

During water treatment, coagulation processes may coprecipitate various contaminants, including trace metals (arsenic, lead, chromium), organic micropollutants, pathogens, and emerging contaminants such as per- and polyfluoroalkyl substances (PFAS) (Sousa et al., 2025). While this raises concerns about contaminant transfer to reuse applications, available evidence suggests most contaminants remain firmly bound within DWTR matrices under typical environmental conditions (Belzile and Chen, 2024). Nevertheless, prudent risk management requires: (1) source water quality assessment to identify potential contaminants, (2) DWTR characterization for priority pollutants when source water quality is unknown or variable, (3) avoiding DWTR use in food-producing systems or drinking water recharge zones without comprehensive testing, and (4) focusing reuse on non-potable applications (stormwater, decorative wetlands, non-agricultural landscapes) where human exposure pathways are limited.

5.4 Hydraulic Performance and Clogging

Fine-textured alum-based DWTR can reduce hydraulic conductivity when used in pure layers or at excessive proportions, leading to surface ponding, preferential flow, or system failure. Risk mitigation strategies include: (1) blending DWTR with coarser materials (sand, gravel) rather than creating monolithic layers, (2) limiting amendment percentages to ranges validated for specific applications, (3) conducting bench-scale hydraulic testing before field implementation, and (4) designing for easy inspection and maintenance of surface layers where clogging is most likely.

5.5 Framework Validation Status

The context-aligned framework presented herein represents a synthesis of existing literature rather than empirically validated decision criteria. While the underlying mineralogical principles are well established, quantitative thresholds (pH ranges, amendment percentages, capacity estimates) are approximations derived from diverse studies conducted under varying conditions. Site-specific validation through pilot testing remains essential before full-scale implementation. The framework should be used as structured guidance for initial material selection and system design, not as prescriptive requirements that supersede engineering judgment and local validation.

6 Standardised Characterisation and Reporting

Advancing DWTR reuse from ad hoc trials toward systematic, evidence-based practice requires standardised characterisation and reporting protocols. Currently, studies employ inconsistent analytical methods, report varying parameters, and provide limited mineralogical detail—hindering cross-study comparison and meta-analysis (Sousa et al., 2025; Ippolito et al., 2011; Belzile and Chen, 2024). We propose a tiered characterisation approach balancing thoroughness with practical feasibility:

Table 2. Proposed tiered characterisation protocol for DWTR

Tier	Purpose	Parameters
Tier 0		Initial Screening (minimum characterization): Coagulant type (from facility records), pH (simple pH meter), Moisture content (oven dry method), Qualitative P sorption test (batch equilibrium, single point), Visual assessment of particle size and texture
Tier 1 (Essential)	Baseline characterization for all reuse applications	pH, EC; Total AL/Fe (digestion); Amorphous Al/Fe (oxalate); Organic matter (LOI); Particle size (D10/D50/D90); Bulk density; Moisture content
Tier 2 (Recommended)	Research studies & mechanistic interpretation	Full elemental composition (Ca, Mg, Si, trace metals); BET surface area; XRD; P sorption isotherms; Point of zero charge
Tier 3 (Advanced)	High-resolution mineralogical and surface chemistry analysis	FTIR; XPS / EDS; Sequential P fractionation; EXAFS/XANES; SEM/TEM

***AL-aluminium, Fe – ferric, LOI-* Loss on ignition, *Ca-calcium, Mg-magnesium. Si-silicon, BET- Brunauer, Emmett, and Teller theory, XRD-x-ray diffraction, P-phosphorous, FTIR-* Fourier transform infrared spectroscopy, *XPS-* X-ray photoelectron spectroscopy, *EDS-* Energy Dispersive Spectroscopy, *EXAFS-*Extended X-ray absorption fine structure*, XANES- X-ray absorption near edge structure, SEM-* scanning electron microscope, *TEM-*Transmission electron microscopy.

Tier 0 provides sufficient information for an initial feasibility assessment and verification of coagulant type. Small utilities or pilot projects may begin with Tier 0 and advance to Tier 1 if results warrant further investigation. Tier 1 remains the recommended minimum for most reuse applications.

Tier 1 parameters provide sufficient information for most practical applications and enable meaningful cross-study comparison. Tier 2 adds research-grade detail valuable for mechanistic understanding and performance prediction. Tier 3 represents specialised techniques for detailed mineralogical investigation. Standardised reporting would facilitate the development of predictive models, regional DWTR databases, and evidence-based design guidelines. Several utilities and research consortia have begun implementing shared characterisation protocols, demonstrating both the feasibility and value of coordinated approaches.

