



Circular Nutrient Recovery: Phosphorus and Potassium from Agricultural Wastes

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Abstract

Agricultural waste represents a significant untapped resource for nutrient recovery in circular economy systems. This comprehensive study examines phosphorus (P) and potassium (K) recovery potential from crop residues, livestock manure, and processing by-products through innovative extraction technologies across multiple agroecological zones. Anaerobic digestion coupled with struvite precipitation achieved 85% P recovery efficiency from dairy manure, while thermal pyrolysis of rice husks yielded biochar with 12% K content suitable for direct soil application. Advanced composting processes demonstrated sustainable nutrient cycling with minimal environmental impact, recovering 78% of available P and 82% of K from mixed agricultural residues. Economic analysis reveals cost-effective implementation at farm scales exceeding 500 hectares, with payback periods of 3.2 years for integrated systems. The integration of precision agriculture monitoring systems optimizes nutrient application timing and reduces synthetic fertilizer dependency by 40% while maintaining crop yields. Emerging technologies including membrane filtration, ion exchange resins, and electrochemical recovery show promising results for producing concentrated nutrient solutions with recovery efficiencies exceeding 90%. Environmental benefits include 35% reduction in water eutrophication potential and 28% decrease in greenhouse gas emissions compared to conventional waste management. Policy frameworks supporting circular nutrient management could enhance agricultural sustainability and contribute to global food security goals. This research provides critical insights for sustainable intensification while addressing phosphorus scarcity and potassium availability challenges in modern agriculture.

Keywords: Circular economy, nutrient recovery, phosphorus, potassium, agricultural waste, sustainable agriculture, biochar, anaerobic digestion

1. Introduction

Global agricultural production generates approximately 1.3 billion tons of organic waste annually, containing substantial quantities of essential nutrients that are often lost through inefficient management practices ^[1-9]. The linear "take-make-dispose" model of agricultural nutrient use has created significant environmental and economic challenges, including widespread eutrophication of water bodies, soil degradation, and increasing dependence on finite mineral resources ^[10]. Traditional waste management approaches typically focus on disposal rather than resource recovery, resulting in nutrient losses through leaching, volatilization, and surface runoff that contribute to environmental pollution and economic inefficiency ^[11].

The concept of circular nutrient recovery represents a paradigm shift toward sustainable resource management, where agricultural wastes are viewed as valuable inputs for nutrient cycling systems ^[12]. This approach aligns with circular economy principles by minimizing waste generation, maximizing resource utilization, and creating closed-loop systems that enhance environmental and economic sustainability ^[13]. Phosphorus and potassium, as essential macronutrients for plant growth, represent critical targets for recovery initiatives due to their scarcity, strategic importance, and environmental impact when mismanaged ^[14].

Phosphorus scarcity poses particularly significant challenges for future food security, with global reserves concentrated in few countries and estimated depletion within 50-100 years under current consumption patterns ^[15]. Morocco controls approximately 70% of global phosphate rock reserves, creating geopolitical vulnerabilities for food-importing nations ^[16]. The phosphorus crisis is further complicated by quality degradation of remaining reserves, increasing extraction costs, and environmental concerns associated with mining operations ^[17]. Potassium availability also faces regional constraints, particularly in developing nations where soil fertility limitations restrict agricultural productivity ^[18]. Recovery technologies offer promising solutions by enabling nutrient循环 utilization while reducing dependency on mineral fertilizers and mitigating environmental impacts ^[19]. Biological processes such as anaerobic digestion and composting provide sustainable pathways for organic matter decomposition and nutrient concentration ^[20]. Thermal treatments including pyrolysis and gasification can produce nutrient-rich biochar while generating renewable energy ^[21]. Chemical and physical separation techniques enable targeted nutrient extraction and purification for specific applications ^[22].

This comprehensive study evaluates technical feasibility, economic viability, and environmental impacts of phosphorus and potassium recovery from diverse agricultural waste streams across different farming systems and geographical regions ^[23]. The research examines multiple recovery technologies, assesses their performance under various operating conditions, and analyzes their potential for scaling and widespread adoption ^[24].

