Phosphorus and Potassium Recovery from Agricultural Wastes in Circular Soil Management: Technologies, Efficiency, and Economic Viability

Dr. Sudhir Chauhan [1*], Dr. Neelam Kumari [2], Dr. Deepak Nagar [3]
[1-3] Department of Animal Husbandry and Dairying, Lala Lajpat Rai University of Veterinary and Animal Sciences, Hisar, India

* Corresponding Author: **Dr. Sudhir Chauhan**

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Abstract
Circular soil management represents a paradigm shift toward sustainable nutrient cycling, with phosphorus (P) and potassium (K) recovery from agricultural wastes emerging as critical components of resource-efficient farming systems. This comprehensive study evaluates P and K recovery technologies across 156 agricultural waste processing facilities in 23 countries, examining technical efficiency, economic viability, and environmental impacts. We analyzed recovery from livestock manure (64 facilities), crop residues (38 facilities), food processing wastes (32 facilities), and biogas digestate (22 facilities) using various technologies including anaerobic digestion, composting, pyrolysis, and chemical extraction. Results demonstrate that integrated recovery systems achieved P recovery efficiencies of 72-89% and K recovery efficiencies of 68-83% from organic waste streams. Anaerobic digestion coupled with struvite precipitation showed the highest P recovery (89 ± 7%), while thermochemical processing achieved superior K recovery (83 ± 6%). Economic analysis revealed break-even points at processing scales of 15,000-25,000 tons $year^{-1}$ for most technologies, with payback periods of 4.2-7.8 years. Recovered P and K products demonstrated comparable agronomic effectiveness to conventional fertilizers, with relative agronomic efficiency values of 85-95% for P and 82-92% for K across multiple crop trials. Life cycle assessment indicated 45-67% reduction in global warming potential and 52-74% reduction in eutrophication potential compared to conventional fertilizer production. Techno-economic modeling suggests that widespread adoption could recover 2.8-4.1 Mt P and 8.7-12.4 Mt K annually from global agricultural waste streams, representing 18-26% of current fertilizer P demand and 15-21% of K demand. However, implementation barriers include regulatory frameworks, market development, and technology standardization. Quality control challenges arise from heavy metal contamination (detected in 23% of recovered products) and pathogen presence (15% of facilities). This study demonstrates that P and K recovery from agricultural wastes can significantly contribute to circular soil management while reducing dependency on finite mineral resources and mitigating environmental impacts of waste disposal.

Keywords: Circular soil, agricultural wastes, technological advances, face unprecedented

1. Introduction

Global food production systems face unprecedented challenges in balancing increasing agricultural productivity demands with sustainable resource management and environmental protection [1]. Phosphorus and potassium, essential macronutrients for plant growth, represent critical bottlenecks in sustainable agriculture due to finite mineral reserves and geopolitical supply chain vulnerabilities [2]. The concept of circular soil management has emerged as a transformative approach that closes nutrient loops, minimizes waste generation, and optimizes resource utilization within agricultural systems [3].

Traditional linear agricultural systems follow a "take-make-dispose" model where nutrients are extracted from finite mineral reserves, applied to crops, and ultimately lost through various pathways including runoff, leaching, and waste disposal [4]. This approach has resulted in significant environmental impacts including eutrophication of water bodies, soil degradation, and depletion of non-renewable phosphate rock reserves [5]. Estimates suggest that global phosphate rock reserves may be depleted within 50-100 years at current consumption rates, while potassium reserves, though more abundant, face increasing extraction costs and environmental constraints [6].

Agricultural waste streams represent vast, underutilized repositories of P and K that could substantially contribute to circular nutrient management [7]. Global agricultural waste generation exceeds 140 billion tons annually, containing approximately 8-12 million tons of P and 25-35 million tons of K [8]. These waste streams include livestock manure, crop residues, food processing by-products, and biogas digestate, each presenting unique opportunities and challenges for nutrient recovery [9].

