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REVIEW **Open Access**

Process water from hydrothermal carbonization: from waste to liquid fertilizer and soil health amendment in circular bioeconomy

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Abstract

Hydrothermal carbonization (HTC) transforms wet or dry biomass into hydrochar, generating a nutrient-rich process water, hereafter termed HTC-PW, which is often overlooked as waste. This review synthesizes current knowledge on HTC-PW composition, including varied pH (3.5–9.2), high organic content (TOC 4,000–31,700 mg L^{-1}), and nutrients such as NH_4^+–N (up to 4,400 mg L^{-1}) and potassium (5,870–6,330 mg L^{-1}), derived from feedstocks such as sewage sludge and food waste. Process controls such as temperature and residence time tune HTC-PW properties for agronomic use, enabling enhanced partitioning of elements between solid and liquid phases. Pathways include direct fertigation, co-application with biogas slurry, and conditioned recovery, such as struvite precipitation yielding 92–99% P and 43–88% N. Performance metrics demonstrate yield increases of 6.7–29.2% and improved nutrient use efficiency of 15–30% in crops such as rice, alongside microbiome shifts favoring bacterial communities for better nutrients cycling. Beyond fertilization, valorization routes encompass anaerobic digestion for biogas (250–350 mL CH_4 g^{-1} COD, with 70–85% COD removal) and catalytic reforming for H_2. Risks such as salinity (EC 5–24 mS cm^{-1}) and context-dependent N_2O responses (suppression under inhibitory organics versus pulses under high NH_4^+ loading) necessitate bioassays and regulatory compliance, while techno-economic analysis and life-cycle assessment indicate scenario-dependent benefits, including economic savings where avoided wastewater-treatment credits apply and 20–50% reductions in global warming potential when mineral fertilizer substitution is credited. Gaps in long-term trials and scalability are identified, with future directions emphasizing machine learning for predictive optimization of HTC-PW properties and applications. Overall, current evidence supports HTC-PW primarily as a nutrient-rich liquid amendment (fertilizer-like input) that alters soil DOM and microbial processes, while direct evidence for consistent improvements in soil physical structure remains limited and warrants targeted measurement in future field trials.

Highlights

- HTC-PW is rich in NH_4^+, P, K, and organics, offering strong agronomic potential.
- Process controls tune HTC-PW composition for safer and more effective soil and crop applications.
- HTC-PW use boosts soil DOM, nutrient retention, and yields, while valorization recovers N, P, and energy.

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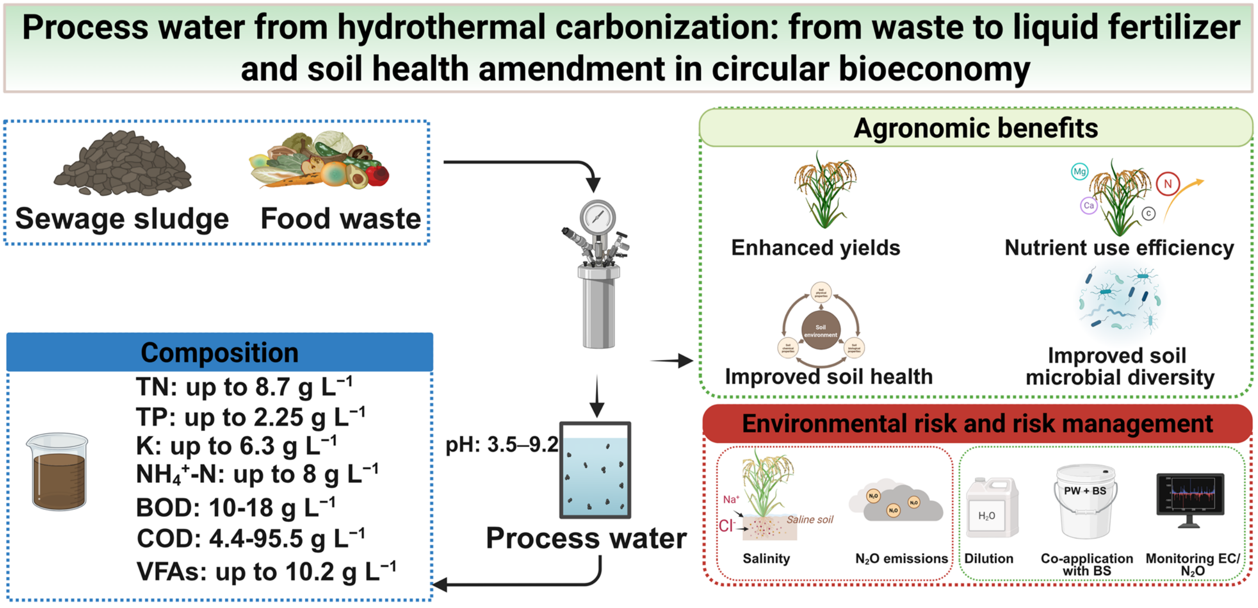
Keywords Energy, Greenhouse gas, Hydrochar, Life cycle assessment, Sustainable agriculture, Waste management

Graphical Abstract



1 Introduction

Hydrothermal carbonization (HTC) is an emerging thermochemical process that mimics natural coalification to convert wet biomass and organic wastes into a carbon-rich solid (hydrochar) without energy-intensive drying (Berge et al. 2011; Li et al. 2023b; Yu et al. 2024). In HTC, a water–biomass slurry (typically 5–10:1 mass ratio) is heated to 180–280 °C under autogenous pressure for about 0.25–2 h. This promotes hydrolysis, dehydration, decarboxylation, and aromatization reactions (Chu et al. 2020a, 2021b; Ischia et al. 2025). These reactions break down polymers into smaller molecules, some of which re-polymerize into hydrophobic, energy-dense hydrochar while releasing CO_2 and producing a large volume of process water (HTC-PW). In this review, HTC-PW refers to the aqueous liquid fraction separated from the HTC slurry after reaction and solid–liquid separation. It contains dissolved and suspended organics and inorganics released and transformed during HTC. Because water remains liquid throughout the process, HTC tolerates high-moisture feedstocks such as food waste (Dhull et al. 2024; Periyavaram et al. 2023), sewage sludge (Chu et al. 2020c; Liu et al. 2025), and microalgae (Chu et al. 2020b; 2021a), eliminating drying costs and making HTC attractive for decentralized waste management and circular bioeconomy applications.

Although hydrochar has received considerable attention as soil amendment (Lan et al. 2025; Yu et al. 2019) and adsorbent (Li et al. 2021b), it captures merely about 30–70% of the dry feed carbon as hydrochar. Nevertheless, the remainder ends up as soluble organics and minerals in the HTC-PW (Feng et al. 2025b; Meng et al. 2025; Nguyen et al. 2023) (Fig. 1). Historically, HTC-PW was regarded as a waste byproduct, due to containing organic acids, phenolics, furans, nutrients, and heavy metals (Czerwińska et al. 2023; González-Arias et al. 2023; Stemann et al. 2013). As a result, most research and technology development have focused on optimizing hydrochar production, while HTC-PW has been underutilized (Fig. 1).

Recent studies are changing this perception. HTC-PW is now seen as a nutrient-rich liquid with agronomic potential. For example, Li et al., (2025) demonstrated the potential of HTC-PW to recycle carbon and nitrogen (N) into paddy fields, significantly improving soil dissolved organic matter (DOM) and N retention. Composting trials report that adding HTC-PW reduces ammonia (NH_3) and nitrous oxide (N_2O) emissions and accelerates humification (Feng et al. 2025b; Wang et al. 2025). The renewed attention reflects a growing shift in research and practice from linear waste disposal toward circular nutrient recovery systems—an essential component of the

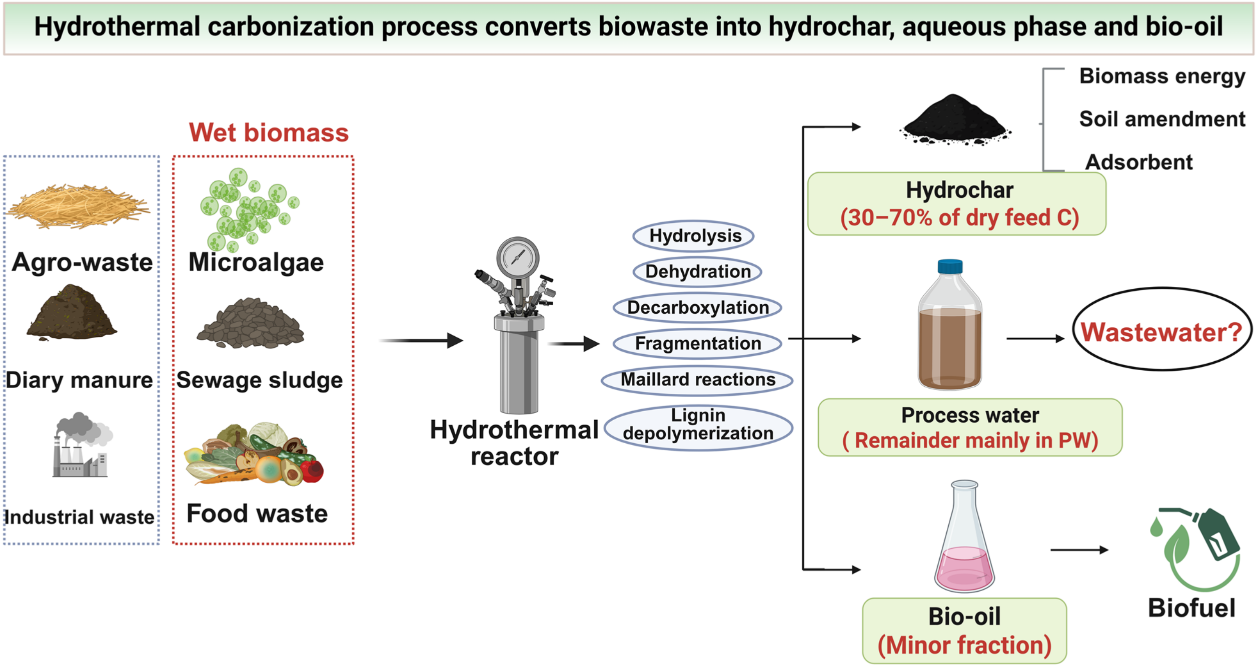


Fig. 1 Schematic diagram of the hydrothermal carbonization process, emphasizing key reaction pathways and generation of hydrochar, HTC-PW, and bio-oil

circular bioeconomy and sustainable development goals, particularly in agriculture and environmental protection.