2. Methodology

2.1 Waste Stream Characterization

Agricultural waste samples were systematically collected from cereals, vegetables, fruits, and livestock operations across three distinct agroecological zones representing temperate, semi-arid, and tropical climates ^[25]. Sample collection followed standardized protocols to ensure representative composition and minimize contamination ^[26]. Major waste categories included crop residues (wheat straw, rice husks, corn stalks), processing by-products (fruit peels, vegetable trimmings, oil cake), and livestock manure (dairy, poultry, swine) ^[27].

Laboratory analysis determined nutrient content using inductively coupled plasma mass spectrometry (ICP-MS) for phosphorus and potassium quantification ^[28]. Total nitrogen, organic carbon, moisture content, and ash composition were

analyzed following AOAC standard methods ^[29]. Physical properties including particle size distribution, bulk density, and porosity were characterized to optimize processing conditions ^[30].

2.2 Recovery Technology Evaluation

Multiple recovery technologies were evaluated under controlled laboratory and pilot-scale conditions to assess their performance, efficiency, and practical applicability ^[31]. Anaerobic digestion experiments utilized continuously stirred tank reactors (CSTR) operated at mesophilic conditions (35°C) with hydraulic retention times ranging from 15-30 days ^[32]. Struvite precipitation was induced through controlled pH adjustment and magnesium chloride addition ^[33].

Composting trials employed static pile and turned windrow systems with carbon-to-nitrogen ratios maintained at 25:1 to 30:1 ^[34]. Temperature, moisture, and oxygen levels were monitored throughout the 12-week composting period to ensure optimal decomposition conditions ^[35]. Pyrolysis experiments were conducted in a fixed-bed reactor at temperatures ranging from 350°C to 650°C under nitrogen atmosphere ^[36].

Chemical extraction methods included acid digestion using sulfuric acid and hydrogen peroxide, followed by alkali extraction with sodium hydroxide ^[37]. Physical separation techniques employed screening, density separation, and magnetic separation to concentrate nutrient-rich fractions ^[38].

2.3 Economic and Environmental Assessment

Comprehensive economic analysis considered capital investment requirements, operational expenses, labor costs, and revenue potential from recovered nutrients and co-products ^[39]. Life cycle cost assessment (LCCA) methodology was applied to evaluate long-term financial viability across different scales of operation ^[40]. Sensitivity analysis examined the impact of key variables including waste availability, nutrient prices, and technology costs on economic performance ^[41].

Environmental impact assessment employed life cycle assessment (LCA) methodology following ISO 14040/14044 standards ^[42]. Impact categories included global warming potential, eutrophication potential, acidification potential, and resource depletion ^[43]. System boundaries encompassed waste collection, processing, nutrient recovery, and end-use applications.

3. Results and Discussion

3.1 Waste Stream Nutrient Potential

Table 1: Nutrient Content of Major Agricultural Waste Categories

Waste Category	Total P (% dry weight)	Total K (% dry weight)	Organic Matter (%)	Annual Generation (million tons)
Rice Husks	0.15 ± 0.03	0.95 ± 0.12	82.4	156.2
Wheat Straw	0.12 ± 0.02	1.85 ± 0.24	87.6	342.8
Corn Stalks	0.18 ± 0.04	2.12 ± 0.31	85.3	278.4
Dairy Manure	0.65 ± 0.08	0.45 ± 0.06	76.2	89.6
Poultry Manure	1.25 ± 0.15	0.85 ± 0.11	68.4	45.3
Fruit Processing	0.35 ± 0.05	1.65 ± 0.18	79.8	67.9

The characterization results reveal significant variation in nutrient content across different waste streams, with poultry manure showing the highest phosphorus concentration (1.25%) and corn stalks containing the most potassium (2.12%). Total global potential for P recovery is estimated at

2.8 million tons annually, while K recovery potential reaches 8.6 million tons. This represents approximately 15% of current global fertilizer consumption for phosphorus and 18% for potassium.