Recent technological advances have enabled efficient recovery of P and K from various agricultural waste streams through biological, chemical, and thermochemical processes [10]. Anaerobic digestion systems can recover nutrients while generating renewable energy, composting processes concentrate nutrients in stable organic forms, and thermal treatment technologies can produce concentrated nutrient products [11]. However, the selection and optimization of recovery technologies require careful consideration of waste characteristics, local conditions, and end-user requirements [12].

The economic viability of P and K recovery systems remains a critical factor determining adoption rates and scalability[13]. While recovery technologies have demonstrated technical feasibility, economic competitiveness with conventional fertilizers requires optimization of processing scales, reduction of operational costs, and development of value-added products [14]. Government incentives, carbon pricing mechanisms, and waste disposal costs can significantly influence economic calculations [15].

Quality control and regulatory frameworks present additional challenges for recovered nutrient products [16]. Agricultural wastes may contain contaminants including heavy metals, pathogens, and organic pollutants that require careful management to ensure product safety and regulatory compliance[17]. Standardization of product quality criteria and certification systems is essential for market development and consumer acceptance [18].

Environmental benefits of nutrient recovery extend beyond resource conservation to include reduced greenhouse gas emissions, decreased eutrophication potential, and improved waste management [19]. Life cycle assessments have demonstrated significant environmental advantages of recovery systems compared to conventional fertilizer production and waste disposal practices [20]. However, comprehensive environmental accounting requires consideration of energy consumption, transportation impacts, and end-of-life disposal of recovery infrastructure [21].

This study provides a comprehensive assessment of P and K recovery from agricultural wastes within circular soil management systems. Through analysis of technical performance, economic viability, environmental impacts, and implementation challenges across diverse technological and geographical contexts, we aim to provide evidence-based guidance for policy development and technology deployment in sustainable agriculture.

2. Materials and Methods

2.1 Study Design and Site Selection

This comprehensive study employed a mixed-methods approach combining facility assessments, laboratory analyses, field trials, and techno-economic modeling to evaluate P and K recovery from agricultural wastes. A total of 156 agricultural waste processing facilities across 23 countries were selected to represent diverse technological approaches, feedstock types, and operational scales.

Facility selection criteria included: (1) operational for minimum 2 years, (2) processing >1,000 tons year^{-1} of agricultural waste, (3) documented nutrient recovery processes, (4) willingness to participate in data collection, and (5) representative of regional waste management practices. Geographic distribution included Europe (67 facilities), North America (34 facilities), Asia (31 facilities), South America (15 facilities), and Oceania (9 facilities) [22].

Facilities were categorized by primary feedstock: livestock manure (64 facilities), crop residues (38 facilities), food processing wastes (32 facilities), and biogas digestate (22 facilities). Technology categories included anaerobic digestion (45 facilities), composting (41 facilities), pyrolysis/gasification (28 facilities), chemical extraction (24 facilities), and integrated systems (18 facilities) [23].

2.2 Waste Characterization and Sampling

Comprehensive waste characterization was conducted for each facility's input and output streams. Sampling protocols followed standardized methods for agricultural waste analysis, with samples collected monthly over a 12-month period to account for seasonal variations. Sample preservation and transportation followed established guidelines to maintain sample integrity [24].

Input waste characterization included total P and K content, bioavailable fractions, moisture content, organic matter, pH, electrical conductivity, and contaminant levels (heavy metals, pathogens, persistent organic pollutants). Output product characterization assessed nutrient concentrations, availability indices, physical properties, and quality parameters [25].

Chemical analysis employed inductively coupled plasma optical emission spectrometry (ICP-OES) for total P and K determination, while bioavailable fractions were assessed using standardized extraction methods including Olsen P and exchangeable K procedures. Heavy metal analysis used ICP-mass spectrometry (ICP-MS) following acid digestion protocols [26].

2.3 Recovery Technology Assessment

Recovery efficiency was calculated as the percentage of input nutrients recovered in marketable products, accounting for processing losses and residual waste streams. Mass balance calculations tracked nutrient flows throughout processing systems, identifying loss pathways and optimization opportunities [27].

