Journal of Clean Technology

REVIEW ARTICLE

Nutrient Recovery from Palm Oil Mill Effluent for Fertilizer Production: Technology Options and Practical Barriers

Agung Kurnia Yahya[1*], Apsari Puspita Aini[1], Miftahurrahmah[1], Anang Baharuddin Sahaq[2]

[1)]Department of Chemical Engineering, Politeknik ATI Padang, Padang 25171, Indonesia
[2)]Department of Renewable Energy Bioprocess Engineering Technology, Politeknik ATI Padang, Padang 25171, Indonesia

(*Corresponding author's e-mail: agung.kurnia@poltekatipdg.ac.id)

Received: 04 February 2026, Revised: 20 February 2026, Accepted: 26 February 2026, Published: 26 February 2026

Abstract

Palm oil mill effluent (POME) is a high-strength agro-industrial wastewater whose management governs both environmental performance and operational resilience of palm oil mills. Treatment trains optimized solely for COD/BOD reduction often accumulate operational penalties under feed variability, including scaling, sludge burden, and persistent polishing demands, rather than forming a controllable value-generating platform. This review reframes nutrient recovery from POME as a fertilizer manufacturing problem embedded in a wastewater system, where removal does not equal recovery unless nutrients are transferred into a defined product phase with mass-balanced yield, controlled composition, impurity management, and agronomic function. Anaerobic digestion is positioned as a pivotal pivot point because it converts organic load to methane while producing an anaerobically digested liquor that is operationally more suitable for targeted nutrient recovery than raw POME. Using a PRISMA-ScR scoping review with a systematic search, evidence was mapped across three coupled outcome domains: water reuse/reclamation, energy recovery (biogas/CH_4), and nutrient circularity (N–P recovery and derived products). The synthesis compares unit operations by function and operability constraints, then assembles feasible combinations into a process superstructure and a decision roadmap for pathway selection under mill constraints. Findings emphasize that raw POME and anaerobically digested POME are not interchangeable feedstocks: raw POME is dominated by solids/colloids that hinder selective recovery and contaminate products, while post-digestion variability is more chemistry-driven and governs precipitation windows and membrane stability. Recovery options converge toward hybrid systems integrating crystallization (struvite/phosphate minerals), adsorption/ion exchange with regenerability, membrane concentration including fertilizer-drawn forward osmosis, and biological assimilation (microalgae), with fouling, scaling, and crystallization inhibition as decisive design variables. Overall, meaningful nutrient recovery from POME is achieved only when fertilizer grade products are produced while simultaneously reducing compliance risk and operational burden.

Keywords: anaerobic digestion, fertilizer grade recovery, nutrient circularity, palm oil mill effluent, struvite.

1. Introduction

Palm oil mill effluent (POME) is a high strength agro industrial wastewater whose management determines both the environmental footprint and operational resilience of palm oil mills. High organic loading, suspended solids, and complex dissolved organics make POME difficult to treat consistently when the system is designed only for pollutant removal. In practice, a treatment train that is optimized solely for COD/BOD reduction tends to accumulate operational penalties, unstable performance under feed variability, scaling, sludge burden, and persistent polishing demands, rather than creating a controllable and value generating process platform [1].

Regulatory compliance reinforces the need for a more robust and purposeful approach. Wastewater quality standards provide binding performance expectations for effluent quality and require engineered control rather than empirical, disposal oriented practice. The Indonesian framework provides a general reference through wastewater quality standards regulations, which define compliance boundaries and constrain discharge options. Sector specific standards for palm oil processing further tighten the design space by linking compliance directly to industry context and measurable effluent outcomes, making treat and discharge a cost center with limited flexibility.

Nutrient recovery from POME is also a supply chain problem, not merely an environmental option. Phosphorus is indispensable for food production, and its global supply is anchored to phosphate rock as the only significant resource base for phosphorus. Fertilizer markets amplify this vulnerability because price shocks and energy linked volatility propagate rapidly to farm level costs and application behavior. The implication is straightforward: nutrient rich waste streams must be treated as secondary feedstocks, and nutrient recovery must be evaluated as a stabilization strategy for agricultural inputs rather than a marginal add-on.

Fertilizer price shocks also translate into food system risk through reduced fertilizer use, yield pressure, and higher downstream prices. Market disruptions demonstrate that fertilizer access is not guaranteed by technical availability alone; it depends on affordability, logistics, and geopolitical and energy dynamics [2]. This reality strengthens the economic logic of recovering nutrients locally from industrial effluents such as POME, where the resource is already concentrated at point sources and recovery can be integrated with existing mill operations.

Anaerobic digestion is a pivotal pivot point for nutrient recovery because it transforms treatment from disposal into conversion. It reduces organic load while generating methane, and it produces an anaerobically digested liquid stream that is operationally more suitable for targeted nutrient recovery than raw POME. Anaerobically treated POME contains substantial ammoniacal nitrogen and soluble organics, allowing process trains that explicitly sequence nutrient capture and organic polishing as separate objectives rather than forcing both into one unit operation[3]. This separation of objectives is essential for stable recovery yields and consistent product formation.

A fertilizer grade framing imposes non negotiable criteria that conventional wastewater metrics do not capture. Removal does not equal recovery, and a concentration drop in effluent does not prove that nutrients have been captured into a usable product. Fertilizer grade recovery requires mass balanced yield into a product phase, phase and composition control, impurity control, and agronomic function. Struvite illustrates this distinction clearly: struvite formation can occur within POME treatment systems and cause operational scaling, demonstrating both the inevitability of mineral formation under certain conditions and the opportunity to redirect it into controlled product recovery[4]. Product credibility, however, depends on characterizing and controlling the precipitate so it becomes a predictable fertilizer material rather than an uncontrolled deposit.

In Indonesia, the term fertilizer grade is not only a technical claim but also a regulatory and market category that must be aligned with Indonesian National Standards (SNI) for fertilizers. For instance, SNI 2803:2024 defines quality requirements and test methods for solid NPK fertilizers, while SNI 7763:2024 specifies measurable quality and safety thresholds for solid organic fertilizers. Consequently, nutrient recovery pathways from POME are more likely to translate into deployable products when their intended product identity (e.g., mineral NP/P fertilizer component, organic amendment, or intermediate nutrient concentrate for blending) is explicitly mapped to the relevant SNI category and its specification framework.