The underutilization of the HTC-PW highlights a gap in the literature between research on hydrochar and HTC-PW. While numerous reviews document hydrochar production, activation and applications (Dhull et al. 2024; Huang et al. 2023), only a handful of studies have systematically characterized the aqueous phase and explored its valorization routes (Meng et al. 2025). This imbalance is problematic because the HTC-PW can represent up to 70% of the initial mass and contains valuable nutrients and organics (Nguyen et al. 2023). Treating it as waste contradicts the principles of the circular economy, which aims to close material and energy loops by conserving, reusing and recycling resources (Corrochano et al. 2025). A circular bioeconomy framework suggests that wastes should be converted into inputs for other processes, thereby reducing environmental impacts and creating economic value. In the context of HTC, this means designing integrated systems where the HTC-PW is recovered as a nutrient-rich liquid amendment (fertilizer-like input) or feedstock for nutrient recovery (Li et al. 2023a, 2025; Xu et al. 2026), the hydrochar is used as a soil amendment or energy source (Chu et al. 2023; Liu et al. 2024; Gievers et al. 2025; Li et al. 2021c), and the small gas fraction is captured for heat or power (Guo et al. 2024b). Such integration can improve the overall resource efficiency of HTC, reduce external fertilizer inputs, and lower the cost associated with effluent treatment.

This review therefore focuses on the HTC-PW—its composition, transformation pathways, and potential as a nutrient-rich liquid amendment for crop and soil management. Literature was selected to represent the most relevant and recent peer-reviewed studies on HTC-PW, prioritizing papers that report (i) HTC-PW composition (nutrients and key inhibitory/toxic compounds) and/or (ii) demonstrated transformation, conditioning, recovery, or agronomic application outcomes. Studies not directly focused on HTC-PW or lacking HTC-PW-related data were not considered. By synthesizing current knowledge, we aim to highlight the opportunities and challenges in turning a perceived waste stream into a valuable resource within the circular bioeconomy. Addressing this gap is essential for realizing the full benefits of hydrothermal carbonization and moving from a "waste disposal" mindset toward a resource-recovery perspective.

2 Composition of HTC-PW

2.1 Physical properties

HTC-PW exhibits distinct physicochemical properties driven by feedstock (Table 1). It is typically acidic, with a pH ranging from 3.5 to 5.6 for most lignocellulosic biomass-derived HTC-PW, attributable to the accumulation of organic acids from hydrolysis and dehydration reactions (Colin et al. 2025; Mäkelä et al. 2018; Stemann et al.

Table 1 Typical composition of HTC-PW from various feedstocks

Feedstock	pH	EC (mS cm^{-1})	TOC (mg L^{-1})	COD (mg L^{-1})	BOD (mg L^{-1})	VFAs (mg L^{-1})
Sewage sludge	5.5–9.2	10–24	4,000–30,000	10,000–95,500	10,000–18,000	200–700
Food waste	6.5–9.2	8–20	18,000–62,350	18,610–84,400	NS	Up to 10,200
Lignocellulosic	3.5–5.6	5–12	5,600–9,500	18,610–41,350	NS	Up to 1,300
Animal manure	4.4–6.4	10–24	5,600–6,500	4,400–10,000	NS	NS
Macro/microalgae	3.9–8.0	6–15	8,204–20,900	58,000	NS	NS

Feedstock	Furans (mg L^{-1})	TN (mg L^{-1})	NH_4^+-N (mg L^{-1})	TP (mg L^{-1})	K (mg L^{-1})
Sewage sludge	0.2–1,230	1,493–4,020	320–7,980	21–2,047	633–666
Food waste	0.2–1,230	> 4,000	Up to 4,400	Up to 2,000	Up to 6,330
Lignocellulosic	50–1,230	< 500	229–840	< 1,000	NS
Animal manure	NS	3,940–5,030	Up to 4,400	940–2,250	5,870–6,330
Macro/microalgae	NS	0.9–8,700	Up to 2,200	NS	NS

The values are indicative and depend on temperature, residence time, solids loading, pH, and recirculation

The data were mainly summarized from the references: Stemann et al. (2013); Heilmann et al. (2014); Mäkelä et al. (2018); Aragón-Briceño et al. (2020); Langone and Basso (2020); Celletti et al. (2021); Shrestha et al. (2021); Nguyen et al. (2023); Periyavaram et al. (2023); Ender et al. (2024); Ipiales et al. (2024); Meng et al. (2025)

NS not specified, *BOD* biochemical oxygen demand, *COD* chemical oxygen demand, *EC* electrical conductivity, *K* potassium, *TN* total nitrogen, *TP* total phosphorus, *VFA* volatile fatty acids

2013). However, in protein-rich feedstocks such as sewage sludge or food waste, pH can range from less acidic to alkaline (about 5.5–9.2) due to NH_3 release and buffering capacity (Langone and Basso 2020; Periyavaram et al. 2023). Higher HTC temperatures tend to increase acidity because more organic acid are formed, whereas alkaline additives such as CaO can raise pH up to 10.0 (Aragón-Briceño et al. 2020).

The color of HTC-PW varies from yellow to dark brown or black, owing to humic substances, melanoidins from Maillard reactions, and phenolic compounds (Guo et al. 2025; Ipiales et al. 2024). Lower temperatures (180–220 °C) generally produce darker PW, whereas very severe conditions (> 300 °C) can lighten the effluent because many organics gasify (Ender et al. 2024). For sludge-derived HTC-PW, the liquid is often more turbid due to suspended solids, with recirculation exacerbating darkening from accumulated chromophores (Xu et al. 2020). Conductivity (5–24 mS cm^{-1}) is high due to dissolved salts and increases with recirculation as salts accumulate (Ipiales et al. 2024; Yan et al. 2023). HTC-PW often has an aromatic odor from volatile organics and low viscosity (80–95% water content) (Nguyen et al. 2023).

2.2 Organic components

The organic fraction dominates HTC-PW, comprising 70–90% of the dissolved solids and posing both challenges and opportunities. Total organic carbon (TOC) is extremely high, at 4,000–31,700 mg L^{-1}, with chemical oxygen demand (COD) up to 4,900–78,000 mg L^{-1} and biochemical oxygen demand (BOD) up to 1,700–42,000 mg L^{-1}, reflecting high pollution potential but moderate biodegradability (COD/BOD ratios ratios of 2.0–2.7) (Aragón-Briceño et al. 2020; Ender et al. 2024; Mäkelä et al. 2018). Volatile fatty acids (VFAs), especially acetic acid, often exceeding 20,000 mg L^{-1}, can account for about half of the total organics, which are mainly derived from carbohydrate degradation (Ipiales et al. 2024; Stemann et al. 2013; Xu et al. 2020). Lignocellulosic feedstocks yield furans (e.g., furfural, 5-HMF) and phenols from hemicellulose and lignin breakdown, with concentrations up to about 1,200 mg L^{-1} (Becker et al. 2014; Ipiales et al. 2024; Nguyen et al. 2023). In contrast, HTC-PW from protein-rich feedstocks like sewage sludge or food waste produces more nitrogenous organics (e.g., pyrazines, amides) via Maillard reactions (Aragón-Briceño et al. 2020; Meng et al. 2025; Periyavaram et al. 2023) (Table 1).

Other organics include phenols (290–800 mg L^{-1} from lignin), sugars (glucose, fructose, xylose: decreasing at > 200 °C), and aromatic intermediates (e.g., benzene, pyrazines, ketones) (Aragón-Briceño et al. 2020; Ender et al. 2024; Meng et al. 2025). In lignocellulosic feedstocks such as poplar wood or garden waste, furans and sugars peak at 190–235 °C before declining due to further reactions (Ender et al. 2024; Ipiales et al. 2024; Stemann et al. 2013). Protein-rich sources such as sludge or macroalgae yield more pyrazines and amino acid derivatives via Maillard reactions (Aragón-Briceño et al. 2020; Shrestha et al. 2021; Wang et al. 2019). Many of these organics are phytotoxic, so HTC-PW typically requires dilution or treatment before agricultural application.

2.3 Inorganic components and nutrients

Inorganic components are also abundant in HTC-PW, which underpins its fertilizing potential. Total nitrogen (TN) varies from 100 to 9,300 mg L^{-1}, mainly present as ammonium (NH$_4^+$–N, 0.1–4,400 mg L^{-1}) from protein deamination (Mäkelä et al. 2018; Merzari et al. 2019; Nguyen et al. 2023; Stemann et al. 2013). Protein-rich feedstocks such as sewage sludge and food waste often yield HTC-PW with TN more than 4,000 mg L^{-1} (Langone and Basso 2020; Periyavaram et al. 2023), whereas woody materials such as garden waste or agricultural wastes yield HTC-PW with TN lower than 500 mg L^{-1} (Becker et al. 2014; Ipiales et al. 2024). Total phosphorus (TP) in HTC-PW is often 940–2,250 mg L^{-1} in the form of orthophosphate, accounting for 2–55% of the feed P; acidic conditions enhance P release (Ender et al. 2024; Langone and Basso 2020; Meng et al. 2025). Manure and sludge can produce HTC-PW up to 2,000 mg L^{-1} TP from solubilized phosphates (Boutaieb et al. 2021; Celletti et al. 2021; Heilmann et al. 2014), while wood or certain algae yield less than 1,000 mg L^{-1} (Shrestha et al. 2021; Wang et al. 2019). Potassium (K) is highly soluble, up to 5,870–6,330 mg L^{-1} in manure-derived HTC-PW, and other macronutrients, including calcium (Ca) up to 5,400 mg L^{-1} and variable magnesium (Mg), are plentiful, potentially supporting plant growth (Celletti et al. 2021; Liu et al. 2023; Wang et al. 2025) (Table 1).

Heavy metals (e.g., Cr, Ni, Cu, Cd, Pb) can leach around 1–30% into HTC-PW, increasing their concentration with temperature, but most metals tend to precipitate or bind in the hydrochar at more than 260 °C as sulfides or phosphates (Langone and Basso 2020; Meng et al. 2025; Nguyen et al. 2023). Anions such as chloride and sulfate add to salinity, especially with recirculation (Ipiales et al. 2024). Thus, HTC-PW's nutrient profile is rich, while heavy metal contaminants must be monitored for safe use.

3 Process controls and property tuning: partitioning and recirculation dynamics

HTC process parameters critically influence HTC-PW composition, enabling "design" of its nutrient and organic profile. By adjusting reaction temperature, time, solids loading, pH or additives, and HTC-PW recirculation, operators can optimize nutrient transfer to HTC-PW or hydrochar and manage contaminants. This section outlines how each control affects carbon and nutrient partitioning and overall HTC-PW quality (Fig. 2).