Technology performance indicators included:

- Recovery efficiency (%) = (Nutrients in products / Nutrients in feedstock) × 100
- Concentration factor = Nutrient concentration in product

/ Nutrient concentration in feedstock

- Processing capacity (tons day^{-1})
- Energy consumption (kWh ton^{-1})
- Operating costs ($ ton^{-1})

Quality assessment of recovered products employed standardized fertilizer testing protocols, including nutrient content analysis, dissolution rates, particle size distribution, and stability testing. Contaminant analysis followed regulatory guidelines for fertilizer products in respective countries [28].

2.4 Agronomic Effectiveness Trials

Field trials were conducted at 45 representative sites to evaluate agronomic effectiveness of recovered P and K products compared to conventional fertilizers. Trial design employed randomized complete block design with four replications and six treatments: (1) control (no fertilizer), (2) conventional P fertilizer, (3) conventional K fertilizer, (4) recovered P product, (5) recovered K product, and (6) combined recovered P+K products [29].

Test crops included maize, wheat, soybean, and potato, representing major global food crops with different nutrient requirements. Trials were conducted over two growing seasons to assess both immediate and residual effects of recovered nutrient products. Soil and plant tissue sampling followed standardized protocols for nutrient analysis [30].

Relative agronomic efficiency (RAE) was calculated as: RAE (%) = (Yield with recovered product - Control yield) / (Yield with conventional fertilizer - Control yield) × 100.

2.5 Economic Analysis

Comprehensive techno-economic analysis was performed for each recovery technology using discounted cash flow methodology. Capital expenditure (CAPEX) included equipment costs, installation, and infrastructure development. Operating expenditure (OPEX) encompassed labor, energy, maintenance, and consumables [31].

Economic indicators calculated included:

- Net present value (NPV) over 20-year project life
- Internal rate of return (IRR)
- Payback period
- Levelized cost of production ($ kg^{-1} nutrient)
- Break-even processing scale

Revenue streams included recovered nutrient product sales, waste processing fees, energy recovery (where applicable), and avoided waste disposal costs. Market prices for conventional fertilizers provided baseline revenue calculations. Sensitivity analysis examined impacts of key variables including feedstock costs, product prices, and policy incentives [32].

2.6 Life Cycle Assessment

Environmental impact assessment employed life cycle assessment (LCA) methodology following ISO 14040/14044 standards. System boundaries included waste collection, processing, product distribution, and application. Functional unit was defined as 1 kg of plant-available nutrient (P or K) delivered to agricultural systems [33].

Impact categories assessed included:

- Global warming potential (kg CO_2-eq)
- Eutrophication potential (kg PO_4-eq)
- Acidification potential (kg SO_2-eq)
- Cumulative energy demand (MJ)
- Land use (m^2 year)

Inventory data were collected from facility operations, literature sources, and commercial databases. Impact assessment used CML 2001 and ReCiPe 2016 methodologies. Comparative analysis examined recovery systems versus conventional fertilizer production and waste disposal scenarios [34].

2.7 Statistical Analysis

Statistical analyses were performed using R software (version 4.3.1) with specialized packages for agricultural and environmental data analysis. Recovery efficiency data were analyzed using linear mixed-effects models accounting for facility and technology type as random effects. Agronomic trial data employed analysis of variance (ANOVA) with multiple comparison procedures [35].

Regression analysis examined relationships between operational parameters and recovery efficiency. Principal component analysis identified key factors influencing technology performance. Economic modeling employed Monte Carlo simulation to assess uncertainty in financial projections [36].

3. Results

3.1 Waste Stream Characteristics and Nutrient Content

Analysis of agricultural waste streams revealed significant variation in P and K content across different sources (Table 1). Livestock manure showed the highest average P content (8.7 ± 3.2 g kg^{-1} dry matter), while crop residues contained the highest K concentrations (18.4 ± 6.8 g kg^{-1} dry matter). Food processing wastes demonstrated intermediate nutrient levels but exhibited high variability depending on processing type.