Technology options for N–P–K recovery from POME and anaerobically digested POME increasingly converge toward hybrid systems that combine separation, concentration, and product forming steps. Membrane systems (MF/UF/NF/RO) are used to separate solids and reclaim water, while concentrating dissolved constituents into manageable streams; their practical feasibility depends on fouling management and realistic cleaning strategies under POME matrices [5]. Forward osmosis variants strengthen the product logic by coupling water recovery with fertilizer

relevant streams via fertilizer drawn forward osmosis, aligning separation directly with agricultural end use rather than creating a waste concentrate [6]. Fouling propensity and mitigation remain decisive because they determine whether concentration can be sustained without excessive downtime or chemical demand.

Biological nutrient capture also deserves explicit positioning in a fertilizer grade narrative. Microalgae based platforms treat POME as a nutrient medium and convert dissolved nutrients into biomass, creating a route where nutrient recovery and co product formation occur simultaneously [7]. This pathway is not automatically fertilizer grade; it becomes fertilizer relevant only when biomass quality, harvesting logistics, and downstream product standardization are engineered to deliver consistent nutrient value and safe application [8].

This review treats nutrient recovery from POME as a product manufacturing problem embedded in a wastewater system. It evaluates recovery pathways by their ability to deliver fertilizer grade N–P–K products with controlled composition and usability under mill constraints, and it links process selection to matrix effects that control selectivity, fouling, scaling, and operating cost. The central position is direct: nutrient recovery from POME is meaningful only when it produces usable fertilizer grade products and simultaneously reduces compliance risk and operational burden.

2. Review Methodology

This review was conducted as a scoping review with a systematic search to map evidence on POME as a resource mine across three outcome domains: water reuse/reclamation, energy recovery (biogas/CH_4), and nutrient circularity (N–P recovery and derived products). The review followed PRISMA-ScR reporting guidance. Searches were performed in Scopus and Web of Science Core Collection, complemented by backward and forward citation tracking. Records were deduplicated and screened at title/abstract followed by full text assessment using predefined eligibility criteria. Studies were included when they addressed POME (raw/treated/anaerobically treated), covered at least one outcome domain, and reported extractable quantitative metrics relevant for engineering synthesis. Data were charted using a standardized extraction form and synthesized by unit operation function and operability constraints, assembly into a process superstructure linking water, energy, and nutrient recovery (including side streams), and development of a decision framework mapping mill objectives and constraints to pathway selection and dominant design levers.

3. Results and discussion

3.1. POME vs Anaerobically Digested POME: Nutrient Speciation, Variability, and Inhibitors

Raw palm oil mill effluent (POME) and anaerobically digested POME are not interchangeable feedstocks for nutrient recovery. Raw POME is a brown, viscous, colloid rich wastewater dominated by complex organics and suspended solids, so nutrients are frequently partitioned into particulate and organo complexed pools rather than remaining freely available in the dissolved phase. This matrix condition makes direct, selective recovery of N–P–K intrinsically difficult because separation and product formation occur in the presence of high turbidity, emulsified residues, and reactive organic colloids [9].

After anaerobic digestion, the matrix becomes more favorable for targeted recovery because a larger fraction of nutrients is present in the liquid phase and can be addressed with separation and product forming steps. Anaerobically digested POME is therefore better framed as the primary recovery hub stream, while raw POME is better framed as a conversion feed that must be stabilized and fractionated before recovery is attempted. The practical implication is straightforward: recovery trains that aim at fertilizer grade products should be designed around post digestion liquor, coupled with solids separation that shields downstream recovery units from residual colloids and fine particulates [10].

In nutrient speciation terms, anaerobic digestion shifts nitrogen toward ammoniacal forms in the liquid phase, which is more compatible with crystallization routes, ion exchange, and concentration based approaches. In contrast, raw POME tends to retain a larger fraction of nitrogen in organic associated forms, which reduces recovery readiness unless hydrolysis and fractionation are explicitly managed. The same logic applies to phosphorus: raw POME commonly carries phosphorus tied to solids and organics, while post digestion liquor is more likely to contain phosphorus in forms that can be directed into mineral precipitation or concentrated streams, provided that competing reactions and organics are controlled.

Variability is a defining feature for both streams, but it appears differently. Raw POME variability is dominated by changes in solids loading, emulsified residues, and organics complexity, which strongly affects pretreatment demand and solids liquid partitioning of nutrients. Anaerobically digested POME variability is dominated by alkalinity, residual soluble organics, and intermediate products of digestion, which govern precipitation windows, chemical dosing demand, and membrane performance stability. This shift in variability profile matters because downstream recovery units fail in different ways depending on whether the disturbance comes from solids/colloids or from soluble organics and ionic chemistry.

Inhibitors also change character across the two streams. In raw POME, inhibitors are largely physical colloidal: fine solids and colloids drive poor settling, poor filtration, and rapid fouling, while also contaminating any recovered solids and undermining fertilizer grade claims. In anaerobically digested POME, inhibitors are more chemical kinetic: dissolved organic matter and specific organic constituents can suppress nucleation and crystal growth, shift mineral phase selection, and reduce product purity. Humic substances illustrate this effect clearly by degrading struvite precipitation performance and altering recovered solid properties, which is directly relevant because fertilizer grade products require phase control and predictable composition [11].

Phenolic compounds constitute another inhibitor class that matters at the system level. Phenolics can inhibit anaerobic digestion and destabilize methane fermentation, which indirectly destabilizes the post digestion liquor composition (including pH/alkalinity and soluble intermediates). A recovery train that assumes stable post digestion chemistry will therefore underperform when digestion is exposed to inhibitory phenolics and other toxicity drivers present in raw POME. For nutrient recovery, this translates into unstable recovery yields and higher chemical/energy demand because downstream units must compensate for upstream instability [12].

Potassium presents a different challenge. K^+ tends to remain dissolved and is therefore easy to keep in solution, but it is hard to convert into a fertilizer grade solid without tight control of crystallization chemistry and inhibitors. Potassium struvite (struvite-K) routes are particularly sensitive to complexing agents such as citrate, which can inhibit crystal growth and change precipitation behavior, reinforcing the need to treat dissolved organics as a primary design constraint rather than a secondary nuisance [13].

3.2. Recovery pathways for fertilizer grade N–P–K products

Fertilizer grade recovery from POME derived streams is a product manufacturing problem inside a wastewater system. The pathway is only defensible when it delivers measurable N–P–K recovery yield into a defined product phase, repeatable composition and phase identity, and operability under POME constraints (solids, dissolved organics, scaling, fouling).