3.1 Temperature: the primary selector of N speciation

Temperature strongly dominates HTC-PW speciation. Lower to moderate HTC temperatures (180–220 °C) favor hydrolysis, producing high concentrations of VFAs, sugars, and NH$_4^+$–N in HTC-PW (Ender et al. 2024;

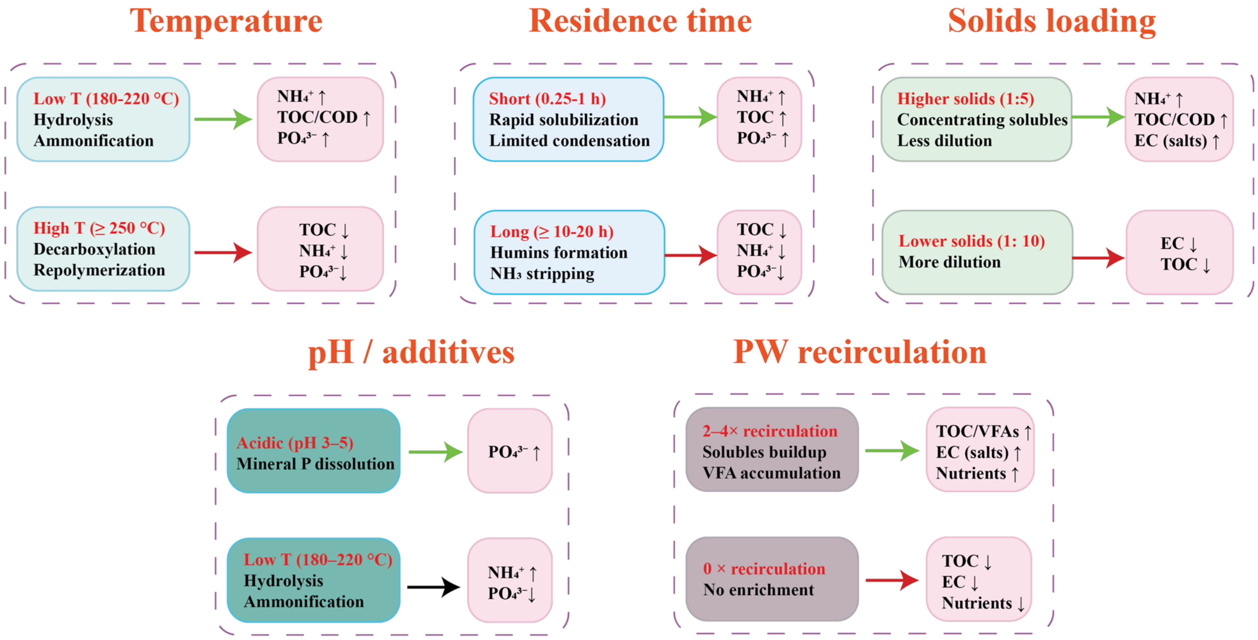


Fig. 2 Effects of key HTC parameters on HTC-PW composition and nutrient partitioning. *COD* chemical oxygen demand, *EC* electrical conductivity, *TOC* total organic carbon, *VFA* volatile fatty acids

Mäkelä et al. 2018; Stemann et al. 2013). For instance, sludge HTC below 220 °C can dissolve roughly half of the feed N into HTC-PW, mainly as bioavailable NH_4^+, and acidic conditions dissolve 40–60% of feed P into orthophosphate (Meng et al. 2025; Shrestha et al. 2021). Above 250 °C, reactions shift toward gasification and aromatization: TOC in HTC-PW drops by 20–50%, and more N converts to inorganic or char-bound recalcitrant forms such as phenols (Ipiales et al. 2024; Periyavaram et al. 2023). This temperature-dependent partitioning is evident in lignocellulosic feedstocks, where furan derivatives peak at 190–235 °C before declining, allowing for "design" of HTC-PW with balanced nutrient profiles for soil application (Becker et al. 2014; Berge et al. 2011; Langone and Basso 2020). Therefore, mild HTC preserves HTC-PW nutrients, which is beneficial for immediate fertilizer value, while severe HTC sequesters more C and some P in hydrochar, yielding a cleaner HTC-PW to minimize nutrient leaching risk in field applications. Overall, designing the temperature allows tuning HTC-PW: low or mild temperatures (180–220 °C) maintain NH_4^+ for limiting nitrate leaching, whereas high temperatures (≥ 220 °C) yield HTC-PW with fewer organics but more recalcitrant aromatics, potentially increasing toxicity.

3.2 Residence time: deciding between extraction and repolymerization

Residence time further refines this tuning. Shorter runs at 0.25–1 h maximize extraction of labile nutrients such as K and Mg, often achieving 70–90% recovery in HTC-PW from manure-derived HTC (Celletti et al. 2021; Nguyen et al. 2023; Stemann et al. 2013). Extended times up to 20 h promote secondary condensation: proteins and sugars can repolymerize via Maillard browning, reducing COD and BOD in HTC-PW by 10–30% and transferring organics into hydrochar solid phase (Aragón-Briceño et al. 2020; Ender et al. 2024; Periyavaram et al. 2023). In sludge HTC, prolonged residence at 200 °C increases P immobilization in hydrochar as phosphates, partitioning only 2–20% to HTC-PW, which can be useful if low-P HTC-PW is desired to avoid eutrophication in soil runoff (Cao et al. 2021; Langone and Basso 2020). Recent data from biomass wastewater HTC show optimal 1–3 h for N and P recovery rates of 43–99%, balancing yield and energy (Liu and Zhang 2025). In practice, short residence yields HTC-PW rich in soluble N and P, which is ideal for fertigation, while a long residence time yields cleaner HTC-PW but with less dissolved nutrients.

3.3 Solids loading: steering nutrient concentration and partitioning

The biomass-to-water ratio of solids loading in HTC controls HTC-PW concentration. Lower loading with more water, such as 1:10 biomass-to-water, produces dilute HTC-PW with lower electrical conductivity (EC at 5–10 mS cm^{-1}) and reduced salt stress, whereas nutrient concentrations are lower (Ipiales et al. 2024; Xu et al. 2020). Higher loadings (e.g., 1:5) concentrate VFAs and nutrients, boosting TOC by 1.5–twofold and increasing NH_4^+–N up to 4,000 mg L^{-1} in sludge HTC-PW, at the expense of viscosity and salinity (Periyavaram et al. 2023; Yan et al. 2023). In co-HTC of mixed wastes such as sewage sludge and rice straw, an optimal loading under acidic conditions solubilized up to 55% of P (Li et al. 2025). Moderate loadings at 5–10 wt% often yield fine hydrochar and HTC-PW whose N-P-K ratios after dilution can mimic commercial fertilizers, for example, a 18:12:16 N:P:K ratio (Celletti et al. 2021; Ipiales et al. 2024; Yan et al. 2023). Thus, loading is a practical lever: low solids favor agronomic readiness, such as low EC, while high solids can be used to create concentrated nutrient solutions for later dilution or recovery.

3.4 pH and mineral catalysts: phosphate and metal gatekeepers

Adjusting pH or adding catalysts strongly affects partitioning. Acidic conditions (pH 3–5, induced by organic acids formation like citric acid) enhance metal and P solubilization, increasing TP in HTC-PW by 20–40% while retaining heavy metals such as Cr and Pb in hydrochar (Aragón-Briceño et al. 2020; Boutaieb et al. 2021; Heilmann et al. 2014). Alkaline additives (CaO or NaOH) shift NH_3 into HTC-PW for NH_4^+ retention and raise pH to reduce acidity-related toxicity, but may precipitate P with Ca in char (Aragón-Briceño et al. 2020; Meng et al. 2025). Catalysts amplify these effects: for example, adding citric acid in food waste HTC boosts VFA yields by 30% and N-doping of hydrochar (Yan et al. 2023), while Lewis acids like $FeCl_3$ catalyze dehydration, partitioning more aromatics into hydrochar and yielding cleaner HTC-PW with lower phenols (Bkangmo Kontchouo et al. 2025). Notably, dosing sewage sludge with Ca or Mg salts at 260 °C forms slow-release phosphate minerals (e.g., hydroxyapatite in Ca-based or soluble $Mg_3(PO_4)_2$ in Mg-based) in hydrochar, increasing TP in the solid by 48.6–86.3% for tailored fertilizer release (Aragón-Briceño et al. 2020; Sarrion et al. 2023; Zhao et al. 2025). These interventions allow "tuning" of HTC-PW for agronomic safety: for example, low-temperature, acid-catalyzed HTC can maximize soluble NH_4^+ in a low-salinity HTC-PW while managing EC below 15 mS cm^{-1} to prevent salt stress in crops (Colin et al. 2025).

3.5 HTC-PW recirculation: closing the loop while tuning quality

HTC-PW recirculation emerges as a key strategy for property tuning, closing loops in circular systems by reusing HTC-PW in subsequent HTC cycles for 1–4 cycles. Recirculation accumulates organics and ions: TOC and COD roughly double, and VFAs can increase by fivefold, making the medium more acidic (Lu et al. 2014; Picone et al. 2024; Xu et al. 2020). In garden-waste HTC, each recirculation darkened HTC-PW due to chromophores while lightening toxicity by degrading furans, boosting nutrient concentration for fertilizer value (Boutaieb et al. 2021; Wang et al. 2019). However, challenges include elevated salinity (EC up to 24 mS cm^{-1}) and potential phytotoxins, necessitating mitigation like partial dilution or bio-purification (Koçer et al. 2023; Mantovani et al. 2022). For agronomy, recirculation at mild conditions, e.g., 200 °C, short time, "designs" HTC-PW with high NH_4^+ and moderate salts, aligning with sustainable goals by minimizing freshwater use and effluent discharge. In practice, 2–3 recirculation loops enrich nutrients without excessive salt build-up.

3.6 Practical design sheet for agronomic HTC-PW

By treating temperature, residence time, solids loading, pH, and recirculation as coupled levers, HTC-PW can be tailored for specific crops and application modes:

- Leafy vegetables are salt-sensitive. Tuning HTC in a mild way at 190–200 °C, 0.5–2 h, and a 1:8–1:10 biomass: water ratio could yield HTC-PW with low salinity and moderate VFA content, suitable for direct use after dilution. 2–3 recirculation loops enrich nutrients gently without excessive salt build-up (Ipiales et al. 2024; Stemann et al. 2013; Xu et al. 2020).
- Paddy rice desires NH_4^+–N as N source. Tuning HTC in a slightly higher severity at 230 °C, 1 h, and 1:6–1:8 biomass: water ratio, with 3–4 recycles, can raise NH_4^+–N into the g L^{-1} range. A post-treatment with CaO can then elevate pH and co-precipitate part of the phosphate into slow-release Ca-phosphate in the char, helping regulate floodwater chemistry (Ender et al. 2024; Ipiales et al. 2024; Stemann et al. 2013).
- Hydroponics or fertigation can adopt a low-severity way at 190 °C, less than 1 h, and 1:10 biomass: water ratio with an acid catalyst to maximize P solubilization. After subsequent neutralization (e.g., KOH) and 1:5 dilution, the HTC-PW can match standard nutrient solution N–P–K profiles (Celletti et al. 2021; Qaramaleki et al. 2023).