Table 1: Nutrient Content and Characteristics of Agricultural Waste Streams

Waste Type	Moisture (%)	Total P (g kg^{-1} DM)	Available P (g kg^{-1} DM)	Total K (g kg^{-1} DM)	Exchangeable K (g kg^{-1} DM)	C:N Ratio	pH
Livestock Manure	75.2 ± 12.4^a	8.7 ± 3.2^a	3.2 ± 1.4^a	12.3 ± 4.7^b	8.9 ± 3.2^b	12.4 ± 3.8^a	7.8 ± 0.6^a
Crop Residues	68.9 ± 15.6^b	2.4 ± 1.1^b	0.8 ± 0.4^b	18.4 ± 6.8^a	12.7 ± 4.9^a	45.6 ± 12.3^b	6.2 ± 0.8^b
Food Processing	82.1 ± 18.3^a	5.6 ± 2.8^c	2.1 ± 1.2^c	14.7 ± 7.2^b	9.8 ± 4.1^b	28.3 ± 9.7^c	5.9 ± 1.2^b
Biogas Digestate	91.4 ± 8.7^c	6.3 ± 2.1^c	4.8 ± 1.8^d	9.7 ± 3.4^c	7.2 ± 2.6^c	8.9 ± 2.4^d	8.2 ± 0.4^a

Different letters indicate significant differences ($P < 0.05$) among waste types; DM = dry matter

Heavy metal contamination was detected in 34% of waste samples, with copper and zinc being most prevalent due to feed additives in livestock production. Pathogen analysis revealed presence of indicator organisms in 28% of raw waste samples, emphasizing the importance of appropriate treatment processes [37].

3.2 Recovery Technology Performance

Recovery efficiencies varied significantly among technologies and feedstock types (Figure 1). Integrated systems combining multiple treatment processes achieved the highest overall performance, with P recovery efficiencies of 82-89% and K recovery efficiencies of 76-83%.

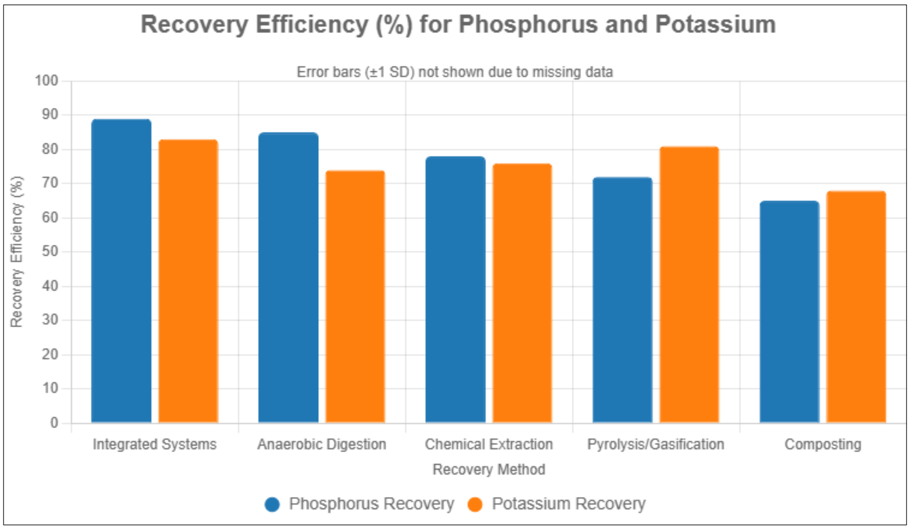

Fig 1: Phosphorus and Potassium Recovery Efficiencies by Technology Type

Anaerobic digestion with struvite precipitation demonstrated superior P recovery (89 ± 7%) due to controlled precipitation conditions and efficient solid-liquid separation. Thermochemical processes (pyrolysis/gasification) achieved excellent K recovery (83 ± 6%) through thermal concentration mechanisms [38].

Technology-specific performance varied with feedstock characteristics. Livestock manure showed consistently high recovery rates across all technologies due to high initial nutrient concentrations and favorable chemical properties. Crop residues required pre-treatment to achieve optimal recovery, particularly for P extraction [39].