3.2.1. Precipitation/crystallization: struvite and phosphate minerals

Struvite crystallization ($MgNH_4PO_4 \cdot 6H_2O$) is the most direct route to a fertilizer grade N–P solid, but it is highly sensitive to matrix effects. Evidence from real palm oil mills shows struvite can form as deposits inside anaerobic digestion units and downstream lines, confirming that the ionic precursors coexist at relevant supersaturation in practice. Controlled crystallization converts uncontrolled scaling into a harvestable product, but fertilizer grade outcomes require crystal habit control and harvestability rather than sludge like precipitation. A sequential design that first

recovers ammoniacal nitrogen via struvite from anaerobically treated POME and then polishes residual soluble COD illustrates a process logic that prioritizes capture as product before oxidation/polishing. Lab scale precipitation on raw POME further confirms feasibility, while also highlighting that reagent dosing and pH control dominate performance [3,4].

Beyond struvite, phosphate mineral recovery broadens the product space. Calcium phosphate (CaP) precipitation/crystallization is widely treated as a low cost P recovery route and is explicitly positioned as a fertilizer relevant product family, but phase selection (amorphous vs crystalline CaP forms) and impurity capture must be controlled to claim fertilizer grade quality. For industrial wastewaters with very high P loads, recovery as amorphous calcium phosphate and vivianite has been demonstrated, reinforcing that phosphate mineral recovery should be evaluated as an engineered mineral product pathway, not only as P removal. Practical precipitation studies also show that pH and calcium dosing shift removal/recovery windows, which directly affects product phase and downstream separability [14–16].

Table 1 Comparative characteristics of raw and anaerobically digested POME and their direct implications for fertilizer grade N–P–K recovery

Dimension	Raw POME	Anaerobically digested POME	Direct implication for fertilizer grade N–P–K recovery
Matrix dominance	Complex organics + colloids + high solids; nutrients partly locked in particulate/organic pools	More recovery relevant dissolved pool; still contains soluble organics that affect kinetics	Raw POME requires aggressive conditioning; post digestion liquor is the preferred recovery point
Variability driver	Solids/O&G/colloids and organic complexity shifts	Alkalinity, soluble organics, digestion intermediates shift	Recovery design must match disturbance type: solids driven vs chemistry driven instability
Dominant inhibitors	Physical interference (settling/filtration/fouling) + product contamination risk	Chemical/kinetic interference (phase control, nucleation/growth inhibition)	Post digestion recovery needs inhibitor aware phase control; raw POME needs solids control first
Biological stability link	Inhibitors present in feed can destabilize digestion upstream	Instability propagates to downstream recovery units via fluctuating chemistry	Nutrient recovery performance depends on controlling upstream inhibition, not only downstream unit operations
Potassium pathway constraint	K present but product pathway not robust under complex organics	Struvite-K routes highly sensitive to complexing/inhibitory species	K recovery is often more realistic via controlled concentration unless inhibitors are actively managed

3.2.2. Potassium recovery routes: K-enrichment and K-phosphate minerals

Potassium (K^+) is usually dissolved and conservative, so fertilizer grade recovery is governed by product definition: either (i) K-enrichment into a liquid fertilizer concentrate or (ii)

conversion into potassium phosphate minerals, mainly magnesium potassium phosphate hexahydrate (MPP, $MgKPO_4 \cdot 6H_2O$, K-struvite).

K-struvite/MPP crystallization is attractive because it yields a solid fertilizer grade carrier of K–P–Mg, but it is more sensitive than MAP-struvite to inhibitors and competing equilibria. Reviews of K-struvite recovery identify pH and reagent strategy as dominant levers and commonly report an optimal alkaline range for stable MPP formation. Fertilizer relevance has been directly tested: MPP recovered from wastewater has been evaluated for seed germination, root development, and ryegrass growth, enabling product claims to be tied to agronomic function rather than only chemical composition [17–19].

Organic matter is a major inhibitor for MPP crystallization. Recent evidence shows that removing organic matter mitigates crystallization inhibition and improves MPP recovery efficiency, making dissolved organics control a primary design variable for potassium mineral products. Complexing agents also matter: citrate can inhibit struvite-K formation by complexing Mg and by adsorption driven effects on crystal growth, which directly impacts yield and crystal habit. Reagent cost is also a design constraint; studies exploring inexpensive magnesium sources (e.g., MgO) illustrate the practical push to reduce chemical OPEX while maintaining phase control [13,17,20,21].

3.2.3. Adsorption/ion exchange: selectivity and regenerability

Adsorption and ion exchange can be fertilizer grade routes when they operate as closed loops: capture → regeneration → fertilizer product stream. Without regeneration into a usable eluate or direct agronomic use of the loaded medium, adsorption is merely pollutant transfer.

Clinoptilolite ion exchange is a practical benchmark for ammonium capture because NH_4^+ selectivity is strong. Fertilizer grade pathways are credible when regeneration yields a defined fertilizer solution. Regeneration of ammonium loaded clinoptilolite to produce a stoichiometric ammonium sulfate solution demonstrates a direct bridge from ion exchange to a recognized fertilizer product stream. Digestate studies also show clinoptilolite can target ammonium and potassium from liquid fractions and position nutrient loaded zeolite as a potential fertilizer or soil amendment, subject to contaminant control. Classic work on biological regeneration of clinoptilolite further underlines that regeneration strategy is not secondary, it is the central determinant of long term recovery performance [22,23].

For phosphate, Mg/Ca-modified biochars are increasingly positioned as adsorption media that can also serve as slow release fertilizer carriers. Studies report high phosphate adsorption capacities on Mg-loaded biochars and explicitly discuss desorption/regeneration behavior, which is critical for defining whether the pathway outputs a fertilizer concentrate or a nutrient loaded solid amendment. Biochar hydrogel composites have also been engineered with fertilizer intent, linking phosphate recovery to slow release behavior rather than only removal. Reviews of Mg/Ca-biochar hybrids emphasize that synthesis routes, reagent intensity, and regenerability govern scalability and cost, so fertilizer grade evaluation must include both performance and producibility [24–27].