Across these use-cases, solids loading balances both nutrient density and phytotoxic risk: lower solids loadings (1:10) favor agronomic readiness at lower salinity, while higher loadings at 1:5–1:6 concentrate VFAs and NH_4^+ for later dilution or recovery (Periyavaram et al. 2023; Yan et al. 2023). Recirculation enriches nutrients but should be capped at 2–3 loops to avoid excessive salt accumulation (Boutaieb et al. 2021; Ipiales et al. 2024; Stemann et al. 2013). Routine monitoring on TOC, pH, EC, and nutrient serves as a simple control panel to keep HTC-PW within agronomic thresholds, shifting HTC from waste handling toward precision fertilizer manufacturing.

4 Agronomic use pathways and performance

HTC-PW's nutrient-rich profile enables diverse agricultural applications. These pathways—direct use, co-application with solids, and conditioned use—leverage HTC-PW's fertilizer attributes to boost crop yield, nutrients use efficiency, and soil health, closing nutrient loops and advancing circular farming. Table 2 has summarized the previous studies on the application of HTC-PW in agricultural performance.

4.1 Direct use: dilution is the key

Direct application of diluted HTC-PW, often via fertigation or hydroponics, exploits its immediate nutrient availability. HTC-PW typically retains 30–70% of feedstock nutrients; notably, it can contain very high soluble NH_4^+ (up to 4,400 mg L^{-1}) and K (5,870–6,330 mg L^{-1}), supplying quick N and K (Becker et al. 2014; Celletti et al. 2021; Nguyen et al. 2023). Organic N or P in HTC-PW provides slower-release fertility. Dose–response studies indicate that optimal dilutions (1:3–1:9) mitigate phytotoxicity from organics such as phenols and furans, with germination assays showing 20–60% N and P release within days (Moloeznik et al. 2024; Niu et al. 2021). In rice paddies, direct application at 25–50% N substitution boosts soil NH_4^+–N by 36–130% and available P by 48–83%, enhancing grain yield by 6.7–29.2% and N concentration by 6–15% (Li et al. 2023a; 2025). Crop response depends on sensitivity: lettuce nearly doubled biomass with low-DOM HTC-PW from mild HTC, while beans and corn gained from micronutrients, improving water-use efficiency via higher stomatal density (Celletti et al. 2021; Ipiales et al. 2024; Qaramaleki et al. 2023).

Soil microbial activity generally increases: in incubation studies 19% of HTC-PW -carbon was respired, priming N mineralization although temporary N immobilization can occur (Watson et al. 2021). Crucially, organics in HTC-PW inhibit nitrification, reducing NH_3 volatilization by 15–46% and suppressing nitrate leaching (Huang et al. 2022a; Li et al. 2025). Performance metrics

Table 2 Literature on HTC-PW: feedstocks, conditions, composition, and agronomic performance

Feedstock	**Study scale**	**Study duration**	**Target**	**Performance**	**Reference**
Chicken manure and rice straw	Lab (photochemical/bench test)	144 h	Rice paddies	DOM in HTC-PW undergoes photobleaching, producing ROS that degrade contaminants like tetracycline	Xie et al. (2024)
Vegetable residues and swine biogas	Greenhouse (paddy soil column study)	Two years	Rice paddies	HTC-PW substituted chemical N fertilizer, boosted soil DOM & total N, reduced NH_3 volatilization, maintained rice N uptake	Li et al. (2025)
Vegetable residues and cattle manure	Field (paddy plot experiment)	Two years	Rice paddies	HTC-PW increased soil NH_4^+-N, DOC, available P, altered microbes, boosted rice yield by up to 29.2%	Li et al. (2023a, b)
Algae sludge	Greenhouse (paddy pot study)	One growing-season of rice	Rice paddies	HTC-PW replacing 25–50% urea maintained yield, cut NH_3 losses by up to 55.5%, increased soil DOM	Wang et al. (2025)
Quercus acutissima leaves	Lab (composting reactors/bench scale)	30 d	Manure composting	HTC-PW at 10% to chicken manure compost cut NH_3 by 23–26%, altered bacterial communities, potential national emission reduction	Feng et al. (2025b)
Sewage sludge and kitchen waste	Greenhouse (paddy soil column study)	One growing-season	Rice paddies	Sewage sludge HTC-PW altered soil DOM & microbiota, DOM–microbiota interactions drove water quality changes; low-dose HCPW reduced COD	Feng et al. (2025a)
Wheat straw	Lab (composting reactors/bench scale)	One growing-season	Manure composting	HTC-PW raised humification index & fulvic acids most, improved compost quality & profitability over BC/HC	Feng et al. (2025c)
Tea residues	Lab (film fabrication + storage test)	8 h	Food packaging	HTC-PW/PVA films showed excellent mechanical, antioxidant, and antibacterial performance, effectively extending banana shelf-life	Zheng et al. (2024)
Cattle manure	Lab/Mesocosm (paddy soil column study)	One growing-season of rice	Rice paddies	Co-application of biogas slurry and HTC-PW substituted urea fertilizer, reducing NH_3 volatilization by up to 65.5% while maintaining productivity	Li et al. (2021a, b, c)
Pig manure	Lab (soil–water interface incubation)	288 h	Rice paddies	HTC-PW altered DOM composition and microbial networks at the soil–water interface, increasing microbial cooperation under low-temperature exposure	Zhang et al. (2023)

Table 2 (continued)

Feedstock	Study scale	Study duration	Target	Performance	Reference
Municipal sludge	Lab (seed germination tests)	48 h	Liquid fertilizer/seed germination	Removed ~ 71% TN and ~ 94% TP while retaining plant-available N and P; fermented HTC-PW enhanced seed germination index (> 70%)	Zhang et al. (2025)
Orange pomace, olive pomace	Lab (microalgae batch cultivation)	30 d	Microalgae cultivation	Diluted HTC-PW (0.25–2%) supported optimal growth rate (160 mg L^{-1} day^{-1}) and doubling time (4.44 days) without altering biochemical composition	Koçer et al. (2023)
Sewage sludge and rice husk	Lab (composting reactors/bench scale)	3 d	HM passivation in composting	HTC-PW addition enhanced humic acid content, improved HM passivation (up to + 23.36%), and reduced HM-resistance genes	Shan et al. (2024b)
Orange pomace, olive pomace	Lab (microalgae cultivation)	30 d	Microalgae cultivation	Low dilution rates of HTC-PW yielded highest growth rates (130 mg L^{-1} day^{-1}) and shortest doubling times (5.33 days); biochemical content unaffected	Tarhan et al. (2021)
Municipal sludge and rice husk	Lab (plant growth test under hyproponic)	25 d	Pak choi growth	HTC-PW reduced phytotoxic molecules, improved pak choi biomass by 31.6–47.6%, tannins promoted growth; lignin dominated produced fractions	Shan et al. (2024a)
Pig and cattle manure	Greenhouse (paddy soil column study)	One growing-season	Wheat growth	Substituting 50–100% urea-N and increased soil DOM by 38.4–158.7%, and raised humification index by 13.7–41.2%	Chen et al. (2022)

highlight improved N use efficiency (up to 20% higher than urea) and soil C/N cycling, with elevated DOM fostering bacterial dominance (Proteobacteria increased by 1.75–2.3-fold) for faster nutrients turnover (Feng et al. 2025a; Zhang et al. 2023). Recent trials with wastewater-derived HTC show 43–99% of N/P recovery in crops and yield gains of 10–15% in rice, effectively turning waste streams into biofertilizers (Liu and Zhang 2025).

4.2 Co-application with biogas slurry (BS): synergistic nutrient delivery and risk mitigation

Co-application of HTC-PW with BS offers a synergistic approach to nutrient delivery, mitigating potential toxicity while enriching the overall fertilizer profile. BS, derived from anaerobic digestion of manure, is typically alkaline (pH 7.4–8.0) and rich in organic matter and nutrients, but its high ammonium content can lead to elevated NH_3 volatilization when applied alone (Chen et al. 2022; Li et al. 2023a). In contrast, HTC-PW often has an acidic pH (3.5–5.6) from organic acids such as VFAs, which can neutralize BS's alkalinity, reducing floodwater pH and suppressing NH_3 loss (Colin et al. 2025; Mäkelä et al. 2018). For instance, mixing HTC-PW from sewage sludge or lignocellulosic biomass with BS at a 1:1 N ratio reduced cumulative NH_3 volatilization by 4.2–65.5% in paddy soils compared to urea alone (Li et al. 2025; Wang et al. 2025). This pH buffering not only mitigates NH_3 toxicity to plants and aquatic systems but also minimizes episodic N_2O spikes associated with high NH_4^+ loads.

Nutrient enrichment is another key benefit: HTC-PW complements BS's high N with additional P, K, and micronutrients solubilized during HTC, balancing N:P:K ratios for better crop uptake. In rice paddies, co-application increased soil DOM by 2.7–59.4%, fostering microbial shifts that enhance denitrification over nitrification (e.g., increased *ureC* and *nirK* gene abundance), improving N retention and cycling (Li et al. 2021a; Wang et al. 2025). The organic components in HTC-PW, such as fulvic acid-like substances, further enrich BS's microbial byproducts, promoting soil humification and long-term fertility without compromising yields, which remained equivalent to urea controls. Microbiome responses include increased bacterial diversity, such as Firmicutes increased by 1.4–3.3-fold, accelerating soil DOM turnover while supporting fungal communities for sustained health (Feng et al. 2025a; Huang et al. 2022a).

Overall, this co-application strategy neutralizes HTC-PW's acidity and potential phytotoxins through BS's buffering and dilution effects, while enriching nutrients for synergistic agronomic performance, as evidenced by reduced volatilization by up to 65.5% and enhanced DOM-driven nutrient efficiency.

4.3 Conditional use: treatments and agronomic readiness

Conditioned use involves pre-treating HTC-PW to refine it for safe application. Neutralization with CaO raises HTC-PW pH to 7–9, precipitating metals and reducing EC by approximately 20%, enabling hydroponic or fertigation use; some studies show Ca-neutralized HTC-PW significantly increased vegetable biomass (Aragón-Briceño et al. 2020; Shan et al. 2024b). Biopolishing via microalgae consumes organics, with growth rates at 130–160 mg L^{-1} day^{-1f}, yielding cleaner HTC-PW and doubling algal biomass (Koçer et al. 2023; Mantovani et al. 2022; Tarhan et al. 2021). Membrane processes, such as filtration and electrodialysis, can concentrate nutrients while removing 50–70% of toxic compounds (Czerwińska et al. 2023; González-Arias et al. 2023). These treatments enhance seedling growth and root elongation, and field data show sustained N mineralization and improved microbiome resilience (Feng et al. 2025a; Spagnuolo et al. 2023). In one recent trial, conditioned HTC-PW from seaweed HTC shows low heavy metals for safe use, while microgravity simulations confirm pyrochar or hydrochar conditioning boosts Malabar spinach water use efficiency by 278% and K uptake up to 174% (NG and Wang 2025). Risks like salinity (EC 5–20 mS cm^{-1}) and toxins are mitigated through dilution or adsorption, preventing yield penalties and ensuring compliance.