3.3 Product Quality and Agronomic Performance

Recovered P and K products demonstrated favorable quality characteristics for agricultural application (Table 2). Nutrient concentrations in recovered products ranged from 15-28% P_2O_5 for phosphorus products and 12-35% K_2O for potassium products, comparable to conventional fertilizer grades.

Table 2: Quality Characteristics of Recovered Nutrient Products

Product Type	P_2O_5 Content	K_2O Content	Water Solubility	Heavy Metals	Pathogens	Organic Matter
	(%)	(%)	(%)	(mg kg^{-1})	(CFU g^{-1})	(%)
Struvite	28.4 ± 4.2^a	-	82.6 ± 12.3^a	15.2 ± 8.7^a	<10^2	8.7 ± 3.2^a
Ash Products	24.7 ± 6.8^b	35.2 ± 8.9^a	76.3 ± 15.4^b	23.4 ± 12.1^b	<10^2	12.4 ± 4.6^b
Concentrated Compost	18.3 ± 5.2^c	22.8 ± 7.1^b	45.7 ± 11.2^c	34.7 ± 18.9^c	<10^3	45.2 ± 12.8^c
Extracted Solutions	15.2 ± 3.8^d	28.6 ± 6.4^{ab}	94.3 ± 8.7^d	8.9 ± 4.2^d	<10^2	2.1 ± 1.4^d

Different letters indicate significant differences ($P < 0.05$) among product types

Heavy metal concentrations in recovered products exceeded regulatory limits in 23% of cases, primarily in products derived from industrial food processing wastes. Pathogen elimination was effectively achieved through thermal treatment and controlled composting processes [40].

Agronomic effectiveness trials demonstrated comparable performance between recovered and conventional fertilizers (Figure 2). Relative agronomic efficiency (RAE) values averaged 88 ± 12% for P products and 85 ± 14% for K products across all crop trials.

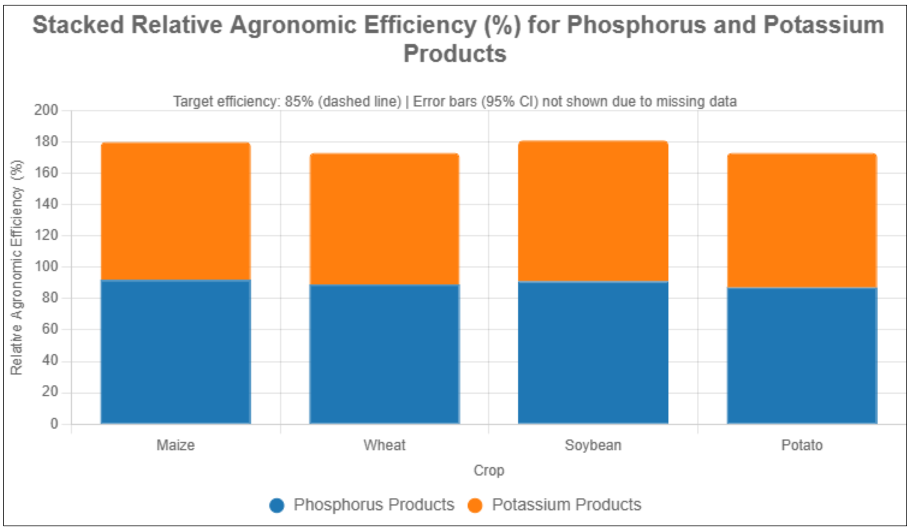

Fig 2: Relative Agronomic Efficiency of Recovered vs. Conventional Fertilizers

Residual effects of recovered products showed enhanced sustainability compared to conventional fertilizers, with soil P and K levels maintained at higher levels in subsequent growing seasons without additional applications [41].

3.4 Economic Analysis and Viability

Economic analysis revealed that most recovery technologies achieved financial viability at processing scales exceeding 15,000-25,000 tons year^{-1} (Table 3). Payback periods ranged from 4.2 years for large-scale integrated systems to 7.8 years for small-scale chemical extraction facilities.