3.2.4. Membrane driven recovery: concentration, fractionation, and water reuse

Membranes create fertilizer grade recovery by producing two outputs: reclaimed water and a nutrient rich concentrate that can be (i) used directly as liquid fertilizer, (ii) blended, or (iii) fed to crystallization. The limiting factor is fouling/scaling under POME derived matrices.

Fertilizer drawn forward osmosis (FDFO) is product aligned because the draw solution is fertilizer based; the process can recover water while producing a fertilizer relevant stream. Studies on anaerobic POME using commercial fertilizers as draw solutions show feasibility for combined water/nutrient recovery [8,28]. Fouling control is decisive: work on anaerobic POME concentration reports fouling propensity and mitigation via hydraulic flushing and osmotic backwashing, reinforcing that recoverability is constrained by cleaning realism, not only by initial flux.

Pressure driven systems (UF/NF/RO) remain important for fractionation and high quality water reuse, but they must be evaluated with explicit pretreatment and cleaning assumptions. Recent reviews and sector focused analyses describe membrane opportunities and limitations for POME, emphasizing that fouling management and integrated configurations determine viability for water reuse and resource recovery [5,29].

3.2.5. Biological assimilation: microalgae platforms and biomass valorization

Microalgae platforms recover nutrients by converting dissolved N and P into biomass, enabling a pathway to biofertilizers, soil conditioners, or biorefinery products. The fertilizer grade hurdle is standardization: biomass composition, contaminants, stabilization, and agronomic performance must be defined.

Reviews and synthesis studies frame POME as a nutrient medium for microalgae cultivation and link phycoremediation to biomass valorization (lipids, biofuel, high value compounds)[1,7,30]. Immobilization strategies directly address harvesting constraints: immobilized green microalgae post treatment of POME demonstrates stable operation and easier biomass recovery by bead collection rather than energy intensive dewatering [31,32]. Integration concepts also matter for fertilizer grade narratives: work on microalgae assisted biogas upgrading and integrated anaerobic digestion–microalgae systems positions nutrient capture and CO_2 utilization as a combined platform rather than isolated unit operations [8,33,34].

3.2.6. Electrochemical routes: enabling steps and hybridization

Electrochemical routes are often best treated as enablers for fertilizer grade recovery rather than stand alone final recovery steps. They can clarify, shift speciation, generate acid/base in situ, and produce nutrient concentrates compatible with fertilizer products.

Electrocoagulation (EC) has a mature role in POME treatment for rapid removal of turbidity and organics; optimization studies show that current density, pH, electrode gap, and time determine treatment efficiency, while electrode passivation and sludge handling remain core constraints. This matters for fertilizer grade recovery because EC can act as a pretreatment that reduces downstream crystallization inhibition and membrane fouling, or it can capture phosphorus into metal phosphate solids depending on electrode materials and operating regime [35].

For nutrient concentration and chemical minimization, bipolar membrane electrodialysis (BMED) is a strong hybrid candidate because it can generate acid/base streams while separating nutrients, enabling downstream ammonia recovery and phosphate precipitation with reduced external chemical inputs [36,37]. Pilot scale selective electrodialysis on liquid digestate demonstrates practical fractionation of nutrient ions and exploration of fertilizer creation routes, while explicitly confronting membrane fouling under real matrices. Pilot scale BP-ED coupled to membrane stripping has also been used to recover ammonia as ammonium sulfate, while highlighting product quality concerns (trace contaminants) that must be reported for fertilizer grade claims [38].

3.2.7. Indicative operating-cost benchmarks normalized by nutrient recovered

To complement the qualitative comparison of recovery pathways, Table 2. compiles literature-reported operating cost proxies expressed on a common functional basis, per unit mass of nutrient recovered, to support transparent cross-technology screening. Because published studies report cost and performance using heterogeneous bases (e.g., per treated volume, per mass of product, or energy intensity), the table distinguishes between reported OPEX proxies (direct monetary cost or specific energy demand) and the normalized cost metric (currency·kg^{-1} nutrient recovered or kWh·kg^{-1} nutrient recovered) obtained by converting volumetric/product based indicators into nutrient based indicators using the recovered nutrient mass or nutrient fraction in

the recovered product. These benchmarks are intended for order of magnitude comparison rather than site specific techno economic conclusions.

Table 2. Comparative data on estimated operating-cost proxies per unit of nutrient recovered

Pathway	**Literature OPEX proxy reported**	**Normalized cost metric**	**Interpretation notes**
Struvite precipitation (high P wastewater)	Cost to recover P as struvite: 2.06 USD·m^{-3}	3.65 USD·kg^{-1} P recovered	Chemical dosing (Mg source, alkalinity/pH control) dominates; normalized cost improves with higher influent P and higher recovery yield [39].
Struvite production (TEA scenarios)	Reported cost: 6.56 USD·kg^{-1} P recovered	6.56 USD·kg^{-1} P recovered	Reagent and process integration sensitive; reflects scenario assumptions (chemicals, utilities, solids handling) [40].
Wet chemical P recovery (Gifhorn/Stuttgart processes)	Reported recovery cost: €9–16 per kg P recovered	€9–16·kg^{-1} P recovered	Typically chemical-intensive (acids/alkalis/precipitants), hence higher OPEX where reagent demand is high [41].
Ion exchange + BMED + membrane contactor (ammonia recovery, low-strength wastewater)	Reported cost: 0.425 USD·kg^{-1} N	0.425 USD·kg^{-1} N recovered	Electricity-driven core steps plus consumables (resin/membrane life) and pretreatment; cost strongly depends on replacement intervals and system utilization [42].
Electrodialysis (ED) ammonia recovery (mixtures; hardness effect)	Specific energy consumption (SEC): 7–31 kWh·kg^{-1} N	7–31 kWh·kg^{-1} N recovered	Electricity-driven; SEC decreases after hardness removal, indicating strong sensitivity to scaling/fouling control [43].
Electrodialysis (two-stage) for NH_4–N reuse (anaerobic digestate liquor)	Mean SEC: 12.9 kWh·kg^{-1} NH_4–N	12.9 kWh·kg^{-1} N recovered	Electricity-driven; reported in an AD liquor context with MF pretreatment; recovery and SEC vary with operating strategy and target concentration [44].
Air stripping + acid absorption (digestate to ammonium sulfate)	Treatment cost: 5.56 USD·m^{-3} digestate	1.77 USD·kg^{-1} N recovered	Heat + base demand can dominate; economics are highly sensitive to NH_4^+ concentration, alkalinity/buffering, and energy integration [45].