In practice, neutralization is typically the lowest-cost and most scalable first step when acidity is the dominant issue and on-site use is feasible; however, it does not necessarily address high EC or inhibitory dissolved organics. Biopolishing is generally suited to contexts where time and operational control are available and where the main objective is to reduce residual organic toxicity while capturing nutrients in biomass. Membrane-based schemes are most appropriate when a consistent, concentrated nutrient stream is needed (e.g., to reduce the burden of transport and dilution burden or enable downstream recovery), but their feasibility depends on pretreatment needs and management of the concentrate. For phenol-rich HTC-PW, adsorption can function as a targeted add-on to improve compatibility for reuse.

4.4 Cross-pathway comparison and selection guidance

The three agronomic pathways share the same goal—recycling HTC-PW nutrients while managing salinity and phytotoxic organics—but they differ in readiness, operational complexity, and risk profile. Direct use after dilution is the simplest route and is most suitable when HTC-PW is produced under mild conditions and can be safely diluted (often 1:3–1:9) to control salinity and toxicity, while still delivering rapid nutrient availability and crop responses. Co-application with BS is best suited to integrated circular farming systems where AD infrastructure already exists. This route offers an intrinsic risk-mitigation mechanism via pH buffering, and it can substantially reduce NH_3 volatilization while improving soil DOM dynamics and nutrient retention. Conditioned use requires additional processing but provides the highest "agronomic readiness" for challenging HTC-PW, enabling safer use in fertigation or controlled soil application.

Practically, a "fit-for-purpose" selection can be made using a minimal screening panel: (i) if EC/toxicity are low after dilution, direct use is feasible; (ii) if BS is locally available, co-application provides buffering and emission mitigation; and (iii) if EC/toxicity are high or consistent quality is required, conditioned use is preferable despite added costs.

5 Valorization and recovery routes beyond direct fertilization

Beyond direct soil application, HTC-PW can be processed to extract nutrients and energy, transforming a waste stream into valuable products. These routes address HTC-PW's high organic load and nutrient imbalance. We consider nutrient recovery (struvite precipitation, ion exchange, electrodialysis), and energy recovery (anaerobic digestion (AD), catalytic reforming). A flowchart of alternative valorization pathways is shown in Fig. 3.

5.1 Nutrient recovery

- Struvite precipitation: Adding Mg under alkaline conditions (pH 8–10) precipitates struvite ($MgNH_4PO_4{\cdot}6H_2O$), capturing NH_4^+ and PO_4^{3-}. HTC-PW from sewage sludge or manure is ideal. In a coupled HTC-struvite system for sewage sludge at 200–260 °C for 1 h, precipitation with HTC-PW recirculation recovered up to 92% P and 88% N as high-purity struvite (> 95%), optimized via response surface methodology to minimize competing ions (Tong et al. 2025). Similarly, for biomass wastewater HTC at 180–220 °C, struvite formation from recirculated HTC-PW yielded 99% P and 43% N recovery, reducing nutrient losses in soil by 11.7–20.7% for P and 12.9–36.9% for N when applied as fertilizer (Liu

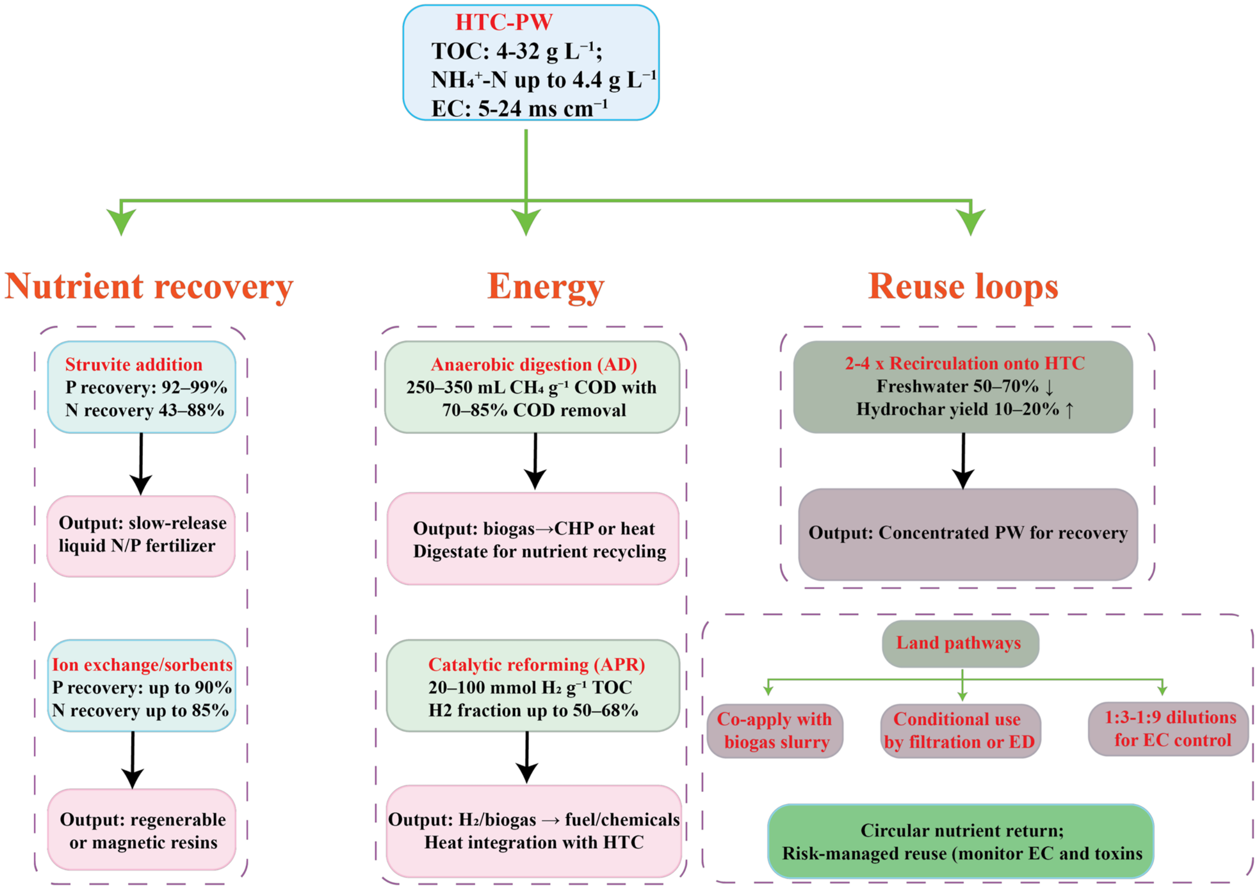


Fig. 3 Flowchart of alternative valorization pathways for HTC-PW, including recovery efficiencies

and Zhang 2025). Mg-modified materials, such as starch cryogels, further enhance recovery from HTC-like effluents, achieving 95% P and 80% N removal for fertilizer substitution (Zhao et al. 2024). Efficiencies are boosted under mild HTC conditions (180 °C, 30 min), where solubilized P is maximized before precipitation (Gou et al. 2024). Challenges include sediment volume and pH control, while integration with recycling minimizes costs and effluent volume.

- Ion exchange: Selective resins can adsorb NH_4^+ and PO_4^{3-} from HTC-PW. This method is effective for low-concentration streams in complex matrices such as HTC-PW, rich in organics such as humics and phenolics. Macroporous resins tested on secondary effluents analogous to HTC-PW achieved 95% nitrate–N removal with reusability up to 50 cycles, at low operational costs (Zeng et al. 2023). In HTC contexts, magnetic resins with quaternary ammonium sites recovered 90% N and 85% P from HTC-PW, maintaining efficiency over cycles via magnetic separation (Tang et al. 2023). For co-HTC of agricultural waste and sludge at 220 °C for 1 h, ion exchange on the HTC-PW improved fertilizer quality, enabling 60% replacement of chemical inputs while enhancing soil N/P ratios (Liu et al. 2025). Modified hydrochars from $FeCl_3$-impregnated HTC (180–260 °C, 1–3 h) served as ion exchangers, with adsorption capacities of 52.5 mg g^{-1} for phosphate and 27.6 mg g^{-1} for NH_4^+ at 45 °C (Zhang et al. 2023). Ion exchange is selective and recyclable, but organics in HTC-PW can foul resins, requiring filtration beforehand.
- Electrodialysis: Electrodialysis uses ion-selective membranes and electric fields to concentrate N and P from HTC-PW, separating cations (e.g., NH_4^+) and anions (e.g., PO_4^{3-}) for recovery without additives. Bipolar-membrane electrodialysis on HTC-like streams has achieved 85% N and 90% P recovery with low energy (0.5–1 kWh m^{-3}), generating in-situ H^+/OH^- for pH control (Cao et al. 2023). One electrodialysis setup extracted 92% P from digestate ash, analogous to HTC-PW, at 2.5 kWh kg^{-1} P (Huang et al. 2022b). For HTC-PW from biomass at 180–260 °C, efficiencies reach 80–95% of ions can migrate under electrodialysis, whereas the high organic loads necessitate pre-treatment to protect membranes (Hamilton et al. 2024). Electrodialysis can operate continuously without chemicals, though it requires power.