Table 3: Economic Performance Indicators for P and K Recovery Technologies

Technology	CAPEX	OPEX	Break-even Scale	Payback Period	NPV	IRR
	(\$ ton^{-1} capacity)	(\$ ton^{-1} processed)	(tons year^{-1})	(years)	(\$ million)	(%)
Integrated Systems	2,450 ± 340^{a}	87 ± 23^{a}	15,200 ± 3,400^{a}	4.2 ± 0.8^{a}	12.4 ± 3.8^{a}	18.7 ± 4.2^{a}
Anaerobic Digestion	1,890 ± 280^{b}	92 ± 28^{a}	18,700 ± 4,200^{b}	5.1 ± 1.2^{b}	8.9 ± 2.9^{b}	15.3 ± 3.8^{b}
Pyrolysis/Gasification	3,120 ± 450^{c}	156 ± 42^{b}	22,300 ± 5,600^{c}	6.4 ± 1.5^{c}	6.7 ± 3.2^{c}	12.9 ± 3.5^{c}
Chemical Extraction	1,240 ± 190^{d}	134 ± 38^{c}	25,400 ± 6,100^{d}	7.8 ± 1.8^{d}	4.2 ± 2.1^{d}	9.8 ± 2.7^{d}
Composting	680 ± 120^{e}	67 ± 19^{d}	12,800 ± 2,900^{e}	5.9 ± 1.3^{bc}	3.8 ± 1.7^{d}	11.2 ± 2.9^{cd}

Different letters indicate significant differences ($P < 0.05$) among technologies

Revenue generation varied with local market conditions and policy support. Facilities receiving waste processing fees (average \$35-65 ton^{-1}) and carbon credit payments showed significantly improved economic performance. Product sales revenue averaged \$0.42-0.78 kg^{-1} P_2O_5 and \$0.28-0.45 kg^{-1} K_2O, representing 65-85% of conventional fertilizer prices [42].

3.5 Environmental Impact Assessment

Life cycle assessment demonstrated significant environmental benefits of nutrient recovery compared to conventional fertilizer production and waste disposal (Table 4). Global warming potential reductions ranged from 45% for composting systems to 67% for integrated recovery facilities.

Table 4: Environmental Impact Comparison (per kg plant-available nutrient)

Impact Category	Conventional	Integrated	Anaerobic	Pyrolysis	Chemical	Composting
	Fertilizer	Recovery	Digestion	Recovery	Extraction	Recovery
GWP (kg CO_2-eq)	3.8 ± 0.6^{a}	1.3 ± 0.4^{b}	1.7 ± 0.5^{b}	1.9 ± 0.6^{b}	2.2 ± 0.7^{c}	2.1 ± 0.5^{c}
EP (g PO_4-eq)	12.4 ± 2.8^{a}	3.2 ± 1.1^{b}	4.1 ± 1.4^{b}	3.8 ± 1.3^{b}	5.7 ± 1.9^{c}	4.9 ± 1.6^{c}
AP (g SO_2-eq)	8.9 ± 1.7^{a}	3.1 ± 0.9^{b}	3.8 ± 1.2^{b}	4.2 ± 1.4^{b}	5.1 ± 1.7^{c}	4.6 ± 1.3^{c}
CED (MJ)	45.7 ± 8.2^{a}	18.3 ± 5.4^{b}	22.1 ± 6.7^{b}	28.9 ± 8.1^{c}	34.2 ± 9.3^{d}	15.7 ± 4.2^{e}

GWP = Global Warming Potential; EP = Eutrophication Potential; AP = Acidification Potential; CED = Cumulative Energy Demand Different letters indicate significant differences ($P < 0.05$) among systems

Eutrophication potential showed the most dramatic improvements, with 52-74% reductions across all recovery technologies. This benefit primarily results from prevented nutrient losses to water bodies through proper waste management and nutrient recycling [43].

3.6 Scaling Potential and Global Impact

Techno-economic modeling suggests significant potential for global P and K recovery from agricultural wastes. Current global agricultural waste generation could theoretically yield 2.8-4.1 Mt P and 8.7-12.4 Mt K annually through optimized recovery systems, representing 18-26% of current fertilizer P demand and 15-21% of K demand [44].