Notes on normalization:

- Struvite row: 3.65 USD·kg^{-1} P = (2.06 USD·m^{-3}) / [(0.594 kg P·m^{-3}) × (0.95 recovery)]. The influent PO_4–P (594 mg·L^{-1}) and the reported volumetric cost are taken from the cited study.
- Air stripping row: 1.77 USD·kg^{-1} N = (5.56 USD·m^{-3}) / [(3.304 kg N·m^{-3}) × (0.95 recovery)], where 3.304 kg N·m^{-3} is computed from NH_4^+ = 0.236 mol·L^{-1} (×14 g N·mol^{-1}).

Table 2. makes the underlying cost structure explicit: P recovery via precipitation/crystallization is generally reagent and pH control dominated, so the apparent cost per kg P recovered is highly sensitive to Mg source selection, alkalinity demand, and whether recovery targets a P-rich sidestream. In contrast, N recovery routes based on ED/BMED are

primarily electricity driven, and energy intensity ($kWh \cdot kg^{-1}$ N) serves as a defensible OPEX proxy, while total costs remain contingent on pretreatment, scaling/fouling control, and component replacement. Air stripping benchmarks further illustrate the strong dependence of cost per kg N on buffering/alkalinity and recoverable NH_4^+ concentration, reinforcing the need to interpret all values as screening-level comparators rather than universal cost constants.

3.3. Product Quality, Safety, and Market Acceptance of POME-Derived Recovered Nutrient Fertilizers

Shifting POME management from pollution control to fertilizer production requires that the output be treated as a marketable fertilizer product rather than a nutrient bearing residue. In circular nutrient systems, the decisive evidence is therefore not solely nutrient removal from the aqueous phase, but the manufacture of a defined product phase with reproducible composition, acceptable impurity levels, and demonstrable agronomic function, aligned with end-use expectations and governance constraints.Purity and product identity [46].

3.3.1. Product identity and phase definition

A fertilizer claim becomes defensible when the recovered material has a clear chemical identity (e.g., struvite, calcium phosphate phases, ammonium salts, K-bearing solids/concentrates) and can be consistently reproduced across operating conditions. For precipitation/crystallization routes, the wastewater matrix and operating window control nucleation, crystal growth, and phase competition; consequently, precipitate formation is not equivalent to producing a fertilizer grade solid. In calcium phosphate recovery, for instance, process parameters such as supersaturation and pH strongly influence which CaP phase(s) form and thus affect the downstream handling and fertilizer value of the recovered product [16].

For struvite pathways, quality is similarly contingent on process design and control; fluidized bed systems explicitly target granular, harvestable crystals rather than fine sludge like precipitates, highlighting the importance of reactor hydrodynamics and separation strategy for product grade outcomes [47].

3.3.2. Nutrient specification, mass balance, and batch to batch consistency

From a fertilizer manufacturing standpoint, products must be specified by nutrient assay (e.g., N–P–K basis), supported by mass balance yield (fraction of influent nutrients captured in the product), and characterized for batch variability under realistic feed fluctuations. The relevance of this criterion is underscored by agronomic evaluations of recovered phosphate fertilizers, where product characterization (nutrient content and co-occurring elements) is explicitly linked to growth response, rather than assuming equivalence based on recovery efficiency alone [48].

3.3.3. Contaminants and safety: heavy metals and emerging contaminants

Market acceptance is strongly conditioned by risk perception and regulatory scrutiny, particularly for fertilizers derived from waste streams. Heavy metals remain a classical constraint, but the discourse has expanded to include emerging contaminants (notably PFAS) that may persist through conventional treatment and concentrate in solids. Evidence from multi facility profiling shows that a wide suite of PFAS can be quantified in biosolids and that treatment choices influence the measured PFAS burden, an important analogy for any POME derived fertilizer route that produces solids or concentrates [49].

Beyond PFAS, governance attention to undesirable elements in phosphate fertilizers more broadly illustrates that contaminant management is not merely a wastewater issue, but a fertilizer supply chain issue affecting legitimacy and traceability [50].

3.3.4. Physical quality and handling: storability, particle size, and application practicality

Even when chemically acceptable, products can fail commercially if physical properties impede distribution and field application. For solid products, fertilizer grade considerations include particle size distribution, moisture stability, dusting tendency, and caking risk, attributes that are tightly coupled to crystallization/aggregation pathways and post processing (dewatering, drying, granulation). The explicit focus on enhanced granulation and separation in struvite recovery research reflects that particle engineering is a central step in moving from recovery chemistry to a tradable fertilizer commodity [47].

3.3.5. Agronomic performance: plant availability and functional equivalence

A fertilizer product must show credible agronomic function, either equivalence or a predictable niche advantage. Recent agronomic evidence indicates that struvite can deliver competitive immediate and residual performance compared with conventional soluble phosphate fertilizers under relevant application regimes, reinforcing that product acceptance ultimately depends on plant available nutrient delivery rather than recovery yield alone [51].

For recovered products beyond struvite (e.g., CaP, P-loaded carriers), controlled comparisons that integrate product characterization with hydroponic/soil trials provide a stronger evidence base for fertilizer grade claims in review synthesis [48].

3.3.6. Social acceptance, legitimacy, and adoption barriers

For recycled nutrient fertilizers, technical viability is necessary but insufficient: adoption depends on stakeholder trust, perceived safety, and confidence in nutrient consistency. Conceptual analyses emphasize that farmer acceptance is shaped by perceived reliability and risk, particularly for fertilizers derived from industrial or sludge like streams, which can trigger skepticism even when technically compliant [52].

Empirical evidence from acceptance research in wastewater related agricultural applications further shows that attitudes and behavioral factors measurably influence acceptance, implying that commercialization pathways should anticipate communication, certification, and provenance strategies as part of product design [53].

Conclusions

This review reframes nutrient recovery from palm oil mill effluent (POME) as fertilizer product manufacturing within a wastewater system, where recovery is defensible only when nutrients are transferred into a defined product phase with mass-balanced yield, controlled composition, impurity control, and agronomic relevance. Anaerobic digestion emerges as a pivotal pivot point because it converts treatment from disposal into conversion, generating methane while producing an anaerobically digested liquor that is operationally more suitable for targeted nutrient recovery than raw POME.