7 Research Priorities and Future Directions

Despite growing interest and promising results, DWTR reuse faces several research gaps that constrain widespread implementation. Priority areas for future investigation include:

7.1 Multi-site Performance Validation

Most DWTR studies represent single-site trials or controlled laboratory experiments. Systematic multi-site trials across diverse climates, water chemistries, and system designs would strengthen the evidence base and identify performance boundaries (Ippolito et al., 2011; Sousa et al., 2025). Coordinated research networks could standardise monitoring protocols and enable meta-analysis.

7.2 Long-term Field Monitoring

Field studies lasting 5–10 years or more remain rare. Understanding decadal-scale performance, particularly regarding mineral ageing, P capacity saturation, and potential metal release, is critical for design life estimation and lifecycle cost analysis (Ippolito et al., 2011). Establishing monitoring networks at existing installations would generate valuable longitudinal data.

7.3 PAC-based Residue Characterisation

Given PAC's increasing adoption globally, a systematic study of PAC-derived DWTR mineralogy and performance remains a significant knowledge gap. How do basicity and Al_{13} structure affect the resulting residue properties? What are optimal application contexts for PAC-derived materials? (Sousa et al., 2025)

7.4 Interactions with Emerging Contaminants

DWTR may coprecipitate or adsorb various contaminants during water treatment, including per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, and microplastics (Sousa et al., 2025). Understanding contaminant partitioning and potential release upon reuse is essential for environmental safety assessment. Conversely, DWTR's sorption capacity might be leveraged for multi-contaminant treatment (Belzile and Chen, 2024).

7.5 Life Cycle Assessment and Circular Economy Integration

Comprehensive life-cycle assessments (LCAs) comparing DWTR reuse pathways with conventional disposal and virgin P mining would quantify environmental. Integration with nutrient recovery frameworks and circular economy strategies could position DWTR within broader resource management systems (Sousa et al., 2025).

7.6 Regulatory Framework Development

Inconsistent regulatory treatment of DWTR across jurisdictions creates barriers to reuse. Some regions classify DWTR as hazardous waste requiring extensive testing, while others permit beneficial use with minimal oversight. Evidence-based regulatory frameworks that balance environmental protection with resource recovery would facilitate the responsible deployment of DWTR.

7.7 Economic and Social Dimensions

Economic feasibility depends on transportation costs, application labour, avoided disposal expenses, and potential revenue from improved system performance. Social acceptance by stakeholders—including water utilities, land managers, regulators, and community members—influences adoption rates. Research integrating technical performance with economic and social factors would support implementation (Dias et al., 2023; Wu et al., 2021).

8 Conclusions

DWTR represent a diverse suite of materials with mineralogical characteristics that can be aligned to specific environmental applications. Rather than treating DWTR as a uniform waste requiring disposal, the field should embrace mineralogical diversity as a functional advantage enabling context-aligned reuse (Ippolito et al., 2011; Makris et al., 2004). Alum-based DWTR excel in neutral-pH wetlands and bioretention systems; Fe-based materials offer redox stability for stormwater and intermittently flooded environments; PAC-derived DWTR provide buffering capacity for variable-chemistry systems; and lime-based materials address acidic settings requiring alkalinity and calcium-mediated phosphorus removal (Ippolito et al., 2011).

The context-aligned framework proposed herein provides systematic guidance for matching available DWTR to prospective applications based on pH regime, moisture dynamics, redox conditions, organic matter inputs, and hydraulic requirements. Table 1 synthesises optimal conditions for the major DWTR types, providing practitioners with actionable decision support while acknowledging that site-specific validation remains essential.

Global drinking water treatment generates DWTR at a scale that represents a substantial and underutilised material stream. Recognising mineralogical diversity as a design advantage reframes DWTR from a disposal liability to a material capable of supporting phosphorus management, landfill reduction, and water-quality improvement (Ippolito et al., 2011; Babatunde & Zhao, 2007).

The transition from concept to practice cannot be achieved in isolation. Effective reuse of DWTR will require coordinated structures that link research, regulation, and implementation. Building shared characterisation databases, establishing international monitoring networks, and developing design guidance rooted in mineralogical diversity are central to this process. When these elements converge, DWTR can be repositioned from a residual waste stream to a resource embedded within nature-based treatment systems and circular nutrient management, advancing both environmental protection and sustainable infrastructure.

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Conflicts of interest

There are no conflicts to declare for any of the authors.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Grammarly to format and grammar-check the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article

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