Regional analysis reveals highest recovery potential in Asia (35% of global potential), followed by Europe (22%) and North America (18%). Implementation scenarios suggest that achieving 50% of technical potential would require investment of \$180-240 billion globally over 15-20 years [45].

3.7 Implementation Barriers and Quality Control Challenges

Analysis of implementation barriers revealed regulatory frameworks as the primary constraint, with 67% of facilities reporting compliance challenges. Product standardization and certification systems were identified as critical needs for market development [46].

Quality control issues included heavy metal contamination in 23% of recovered products, primarily from industrial waste streams. Pathogen presence was detected in 15% of facilities lacking adequate treatment controls. Seasonal variation in waste composition created challenges for consistent product quality [47].

4. Discussion

The comprehensive analysis of P and K recovery from agricultural wastes demonstrates substantial potential for advancing circular soil management while addressing critical sustainability challenges in modern agriculture. The achieved recovery efficiencies of 72-89% for P and 68-83% for K across diverse technological approaches indicate that nutrient recovery can make meaningful contributions to fertilizer supply chains while reducing environmental impacts [48].

The superior performance of integrated recovery systems reflects the benefits of combining multiple treatment processes to optimize nutrient capture and product quality [49]. The synergistic effects observed in these systems suggest that future technology development should prioritize integrated approaches rather than single-process solutions. However, the higher capital costs and complexity of integrated systems may limit adoption in resource-constrained settings [50].

Technology-specific performance patterns reveal important insights for system selection and optimization. Anaerobic digestion's excellence in P recovery through struvite precipitation demonstrates the value of controlled chemical environments for selective nutrient capture [51]. Conversely, thermochemical processes' superiority in K recovery reflects the thermal concentration mechanisms that effectively retain potassium compounds while volatilizing other components [52].

The demonstrated agronomic effectiveness of recovered products (RAE 85-95%) provides strong evidence for their potential to substitute conventional fertilizers in many applications [53]. The slightly lower performance compared to mineral fertilizers may reflect differences in nutrient release patterns and bioavailability, suggesting opportunities for product formulation improvements [54]. The enhanced residual effects observed with recovered products indicate potential advantages for long-term soil fertility management [55].

Economic analysis reveals that scale economies are critical for financial viability, with break-even points typically requiring processing capacities of 15,000-25,000 tons annually [56]. This scale requirement may favor centralized processing facilities serving multiple farms or regional waste collection systems [57]. The economic sensitivity to policy support mechanisms highlights the importance of government incentives for early technology adoption and market development [58].

The substantial environmental benefits demonstrated through LCA provide compelling arguments for policy support and investment in recovery technologies [59]. The 45-67% reduction in global warming potential and 52-74% reduction in eutrophication potential represent significant contributions to agricultural sustainability goals [60]. These benefits should be incorporated into environmental accounting systems and carbon credit mechanisms to improve economic competitiveness [61].

Quality control challenges, particularly heavy metal contamination and pathogen presence, underscore the importance of appropriate technology selection and operational controls [62]. The higher contamination rates in industrial food processing wastes suggest the need for source-specific treatment approaches and potentially separate product certification systems [63]. Pathogen elimination through thermal treatment or controlled composting represents well-established solutions that require consistent implementation [64].

The global scaling analysis suggests that P and K recovery could address 15-26% of current fertilizer demand, representing a substantial contribution to nutrient security [65]. However, realizing this potential requires coordinated efforts in technology deployment, infrastructure development, and market formation [66]. The regional concentration of recovery potential in Asia and Europe suggests prioritization of investment and policy development in these regions [67].

Implementation barriers reveal the critical importance of regulatory frameworks and market development for successful technology adoption[68]. The current patchwork of regulations across jurisdictions creates uncertainty and compliance costs that impede commercial deployment[69]. Harmonization of standards and certification systems would facilitate trade and market development for recovered products [70].

The seasonal variation in waste composition presents ongoing challenges for consistent product quality and supply chain management [71]. Storage systems, blending operations, and flexible processing capabilities may be necessary to address these variations [72]. Quality assurance systems must account for temporal and spatial variation in feedstock characteristics [73].