A central implication is that raw POME and anaerobically digested POME are not interchangeable feedstocks: raw POME is dominated by solids/colloids and complex organics that hinder selective recovery and contaminate products, whereas post-digestion streams shift constraints toward chemistry-driven variability (alkalinity, soluble organics, intermediates) that governs precipitation windows, dosing demand, and membrane stability.

Technology pathways for fertilizer-grade N–P–K recovery converge toward hybrid trains combining separation and concentration with product-forming steps. Crystallization routes (struvite and phosphate minerals) offer direct solid products but require phase and harvestability control to avoid sludge-like precipitation. Membrane-based concentration and fertilizer-drawn forward osmosis align water recovery with fertilizer-relevant concentrates, yet feasibility is dominated by fouling and cleaning realism under POME-derived matrices. Biological assimilation (microalgae) is fertilizer-relevant only when biomass quality, harvesting, and standardization are engineered for consistent nutrient value and safe use. Overall, the most robust

design logic is hybridization: stabilize and fractionate solids, use anaerobic digestion as the conversion pivot, recover nutrients as products before intensive polishing, and treat fouling, scaling, and crystallization inhibition as first-class design variables.

References

[1] M. Muthukumaran, H. Rawindran, A. Noorjahan, M. Parveen, J. Barasarathi, J.P.J. Blessie, S.S. Ali, R.Z. Sayyed, M.K. Awasthi, S. Hassan, B. Ravindran, V. Vatanpour, B.S. Balakumar, Microalgae-based solutions for palm oil mill effluent management: Integrating phycoremediation, biomass and biodiesel production for a greener future, Biomass Bioenergy 191 (2024) 107445. https://doi.org/10.1016/j.biombioe.2024.107445.

[2] R. Vos, J. Glauber, C. Hebebrand, B. Rice, Global shocks to fertilizer markets: Impacts on prices, demand and farm profitability, Food Policy 133 (2025) 102790. https://doi.org/10.1016/j.foodpol.2024.102790.

[3] Y.F. Sea, A.S.M. Chua, G.C. Ngoh, M.F. Rabuni, Integrated Struvite Precipitation and Fenton Oxidation for Nutrient Recovery and Refractory Organic Removal in Palm Oil Mill Effluent, Water (Basel). 16 (2024) 1788. https://doi.org/10.3390/w16131788.

[4] M. Ngatiman, M.S. Jami, M.R. Abu Bakar, V. Subramaniam, S.K. Loh, Investigation of struvite crystals formed in palm oil mill effluent anaerobic digester, Heliyon 7 (2021) e05931. https://doi.org/10.1016/j.heliyon.2021.e05931.

[5] P.T.P. Aryanti, B. Harsono, M.F.W. Biantoro, R. Romariyo, T.A. Putri, A.N. Hakim, G.A. Setia, D.I. Saputra, K. Khoiruddin, The role of membrane technology in palm oil mill effluent (POME) decontamination: Current trends and future prospects, J. Environ. Manage. 374 (2025) 124094. https://doi.org/10.1016/j.jenvman.2025.124094.

[6] R. Abdul Wahid, W.L. Ang, A.W. Mohammad, D.J. Johnson, N. Hilal, Evaluating Fertilizer-Drawn Forward Osmosis Performance in Treating Anaerobic Palm Oil Mill Effluent, Membranes (Basel). 11 (2021) 566. https://doi.org/10.3390/membranes11080566.

[7] S.S. Low, K.X. Bong, M. Mubashir, C.K. Cheng, M.K. Lam, J.W. Lim, Y.C. Ho, K.T. Lee, H.S.H. Munawaroh, P.L. Show, Microalgae Cultivation in Palm Oil Mill Effluent (POME) Treatment and Biofuel Production, Sustainability 13 (2021) 3247. https://doi.org/10.3390/su13063247.

[8] I.N. Djarot, H. Pawignya, T. Handayani, N. Widyastuti, N. Nuha, F.D. Arianti, M.D. Pertiwi, A. Rifai, F. Isharyadi, S.P. Wijayanti, M.M.A. Nur, Enhancing sustainability: microalgae cultivation for biogas enrichment and phycoremediation of palm oil mill effluent - a comprehensive review, Environmental Pollutants and Bioavailability 36 (2024). https://doi.org/10.1080/26395940.2024.2347314.

[9] K.M. Salleh, N.F. Abd Rashid, M. Mostapha, Palm oil mill effluents: generation, characteristics, impacts, and applications for bio-based product recovery in a biorefinery, in: Biorefinery of Industrial Effluents for a Sustainable Circular Economy, Elsevier, 2025: pp. 131–139. https://doi.org/10.1016/B978-0-443-21801-9.00009-4.

[10] Y.X. Low, N.A. Amran, W.N.A. Wan Osman, E.H. Yanez, H. Adamu, Sustainable nutrient recovery via progressive freezing of anaerobically digested POME: Insights into process parameters and trade-offs, J. Environ. Chem. Eng. 14 (2026) 121300. https://doi.org/10.1016/j.jece.2026.121300.

[11] Z. Zhou, D. Hu, W. Ren, Y. Zhao, L.-M. Jiang, L. Wang, Effect of humic substances on phosphorus removal by struvite precipitation, Chemosphere 141 (2015) 94–99. https://doi.org/10.1016/j.chemosphere.2015.06.089.

[12] S. Krishnan, P. Homroskla, K. Saritpongteeraka, O. Suttinun, M. Nasrullah, Y. Tirawanichakul, S. Chaiprapat, Specific degradation of phenolic compounds from palm oil mill effluent using ozonation and its impact on methane fermentation, Chemical Engineering Journal 451 (2023) 138487. https://doi.org/10.1016/j.cej.2022.138487.

[13] A. Viani, L. Zárybnická, R. Ševčík, P. Mácová, J. Machotová, K. Veltruská, Struvite-K crystal growth inhibition by citric acid: Formation of complexes in solution and surface adsorption effects, J. Cryst. Growth 598 (2022) 126858. https://doi.org/10.1016/j.jcrysgro.2022.126858.

[14] D.G. Randall, J. Jalava, B. Vinnerås, P. Simha, Phosphorus recovery as vivianite and amorphous calcium phosphate from high-load industrial wastewater, Front. Environ. Sci. 12 (2024). https://doi.org/10.3389/fenvs.2024.1491220.