5.2 Energy recovery

- Anaerobic digestion (AD): HTC-PW's high organics can be anaerobically digested to methane (CH_4)-rich biogas. HTC-PW (COD/BOD ratios of 2.0–2.7) supports robust methanogenesis from VFAs. For example, AD of food waste HTC at 180–250 °C for 1 h, yielded 250–350 mL CH_4 g^{-1} COD, with 70–85% COD removal in HTC-PW, outperforming standalone AD by 20–30% due to HTC's organic solubilization (Zhou et al. 2024). For sewage sludge HTC-PW at 200 °C, AD removed 80% organic matter and produced 200–300 mL CH_4 g^{-1} VS^{-1} (volatile solids), with methanogens flourishing such as *Methanosaeta* (Pagés-Díaz et al. 2020; Wirth et al. 2015). HTC-PW recirculation further increases biogas: in corn silage HTC at 220 °C, HTC-PW-fed CSTR reactors generated 0.3–0.4 L CH_4 L^{-1} PW^{-1} per day, 15–25% more than non-recirculated setups (He et al. 2022; Meier et al. 2017). Challenges include inhibition from phenols, which can be addressed via dilution or acclimation, but overall energy recovery reaches 60–80% of HTC-PW's potential, linking HTC-PW to bioenergy (Ipiales et al. 2024; Merzari et al. 2019).
- Catalytic reforming: Oxygenated HTC-PW organics, notably VFAs, phenols, and short-chain polyols, can be converted to H_2 or syngas via steam reforming or aqueous phase reforming (APR) over catalysts (Ni, Pt, or Ru). APR typically operates at around 200–260 °C and 15–50 bar is ideal for liquid HTC-PW. For instance, APR of sludge HTC-PW at 220 °C with Pt–Rh-based catalysts has delivered H_2 yields from tens up to 100 mmol H_2 g^{-1} TOC, with gas H_2 fractions up to 68% under 25–29 bar (Oliveira et al. 2022; Zoppi et al. 2022). Lignocellulosic HTC-PW yields 20–50 mmol H_2 g^{-1} C^{-1}, with 70–90% C gasification under APR at 220–260 °C (Di Fraia et al. 2023). When steam-reforming is favored, Ni catalysts at 350–500 °C are standard; Ni loading is tuned to limit coking, and H_2-rich syngas (50–60% H_2) has been reported for oxygenate-rich HTC-PW under these conditions (Santamaria et al. 2021; Su et al. 2025).

Collectively, these pathways enable cascaded, fit-for-purpose valorization of HTC-PW, recovering N, P, and energy while reducing effluent-treatment burdens and freshwater demand. In practice, hybrid process trains—such as mild HTC followed by struvite or electrodialysis and subsequent AD or APR with selective recirculation—should be tailored to feedstock characteristics, regional nutrient and energy markets, and regulatory requirements to maximize environmental and techno-economic performance.

Table 3 Environmental and health risks of HTC-PW application in previous studies. ARG: antibiotic resistance gene

Risk	Impacts	Mitigation strategies	Regulatory references	Studies
Salinity	EC 5–24 mS cm^{-1}; high EC stresses crops and can disperse clays	Dilution (1:3–1:9), or blending with low-EC amendments	No specific EU limit in fertilizers; typical irrigation thresholds EC < 10 mS cm^{-1} to avoid salinity buildup	Song et al. (2022); Ender et al. (2024); Ipiales et al. (2024)
Organics (phenols, furans)	Phenols 290–800 mg L^{-1}; furans 200–1,230 mg L^{-1}; phenols 10–100 mg L^{-1}; phytotoxicity;	Dilution (1:3–1:9); co-application; bioassays prior to field use; biopolishing for phenol-rich HTC-PW	Risk assessment required under (EU) 2020/741 for emerging contaminants in reused water; no specific thresholds for phenols in fertilizers	Biswal and Balasubramanian et al. (2022); Guo et al. (2024a); Colin et al. (2025);
Heavy metals	Cr, Cd, Pb may be elevated, especially in sludge-derived HTC-PW	Source control; dilution; pH adjustment/CaO co-precipitation	(EU) 2019/1009 limits for organic fertilizers: Cd 1.5 mg kg^{-1} DM, Cr(VI) 2 mg kg^{-1}, Hg 1 mg kg^{-1}, Ni 50 mg kg^{-1}, Pb 120 mg kg^{-1}, As 40 mg kg^{-1}	Langone and Basso (2020); Zhang et al. (2023); Meng et al. (2025)
Pathogens and antibiotics	Manue/sludge HTC-PW may carry antibiotics and promote ARGs; microplastics can host ARG biofilms	Sanitation; optional disinfection; select cleaner feeds for direct use	(EU) 2019/1009; *E.coli* < CFU g^{-1} for organic fertilizers; (EU) 2020/741: *E. coli* < 10–10,000 CFU/100 ml depending on reuse class	Song et al. (2022); Ender et al. (2024); Guo et al. (2024a)
N and P leaching and runoff	High N/P mobility causes eutrophication; P runoff increases if undiluted or surface-applied	Dilution; microbial immobilization; application timing and rate control to minimize runoff	Nitrate directive 91/676/EEC limits nitrate to < 50 mg L^{-1} in groundwater; P regulations under Water Framework Directive (2000/60/EC) aim to prevent eutrophication	Burton et al. (2024); Feng et al. (2025a, b, c)
N_2O emissions	Plenty of dissolved N_2O in drainage; episodic spikes from high NH_4^+ loads	Phenolics inhibit nitrification; co-application with buffers; optimized N loading	No direct N_2O limits in fertilizers; regulated under Effort Sharing Regulation (EU) 2018/842 for national GHG inventories	Li et al. (2021c); Burton et al. (2024); Feng et al. (2025b)

6 Environmental and health risk assessment

HTC-PW must be managed to protect the environment and health. Key concerns include salinity, residual toxins, heavy metals, microplastics, potential eutrophication due to nutrients leaching and runoff, as well as GHG emissions. A list of previous studies regarding environmental and health risks of HTC-PW application is shown in Table 3.

6.1 Salinity, heavy metals, organic toxins and contaminants

HTC-PW often has high salinity (EC 5–24 mS cm^{-1}), especially after recirculation, which can stress crops and damage soil structure via clay dispersion if applied undiluted (Ipiales et al. 2024). These risks are mitigated by dilution or blending with low-EC amendments (Ender et al. 2024). Heavy metals (Cr, Cd, Pb, etc.) can reach concerning levels in HTC-PW, particularly from sewage sludge (Meng et al. 2025); though often below crop thresholds after dilution, sludge-derived HTC-PW must be monitored closely.

Phenolic compounds are major drivers of acute toxicity in HTC-PW. Lignin-derived phenols in HTC-PW are frequently reported at 290–800 mg L^{-1} (Aragón-Briceño et al. 2020; Ender et al. 2024; Meng et al. 2025), while furans can reach 200–1,230 mg L^{-1} (Becker et al. 2014; Ipiales et al. 2024; Nguyen et al. 2023), indicating that untreated HTC-PW can contain inhibitor levels high enough to impair biota and plants. Reported EC50 values for phenols for aquatic organisms are on the order of 10–100 mg L^{-1} (Biswal and Balasubramanian 2022; Guo et al. 2024a; Colin et al. 2025), which means that raw HTC-PW phenol levels may exceed these thresholds by roughly 3–80-fold. In agronomic studies, this risk is commonly managed through dose–response dilution (often 1:3–1:9) (Moloeznik Paniagua et al. 2024; Niu et al. 2021), co-application with other amendments, and pre-use toxicity screening.

Antibiotics and pathogens warrant attention. Manure- or sludge-derived HTC-PW can contain antibiotics, such as tetracyclines, sulfonamides, that adsorb to organics and promote antibiotic resistance genes (ARGs) in soil. Microplastics, if present in feed, can concentrate antibiotics and harbor ARG-carrying biofilms via hydrophobic and electrostatic interactions (Biswal and Balasubramanian 2022; Guo et al. 2024a). HTC at over 180 °C greatly reduces viable pathogens in waste, but some microbial residues may persist in HTC-PW, suggesting a need for post-HTC sanitation (Ender et al. 2024; Langone and Basso 2020; Zhang et al. 2023). Notably, environmental studies suggest that high salinity can limit long-range dispersal of bacteria on microplastics (Song et al. 2022). Overall, safe reuse of HTC-PW demands a risk-management approach: routine monitoring of salinity, metals, antibiotics or ARGs, and microplastics; ecotoxicological testing; and targeted conditioning by dilution, neutralization, precipitation, and biopolishing to keep hazards below crop and regulatory limits while preserving nutrient value.

6.2 Leaching, N_2O emissions, groundwater protection

Leaching of nutrients and contaminants from HTC-PW-amended soils poses groundwater risks, with high N and P mobility leading to eutrophication. In paddy fields, HTC-PW application reduces N leaching by 12.9–36.9% via microbial immobilization but increases P runoff if undiluted (Feng et al. 2025a). N_2O emissions, a potent GHG, arise from denitrification in amended soils; dissolved N_2O in drainage water from agricultural fields averages 0.83 kg N ha^{-1} annually, often exceeding surface emissions, with peaks during winter thaws (Burton et al. 2024). HTC-PW can influence N_2O in two opposing ways, and the net response depends on HTC-PW chemistry and N loading. When HTC-PW contains sufficient inhibitory organics, nitrification can be temporarily suppressed, which reduces NO_3^- supply and can lower N_2O formation; consistent with this mechanism, HTC-PW conditioning during composting has been reported to reduce N_2O emissions by approximately 10–20% (Feng et al. 2025b), and HTC-PW organics have been linked to reduced nitrification and N losses in agronomic systems (Huang et al. 2022a; Li et al. 2025). In contrast, concentrated HTC-PW or high NH_4^+ inputs can create localized N "hotspots"; once inhibition is weakened, such as by dilution, rapid nitrification–denitrification during irrigation or drainage can generate short-lived N_2O pulses, consistent with strong event-driven dissolved N_2O losses in drainage waters (Burton et al. 2024). Therefore, reporting HTC-PW NH_4^+ loading together with indicators of inhibitory organics (e.g., phenolic proxies or TOC) is critical for interpreting whether HTC-PW is likely to act as a net N_2O mitigator or a potential source under a given soil–water regime. Overall, these findings highlight the dual potential of HTC-PW as a resource and risk factor; while it can enhance nutrient cycling, unmanaged application exacerbates leaching and emissions. Figure 4 exhibits the mechanistic map illustrating performance benefits versus risks across HTC-PW application.