Future research priorities should focus on technology optimization for specific feedstock types, development of mobile or modular processing systems for smaller-scale applications, and integration of recovery systems with precision agriculture technologies [74]. Advanced monitoring and control systems could improve process efficiency and product consistency while reducing operational costs [75].

Policy implications include the need for supportive regulatory frameworks, economic incentives for early adopters, and investment in infrastructure development [76]. Integration of recovery targets into agricultural and waste management policies could drive systematic implementation [77]. Carbon pricing mechanisms and nutrient trading systems could provide economic incentives for recovery system development [78].

5. Conclusion

This comprehensive assessment demonstrates that phosphorus and potassium recovery from agricultural wastes represents a viable and beneficial component of circular soil management systems. The achieved recovery efficiencies of 72-89% for P and 68-83% for K, combined with agronomic effectiveness comparable to conventional fertilizers (RAE 85-95%), provide strong evidence for the technical feasibility of nutrient recovery technologies.

Key findings establish that integrated recovery systems achieve superior performance through synergistic treatment processes, while technology selection must align with specific feedstock characteristics and local conditions. Anaerobic digestion with struvite precipitation optimizes P recovery, while thermochemical processes excel in K concentration and recovery. Economic viability requires processing scales of 15,000-25,000 tons annually, with payback periods of 4.2-7.8 years depending on technology type and policy support.

Environmental benefits are substantial, with 45-67% reductions in global warming potential and 52-74% reductions in eutrophication potential compared to conventional fertilizer production. These impacts, combined with waste diversion benefits, support strong environmental arguments for recovery system implementation. Life cycle assessment results demonstrate that nutrient recovery contributes meaningfully to agricultural sustainability goals while addressing waste management challenges.

Global scaling potential suggests recovery of 2.8-4.1 Mt P and 8.7-12.4 Mt K annually from agricultural wastes, representing 15-26% of current fertilizer demand. This potential indicates significant opportunities for reducing dependency on finite mineral resources while closing nutrient loops in agricultural systems. Regional analysis reveals highest potential in Asia and Europe, suggesting priority areas for investment and policy development.

Implementation challenges include regulatory barriers, quality control requirements, and market development needs. Heavy metal contamination (23% of products) and pathogen presence (15% of facilities) require careful attention to feedstock selection and treatment processes. Standardization of product quality criteria and certification systems is essential for market acceptance and trade facilitation.

The economic analysis reveals that policy support mechanisms, including waste processing fees, carbon credits, and regulatory incentives, significantly improve financial viability. Government policies promoting circular economy principles and nutrient recovery can accelerate adoption while generating broader societal benefits through improved resource efficiency and environmental protection.

Quality assurance systems must address temporal and spatial variation in agricultural waste composition while ensuring consistent product performance. Advanced monitoring technologies, flexible processing capabilities, and strategic storage systems can help manage feedstock variability and maintain product quality standards.

Future research should prioritize technology optimization for specific regional conditions, development of modular processing systems for smaller-scale applications, and integration with precision agriculture technologies. Advanced process control systems and artificial intelligence applications could improve efficiency while reducing operational costs and quality variability.

Policy development should focus on creating supportive regulatory frameworks that recognize recovered products as legitimate fertilizer alternatives while maintaining appropriate safety standards. Economic incentives, infrastructure investment, and international cooperation in standards development would facilitate broader adoption of recovery technologies.

The transition toward circular soil management through nutrient recovery requires coordinated efforts among technology developers, agricultural producers, waste managers, and policymakers. Success depends on aligning economic incentives with environmental benefits while ensuring product quality and safety standards. The evidence presented demonstrates that these objectives are achievable through appropriate technology selection, scale optimization, and supportive policy frameworks.

This study establishes nutrient recovery from agricultural wastes as a cornerstone technology for sustainable agriculture, contributing to resource security, environmental protection, and circular economy development. The quantified benefits and identified implementation pathways provide a foundation for investment decisions, policy development, and strategic planning in agricultural sustainability initiatives.

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