[15] M.L. Christensen, C. Cvitanich, C.A. Quist-Jensen, M. Thau, B. Malmgren-Hansen, Precipitation and recovery of phosphorus from the wastewater hydrolysis tank, Science of The Total Environment 813 (2022) 151875. https://doi.org/10.1016/j.scitotenv.2021.151875.
[16] L. Deng, B.R. Dhar, Phosphorus recovery from wastewater via calcium phosphate precipitation: A critical review of methods, progress, and insights, Chemosphere 330 (2023) 138685. https://doi.org/10.1016/j.chemosphere.2023.138685.
[17] G. Wang, Y. Shi, J. Zhang, D. Qu, X. Bai, Investigation of potassium magnesium phosphate for wastewater recovering towards sustainable cities, Sustain. Cities Soc. 96 (2023) 104638. https://doi.org/10.1016/j.scs.2023.104638.
[18] A. Yesigat, A. Worku, A. Mekonnen, W. Bae, G.L. Feyisa, S. Gatew, J.-L. Han, W. Liu, A. Wang, A. Guadie, Phosphorus recovery as K-struvite from a waste stream: A review of influencing factors, advantages, disadvantages and challenges, Environ. Res. 214 (2022) 114086. https://doi.org/10.1016/j.envres.2022.114086.
[19] I. Kabdaşlı, A. Siciliano, C. Limonti, O. Tünay, Is K-Struvite Precipitation a Plausible Nutrient Recovery Method from Potassium-Containing Wastes?—A Review, Sustainability 14 (2022) 11680. https://doi.org/10.3390/su141811680.
[20] F.N. Türk, M.Ş.A. Eren, H. Arslanoğlu, Obtaining, Characterizing, and Evaluation of Potassium-Struvite (KMgPO4.6H2O) in Phosphorus Removal from Water: Investigation of Low-Cost Mgo Use, Water Conservation Science and Engineering 9 (2024) 68. https://doi.org/10.1007/s41101-024-00304-5.
[21] J. Yang, L. Chen, L. Yang, X. Jiang, L. Deng, X. Tang, W. Wang, Organic matter removal mitigates crystallization inhibition to enhance co-recovery of potassium and phosphorus from wastewater, Environ. Res. 279 (2025) 121758. https://doi.org/10.1016/j.envres.2025.121758.
[22] S. Wasielewski, E. Rott, R. Minke, H. Steinmetz, Recovery of Ammonium Sulfate Solution by Regeneration of Loaded Clinoptilolite, Nanomaterials 12 (2022) 525. https://doi.org/10.3390/nano12030525.
[23] F. Sadrzadeh, B.B. Baykal, M. Altinbas, An Investigation on the Importance of Initial Loading in the Removal of Nutrients from Liquid Digestate Through Sorption and Nutrient Recovery from the Solid Phase To Be Used as Fertilizer, Water Air Soil Pollut. 234 (2023) 706. https://doi.org/10.1007/s11270-023-06717-7.
[24] H. Samaraweera, K.N. Palansooriya, P.D. Dissanayake, A.H. Khan, M. Sillanpää, T. Mlsna, Sustainable phosphate removal using Mg/Ca-modified biochar hybrids: Current trends and future outlooks, Case Studies in Chemical and Environmental Engineering 8 (2023) 100528. https://doi.org/10.1016/j.cscee.2023.100528.
[25] C.-Y. Wang, H.-D. Zhou, Q. Wang, B.-X. Xu, G. Zhu, Efficiency and mechanism of phosphate adsorption and desorption of a novel Mg-loaded biochar material, Environmental Science and Pollution Research 31 (2023) 4425–4438. https://doi.org/10.1007/s11356-023-31400-z.
[26] Z. Guo, D. Zhang, L. Ma, Q. Dai, R. Yang, R. Ao, Magnesium modified algae biochar for phosphorus adsorption: Synthesis, experimental analysis, DFT calculations and regeneration, Journal of Water Process Engineering 71 (2025) 107169. https://doi.org/10.1016/j.jwpe.2025.107169.
[27] N.M. Mohamad Sarbani, H. Harada, M. Aoyagi, E. Hidayat, Dual-Functioned Magnesium-Enriched Biochar Hydrogels for Phosphate Recovery and Slow-Release Nutrient Delivery, Water (Basel). 17 (2025) 2235. https://doi.org/10.3390/w17152235.
[28] L. Chekli, Y. Kim, S. Phuntsho, S. Li, N. Ghaffour, T. Leiknes, H.K. Shon, Evaluation of fertilizer-drawn forward osmosis for sustainable agriculture and water reuse in arid regions, J. Environ. Manage. 187 (2017) 137–145. https://doi.org/10.1016/j.jenvman.2016.11.021.
[29] I.U. Khan, M.A. Rahman, M.H.D. Othman, M. Iftikhar, A. Jilani, S. Mehmood, M.B. Shakoor, M. Rizwan, J.W.H. Yong, Innovative Solutions for Palm Oil Mill Effluent Treatment: A Membrane Technology Perspective, ACS ES&T Water 5 (2025) 3538–3562. https://doi.org/10.1021/acsestwater.4c00432.
[30] K.A. Tan, W.O. Wan Maznah, N. Morad, J. Lalung, N. Ismail, A. Talebi, A.A. Oyekanmi, Advances in POME treatment methods: potentials of phycoremediation, with a focus on South East Asia, International Journal of Environmental Science and Technology 19 (2022) 8113–8130. https://doi.org/10.1007/s13762-021-03436-6.
[31] K.A. Tan, J. Lalung, N. Morad, N. Ismail, W.M. Wan Omar, M.A. Khan, M. Sillanpää, M. Rafatullah, Post-Treatment of Palm Oil Mill Effluent Using Immobilised Green Microalgae Chlorococcum oleofaciens, Sustainability 13 (2021) 11562. https://doi.org/10.3390/su132111562.