Because current evidence is still limited and highly heterogeneous across feedstocks, soils, crops, and study scales, universal minimum-parameter standards for HTC-PW are not yet defensible. Nevertheless, for first-pass evaluation prior to land application, a provisional core screening panel should include at least pH, EC,

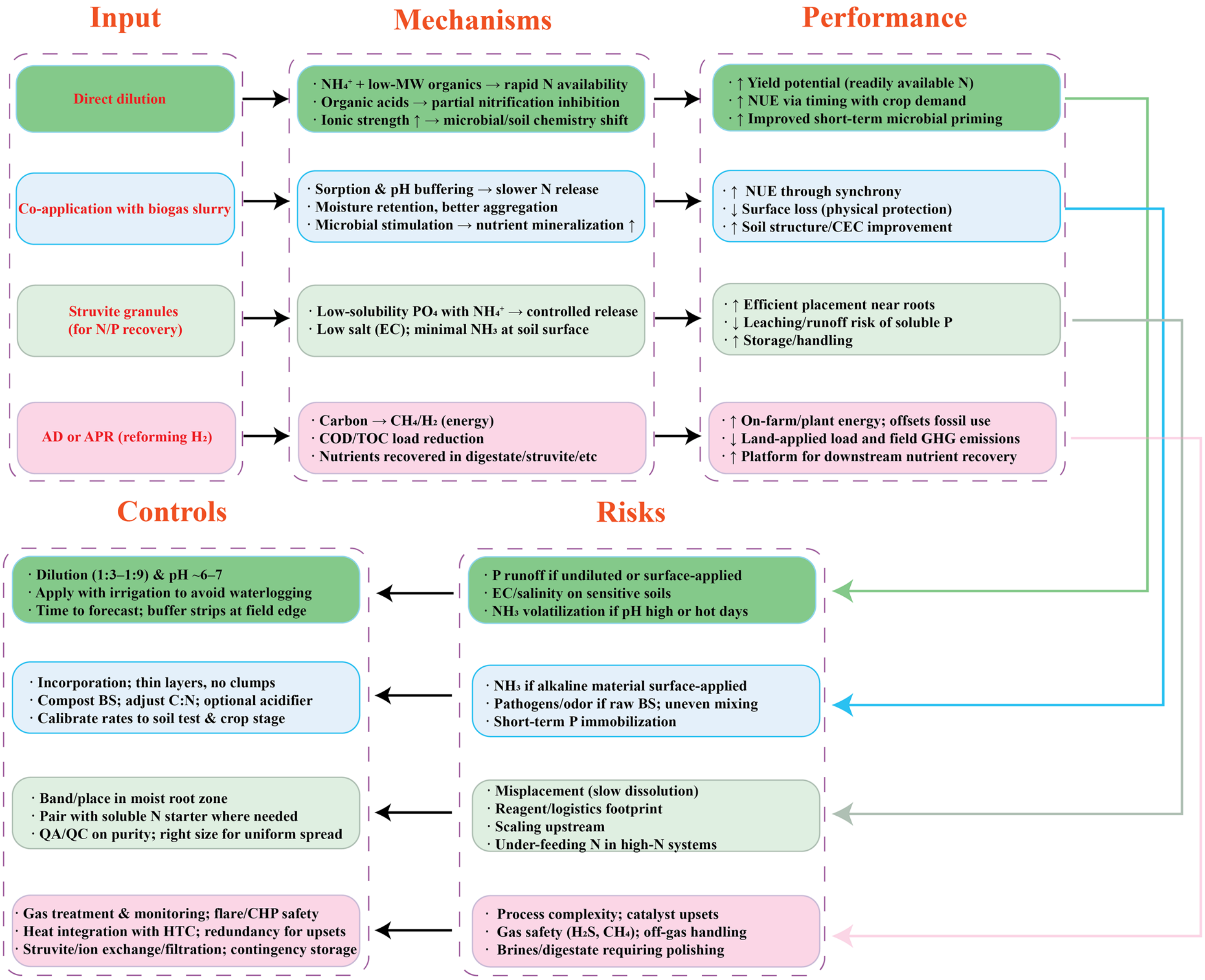


Fig. 4 Mechanistic map illustrating performance benefits versus risks across HTC-PW application routes

TOC or COD, NH_4^+–N, PO_4^{3-}–P or TP, K, and indicators of inhibitory organics (e.g., phenol/furan proxies), together with feedstock-dependent contaminants such as heavy metals and, where manure- or sludge-derived streams are involved, antibiotics/ARG indicators. This panel is proposed as a provisional screening and reporting set, not as a universal regulatory standard.

7 Techno-economic analysis (TEA) and life-cycle assessment (LCA)

7.1 TEA

Techno-economic performance of HTC-PW valorization is highly sensitive to system boundaries and local context; therefore, the reported costs and credits in the literature should be interpreted as scenario-dependent value drivers rather than universal benchmarks (Table 4). Clack et al. (2024) synthesize TEA evidence mainly at the scale of integrated HTC-based sludge management systems, and the wide CAPEX range reported reflects scale, configuration, and degree of plant integration rather than an HTC-PW-only unit. In this context, HTC-PW economics are tightly linked to whether the liquid fraction can be handled within existing infrastructure or requires additional dedicated processing.

From an operating-cost perspective, Table 4 highlights that HTC-PW valorization is commonly framed as a trade-off between added conditioning costs and avoided conventional wastewater-treatment costs. Matuštík et al. (2024) and Picone et al. (2024) report indicative HTC-PW conditioning costs (e.g., dilution, neutralization, or membrane-type steps) and compare them against avoided treatment costs when HTC-PW is diverted from conventional wastewater handling. These benefits are not guaranteed: the “avoided treatment” credit may be reduced or eliminated when discharge regulations still require advanced polishing, when the HTC-PW cannot

Table 4 Indicative techno-economic metrics for HTC-PW management and valorization

Techno-economic item (HTC-PW related)	Indicative range (unit)	What it represents	References
HTC system CAPEX (sewage sludge HTC)	36–921 (thousand USD per t total solids day^{-1})	Wide range reflects scale/configuration and plant integration	Clack et al. (2024)
HTC-PW conditioning cost (dilution/neutralization/membrane-type steps)	0.05–0.20 (€ m^{-3} HTC-PW)	Added operating cost to make HTC-PW suitable for reuse/recovery	Matuštík et al. (2024); Picone et al. (2024)
Avoided conventional wastewater treatment cost	0.50–1.50 (€ m^{-3} HTC-PW)	Cost that can be avoided when HTC-PW is valorized instead of treated as wastewater	Matuštík et al. (2024); Picone et al. (2024)
HTC-PW transport/distribution (50–200 km)	0.1–0.3 (€ m^{-3} HTC-PW)	Logistics penalty for hauling HTC-PW to farms/recovery sites; favors on-site integration	Sarrion et al. (2023)
Sludge/feedstock logistics (collection radius 50–100 km)	0.2–0.5 (€ t^{-1} km^{-1})	Upstream transport cost driver for municipal-scale systems	Sarrion et al. (2023)
Mineral fertilizer benchmark prices (illustrative, year-specific)	N ~ 1.3 (€ kg^{-1} N); P ~ 2.5 (€ kg^{-1} P); K ~ 0.9 (€ kg^{-1} K)	Used to estimate "fertilizer-offset credit" when HTC-PW nutrients displace mineral fertilizers	Farm Bureau (2025)
Struvite recovery from HTC-PW	P: 92–99%; N: 43–88%	Representative nutrient recovery efficiencies reported for HTC-PW-to-struvite pathways	Tong et al. (2025); Zhao et al. (2024)
Struvite product value (illustrative)	0.8–1.2 (€ kg^{-1} product)	Market value range used in TEA-style comparisons (slow-release co-benefit not monetized)	Tong et al. (2025); Zhao et al. (2024)
Nutrient-sales potential (example plant scale)	0.5–1.5 (million € year^{-1})	Example revenue range reported for ~ 100 t TS day^{-1} scale; reported to offset ~ 30–50% OPEX	Clack et al. (2024)
Integration benefits (recirculation/co-location)	Freshwater − 50% to − 70%; cost − 15% to − 30%; hydrochar yield + 10% to + 20%	Reported system-level improvements that indirectly affect HTC-PW economics	Picone et al. (2024)
Farm-scale HTC-PW integrated with AD (manure/food waste)	CAPEX − 20% to − 30%; HTC-PW-to-biogas + 15% to + 25%	Integration can improve economics via shared infrastructure and energy credits	Diez et al. (2024); Farru et al. (2024)

Values are literature-reported ranges and depend on feedstock, plant scale, location, energy prices, and system boundaries. CAPEX: Capital Expenditure

be legally reclassified for beneficial use, or when additional monitoring costs are required. Logistics further constrain feasibility, because transport and distribution of dilute HTC-PW and upstream feedstock logistics can become dominant cost drivers with increasing distance (Sarrion et al. 2023).

Revenue and "credits" in TEA scenarios typically come from nutrient recovery/substitution and from integration benefits. Fertilizer-substitution credits (Farm Bureau 2025) and recovery pathways such as struvite precipitation (Tong et al. 2025; Zhao et al. 2024) are commonly used to monetize the nutrient value in HTC-PW (Table 4). However, fertilizer credits may not apply when recovered products do not meet local fertilizer specifications, when markets and end users are not accessible, or when nutrient concentration and dilution requirements offset the value of the recovered nutrients. Integration strategies can improve feasibility by reducing freshwater use and costs (e.g., recirculation/co-location effects reported by Picone et al. 2024) and by sharing infrastructure in farm-scale HTC–AD configurations (Diez et al. 2024; Farru et al. 2024). At the same time, integration can also concentrate salts and organics and increase the need for conditioning, so the net benefit depends on feedstock, severity, and the targeted end use. Overall, the economic benefits summarized in Table 4 are best interpreted as context-specific levers that apply only under compatible regulatory conditions and favorable logistics, including co-location, short transport distances, and a viable nutrient end-use pathway.

7.2 LCA

LCA quantifies environmental impacts across cradle-to-grave, revealing HTC-PW's potential to reduce global warming potential (GWP) by 20–50% compared to conventional wastewater treatment. Hotspots include energy for concentration/pretreatment (e.g., evaporation or membranes, 1–5 kWh m^{-3} HTC-PW), contributing 30–50% of GWP due to electricity mixes (0.4–1 kg CO$_2$e kWh^{-1}) (Clack et al. 2024; Sarrion et al. 2023). Pretreatment such as filtration adds

0.1–0.5 kg CO_2e m^{-3}, but integration with renewables (e.g., biogas) cuts this by 40% (Matuštík et al. 2024).

Avoided emissions are significant: Mineral fertilizer production emits 5–10 kg CO_2e kg^{-1} N (Haber–Bosch), 1–2 kg CO_2e kg^{-1} P (mining), and 0.5–1 kg CO_2e kg^{-1} K; HTC-PW substitution avoids 100–300 kg CO_2e t^{-1} TS recycled (Clack et al. 2024; Miao and Zeller 2025). Wastewater treatment avoidance saves 0.5–1.5 kg CO_2e m^{-3}, with HTC reducing sludge volume by 50–70%, cutting landfill/incineration emissions (0.5–2 kg CO_2e t^{-1}) (Sarrion et al. 2023). For farm-scale, LCA shows net GWP −0.2 to −1 t CO_2e t^{-1} TS with nutrient credits; municipal scales amplify savings via logistics optimization (e.g., rail over truck, −20% emissions) (Matuštík et al. 2024). Digester co-location minimizes transport (0–50 km), reducing GWP by 10–15% (Farru et al. 2024).

In summary, current TEA and LCA studies suggest that HTC-PW management and valorization can provide economic and environmental benefits under favorable scenarios, particularly when system boundaries include avoided wastewater-treatment burdens, nutrient-substitution credits, short transport distances, and low-carbon energy inputs. However, these outcomes are highly scenario-dependent and should not be interpreted as general proof of economic viability or GWP reduction across all HTC-PW applications.

8 Current research gaps and future directions

8.1 Current gaps

HTC-PW has received increasing attention as a potential source for soil conditioning and fertilization, yet significant research gaps hinder its widespread adoption. Primary among these is the scarcity of long-term field studies. While pot experiments demonstrate short-term benefits, such as improved N retention and microbial diversity in rice paddies (Feng et al. 2025a; Huang et al. 2022a; Li et al. 2021c, 2025), multi-seasonal trials are rare, leaving questions about enduring impacts on soil organic matter stability, nutrient leaching, and crop quality unanswered. This gap is particularly evident in diverse agroecosystems, where climate and soil type variations could alter PW efficacy.

Toxicity and environmental risk assessments also represent critical voids. HTC-PW contains potentially phytotoxic compounds such as phenols and furans, with EC-50 thresholds indicating risks to aquatic and soil organisms (Colin et al. 2025). However, comprehensive evaluations of chronic exposure, bioaccumulation of heavy metals, or interactions with microplastics are limited, especially for sludge-derived HTC-PW (Meng et al. 2025). Similarly, antibiotic residues and pathogen persistence in manure-based feeds warrant deeper investigation to ensure health safety (Langone and Basso 2020).

Scalability challenges further impede progress. Lab-scale optimizations dominate, but industrial integration—such as co-location with digesters or municipal plants—lacks detailed logistics analyses, including transport costs and energy demands (Clack et al. 2024). Feedstock variability exacerbates this, as PW properties fluctuate with biomass type, necessitating standardized protocols absent in current literature (Nguyen et al. 2023).

A further critical gap is the lack of robust prediction models for HTC-PW quality**.** Although this review shows that HTC-PW composition is strongly governed by multiple factors, current studies still report HTC-PW properties largely on a case-by-case basis. As a result, there is no widely adopted framework that can predict target agronomic indicators (e.g., NH_4^+–N, PO_4^{3-}–P, K, EC, TOC/COD) together with risk-relevant constituents (e.g., phenols/furans, heavy metals, antibiotics for manure/sludge streams) from readily measurable inputs and operating conditions. This limits the design of "fit-for-purpose" based on HTC-PW-derived products, complicates scale-up, and delays regulatory acceptance because safety and consistency cannot be demonstrated a priori.

8.2 Future directions

Looking ahead, future directions should emphasize bridging these gaps through interdisciplinary approaches. Long-term field trials in representative regions could quantify sustained benefits, incorporating metrics such as GHG emissions and biodiversity shifts. Enhanced risk frameworks, including advanced bioassays and fate modeling, are vital for regulatory compliance.

An important future direction is the integration of machine learning into HTC-PW prediction and optimization. Data-driven models can address predictive uncertainties by learning complex interactions between feedstock descriptors and process parameters (e.g., temperature, residence time, solids loading, pH, recirculation) and HTC-PW outcomes, including nutrient concentrations/speciation and risk-relevant components (e.g., salinity indicators, phenolics/furans, and regulated contaminants). Recent applications demonstrate machine learning's efficacy: for instance, gradient boosting models predict hydrochar yield with $R^2 > 0.95$, enabling real-time process adjustments (Luo et al. 2023; Lyu et al. 2024; Meng et al. 2025). In HTC contexts, neural networks optimize energy recovery from HTC-PW via anaerobic digestion, reducing inhibitors such as phenols through parameter tuning (Pagés-Díaz et al. 2020; Zhou et al. 2024). Future machine learning integrations

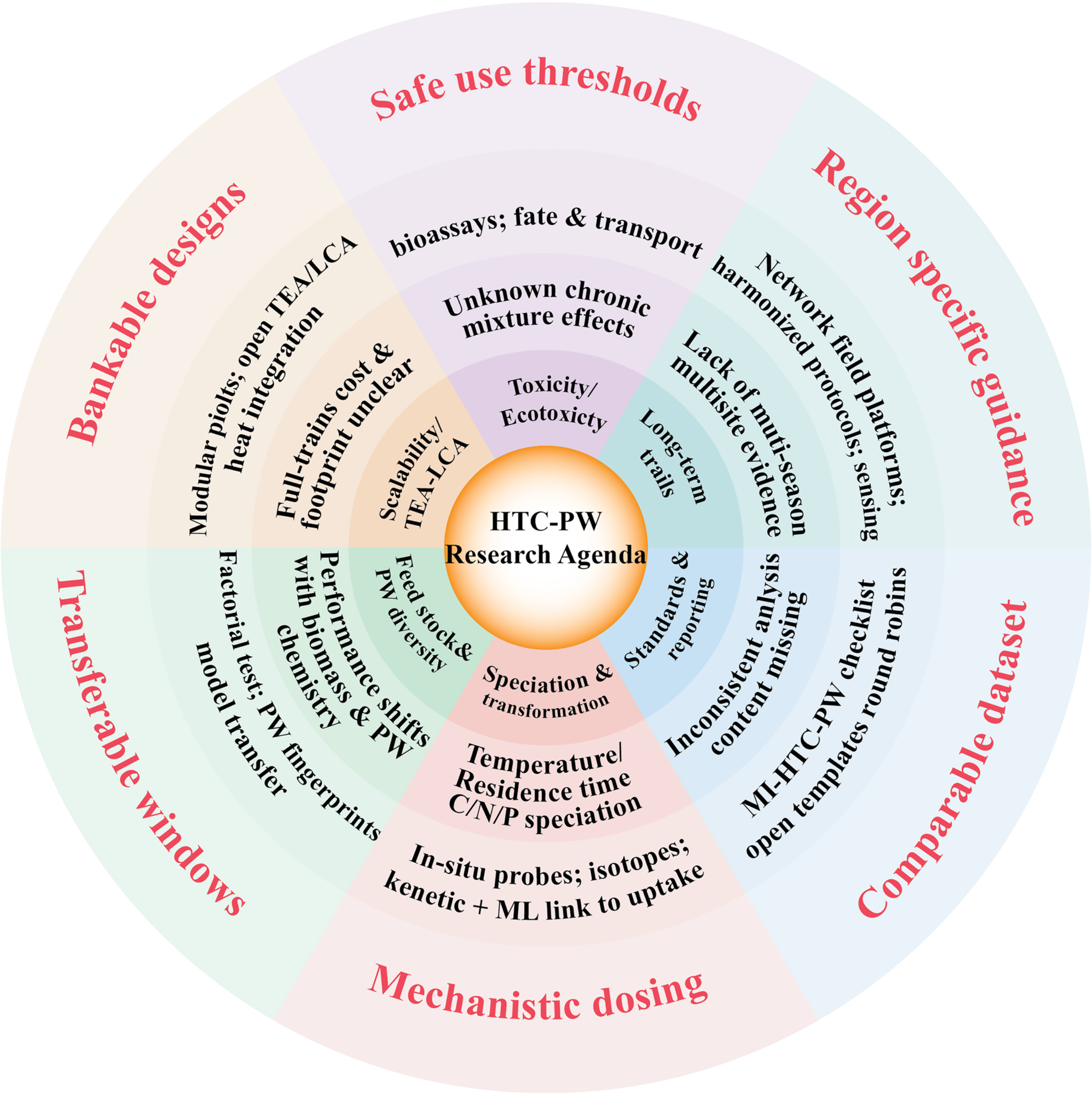


Fig. 5 Research gaps and proposed future directions for HTC-PW application in agronomy

could extend to agronomic simulations, forecasting soil responses to HTC-PW application by training on datasets from field trials, thus accelerating safe scaling and customizing formulations for specific crops or soils. This data-driven approach not only fills modeling gaps but also minimizes experimental iterations, fostering cost-effective innovations.

To enable transferable prediction models, future work should prioritize (i) harmonized reporting of HTC-PW datasets (minimum metadata on feedstock, severity index, and post-treatment), (ii) multi-output models that simultaneously predict nutrient value and hazard indicators, and (iii) uncertainty quantification to support conservative decision-making for land application. Coupling these models with rapid analytics (e.g., UV–Vis/fluorescence fingerprints, online pH/EC/TOC proxies) could support real-time classification of HTC-PW into “direct use,” “needs conditioning,” or “recovery only” categories, effectively forming a decision-support tool for safe agronomic deployment.

Hybrid systems represent another development pathway, merging HTC with technologies such as struvite precipitation for nutrient recovery or biochar co-application for emission mitigation (Liu and Zhang 2025; Tong et al. 2025; Wang et al. 2025). Policy-aligned research, focusing on circular economy metrics, could facilitate commercialization, emphasizing LCA hotspots such as energy use (Matuštík et al. 2024).

Overall, addressing these gaps through targeted studies and machine-learning-assisted tools could support the practical deployment of HTC-PW in agriculture. Figure 5 sums up the current research gaps and proposed future directions.

8.3 Policy, standards, and regulatory pathways

Beyond technical readiness, commercialization requires clear regulatory positioning of HTC-PW, which may be classified as wastewater, reclaimed water, or a byproduct depending on jurisdiction and intended use. Future work should systematically compare regulatory requirements and identify the minimum monitoring set (e.g., nutrients, salinity, key organic toxins, heavy metals, pathogens/ARG indicators where relevant) needed to demonstrate safe land application. Developing tiered quality standards and guidance on labeling or traceability would reduce uncertainty for end-users and regulators. Importantly, policy analysis should be integrated with TEA/LCA (e.g., compliance costs, permitting timelines, incentives/subsidies, and carbon/nutrient credits) to determine when HTC-PW valorization is economically attractive and environmentally beneficial in real deployment scenarios.

9 Conclusion

HTC-PW represents a promising resource within the circular bioeconomy, transitioning from perceived waste to a nutrient-rich liquid amendment and fertilizer substitute pathway. This review highlights its nutrient-rich composition, tunable properties through process controls, and versatile applications in direct use, co-application, and recovery routes such as struvite precipitation and anaerobic digestion. Agronomic benefits include enhanced yields, nutrient use efficiency, and soil health, while energy pathways yield biogas and hydrogen, thus highlighting multiple valorization pathways. Environmental risks such as salinity and N_2O emissions are manageable via dilution and monitoring, with TEA and LCA affirming economic viability and reduced global warming potential. Accordingly, future work should prioritize long-term field validation together with context-specific TEA/LCA to determine where HTC-PW use is practically, environmentally, and agronomically justified, thereby strengthening the basis for broader and safer implementation in agriculture and waste-management systems.

Author contributions

Qingnan Chu: Conceptualization, Writing—original draft, Data curation. Xiangyu Liu: Visualization, Writing—originaldraft. Yangfang Feng: Writing—review and editing. Detian Li: Data curation, Visualization; Shuai Yin: Writing—reviewand editing. Chengrong Chen: Writing—review and editing. Zhimin Sha: Supervision, Funding acquisition, Writing—review and editing. All authors read and approved the final manuscript.

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Data availability

This article is a review and does not report new primary data. All data discussed are extracted from previously published studies cited in the manuscript. Any compiled datasets generated during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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