[32] A. Ahmad, A.H. Bhat, A. Buang, Immobilized Chlorella vulgaris for efficient palm oil mill effluent treatment and heavy metals removal, Desalination Water Treat. 81 (2017) 105–117. https://doi.org/10.5004/dwt.2017.20991.
[33] K. Nath, R. Jana, R. Chowdhury, Integration of Anaerobic Digestion and Algal Cultivation—Prospects and Challenges, in: 2024: pp. 141–179. https://doi.org/10.1007/978-981-97-1406-3_5.
[34] D. Nagarajan, D.-J. Lee, J.-S. Chang, Integration of anaerobic digestion and microalgal cultivation for digestate bioremediation and biogas upgrading, Bioresour. Technol. 290 (2019) 121804. https://doi.org/10.1016/j.biortech.2019.121804.
[35] M. Nasrullah, S. Ansar, S. Krishnan, L. Singh, S.G. Peera, A.W. Zularisam, Electrocoagulation treatment of raw palm oil mill effluent: Optimization process using high current application, Chemosphere 299 (2022) 134387. https://doi.org/10.1016/j.chemosphere.2022.134387.
[36] E.S. Koivisto, T. Reuter, R. Zevenhoven, Performance Optimization of Bipolar Membrane Electrodialysis of Ammonium Sulfate/Bisulfate Reagents for CO_2 Mineralization, ACS ES&T Water 3 (2023) 1953–1962. https://doi.org/10.1021/acsestwater.3c00028.
[37] W. Chen, S. Grimberg, S. Rogers, T. Kim, Bipolar membrane electrodialysis for nutrient recovery from anaerobic digestion dewatering sidestream, Chemical Engineering Journal 488 (2024) 150834. https://doi.org/10.1016/j.cej.2024.150834.
[38] F. Ferrari, M. Pijuan, S. Molenaar, N. Duinslaeger, T. Sleutels, P. Kuntke, J. Radjenovic, Ammonia recovery from anaerobic digester centrate using onsite pilot scale bipolar membrane electrodialysis coupled to membrane stripping, Water Res. 218 (2022) 118504. https://doi.org/10.1016/j.watres.2022.118504.
[39] A. Lavanya, S.T. Ramesh, S. Nandhini, Phosphate recovery from swine wastewater by struvite precipitation and process optimization using response surface methodology, Desalination Water Treat. 164 (2019) 134–143. https://doi.org/10.5004/dwt.2019.24447.
[40] Y. Pinatha, W. Rongchapo, T. Neamhom, P. Pentamwa, Product characterization, application, and techno-economic aspects of phosphorus recovery as struvite from swine wastewater: A case of small-scale swine farm, Science of The Total Environment 982 (2025) 179685. https://doi.org/10.1016/j.scitotenv.2025.179685.
[41] P. Achilleos, K.R. Roberts, I.D. Williams, Struvite precipitation within wastewater treatment: A problem or a circular economy opportunity?, Heliyon 8 (2022) e09862. https://doi.org/10.1016/j.heliyon.2022.e09862.
[42] X. Guo, J. Chen, X. Wang, Y. Li, Y. Liu, B. Jiang, Sustainable ammonia recovery from low strength wastewater by the integrated ion exchange and bipolar membrane electrodialysis with membrane contactor system, Sep. Purif. Technol. 305 (2023) 122429. https://doi.org/10.1016/j.seppur.2022.122429.
[43] H.J. Choi, M. Tahmid, S. Mondal, M.C. Hatzell, Concentrating Ammonia from Wastewater with Electrodialysis, ACS ES&T Water 5 (2025) 5720–5727. https://doi.org/10.1021/acsestwater.5c00721.
[44] L. Weisz, D. Reif, S. Weilguni, V. Parravicini, E. Saracevic, J. Krampe, N. Kreuzinger, Feasibility study of electrodialysis as an ammonium reuse process for covering the nitrogen demand of an industrial wastewater treatment plant, Science of The Total Environment 954 (2024) 176699. https://doi.org/10.1016/j.scitotenv.2024.176699.
[45] M. Errico, L. Fjerbaek Sotoft, A. Kjærhuus Nielsen, B. Norddahl, Treatment costs of ammonia recovery from biogas digestate by air stripping analyzed by process simulation, Clean Technol. Environ. Policy 20 (2018) 1479–1489. https://doi.org/10.1007/s10098-017-1468-0.
[46] A.R. Jupp, S. Beijer, G.C. Narain, W. Schipper, J.C. Slootweg, Phosphorus recovery and recycling – closing the loop, Chem. Soc. Rev. 50 (2021) 87–101. https://doi.org/10.1039/D0CS01150A.
[47] T.-H. Ha, N.N.N. Mahasti, C.-S. Lin, M.-C. Lu, Y.-H. Huang, Enhanced struvite (MgNH4PO4·6H2O) granulation and separation from synthetic wastewater using fluidized-bed crystallization (FBC) technology, Journal of Water Process Engineering 53 (2023) 103855. https://doi.org/10.1016/j.jwpe.2023.103855.
[48] L. Fang, L. Li, Q. Wang, J. Li, C.S. Poon, Agronomic effectiveness of recovered phosphate fertilizer produced from incinerated sewage sludge ash, Waste Dispos. Sustain. Energy 4 (2022) 157–167. https://doi.org/10.1007/s42768-022-00097-0.
[49] J.T. Thompson, N.M. Robey, T.M. Tolaymat, J.A. Bowden, H.M. Solo-Gabriele, T.G. Townsend, Underestimation of Per- and Polyfluoroalkyl Substances in Biosolids: Precursor Transformation During Conventional Treatment, Environ. Sci. Technol. 57 (2023) 3825–3832. https://doi.org/10.1021/acs.est.2c06189.

[50] Z. Lian-kai, L. Xiang, S. Ya-jie, G.L. Bernd, B. Roland, W. Heike, H.H. Silvia, S. Ewald, Risks and governance of heavy metals in European soil applied phosphate fertilizers, China Geology 8 (2025) 560–572. https://doi.org/10.31035/cg2023147.

[51] F. DeLucca-Agrelo, L. Condron, J. Moir, Assessment of the relative agronomic effectiveness of struvite fertilizer in a temperate grassland, Nutr. Cycl. Agroecosyst. 132 (2026) 14. https://doi.org/10.1007/s10705-025-10465-x.

[52] C.M. Cordeiro, E. Sindhøj, Situating the discourse of recycled nutrient fertilizers in circular economy principles for sustainable agriculture, Frontiers in Sustainability 5 (2024). https://doi.org/10.3389/frsus.2024.1465752.

[53] P. Verhoest, B. Gaume, J. Bauwens, P. te Braak, M. Huysmans, Public acceptance of recycled water: A survey of social attitudes toward the consumption of crops grown with treated wastewater, Sustain. Prod. Consum. 34 (2022) 467–475. https://doi.org/10.1016/j.spc.2022.10.003.