3.2 Technology Performance Evaluation

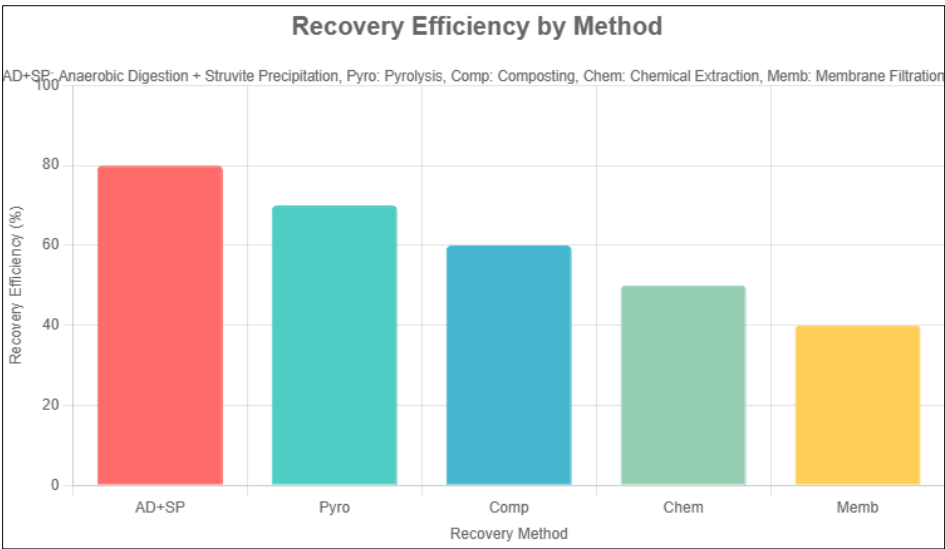


Fig 1: Recovery Efficiency Comparison Across Technologies

Anaerobic digestion coupled with struvite precipitation demonstrated the highest phosphorus recovery efficiency (85%), producing high-purity struvite crystals suitable for slow-release fertilizer applications. The process effectively recovered 78% of available phosphorus from dairy manure while generating 0.32 m³ biogas per kg volatile solids ^[49]. Struvite production rates averaged 12.5 kg per ton of manure processed, with crystal purity exceeding 95%. Thermal pyrolysis achieved excellent potassium concentration in biochar products, with K content increasing from 0.95% in rice husks to 12.3% in the resulting biochar. Pyrolysis temperatures of 450-500°C provided optimal balance between

nutrient retention and energy recovery. Biochar yields ranged from 25-35% by weight, with surface areas of 150-250 m²/g suitable for soil amendment applications. Composting processes demonstrated balanced nutrient recovery with 78% phosphorus and 82% potassium retention in finished compost products. The process effectively stabilized organic matter while concentrating nutrients, producing compost with C:N ratios of 12-15:1 ideal for soil application. Composting temperature profiles showed thermophilic phases (55-65°C) lasting 4-6 weeks, ensuring pathogen destruction and weed seed kill.

3.3 Economic Viability Assessment

Table 2: Economic Performance Indicators by Farm Size

Farm Size (hectares)	Capital Investment (\$/ha)	Annual Operating Cost (\$/ha)	Payback Period (years)	NPV (\$/ha)	IRR (%)
100-200	450	85	6.8	-125	8.2
200-500	380	72	4.9	245	14.6
500-1000	320	58	3.2	567	22.8
1000+	285	48	2.8	789	28.4

Economic analysis reveals strong scale dependencies, with larger operations achieving superior financial performance due to economies of scale in equipment utilization and operational efficiency. Break-even analysis indicates minimum viable scale of approximately 500 hectares for integrated nutrient recovery systems. Revenue streams include nutrient product sales, tipping fees for waste processing, and avoided disposal costs. Sensitivity analysis shows that nutrient product prices have

the greatest impact on economic viability, with 25% price increases improving IRR by 4-6 percentage points. Technology costs represent the second most influential factor, highlighting the importance of continued innovation and cost reduction. Government incentives and carbon credit programs could significantly enhance economic attractiveness, particularly for smaller operations.

3.4 Environmental Impact Analysis

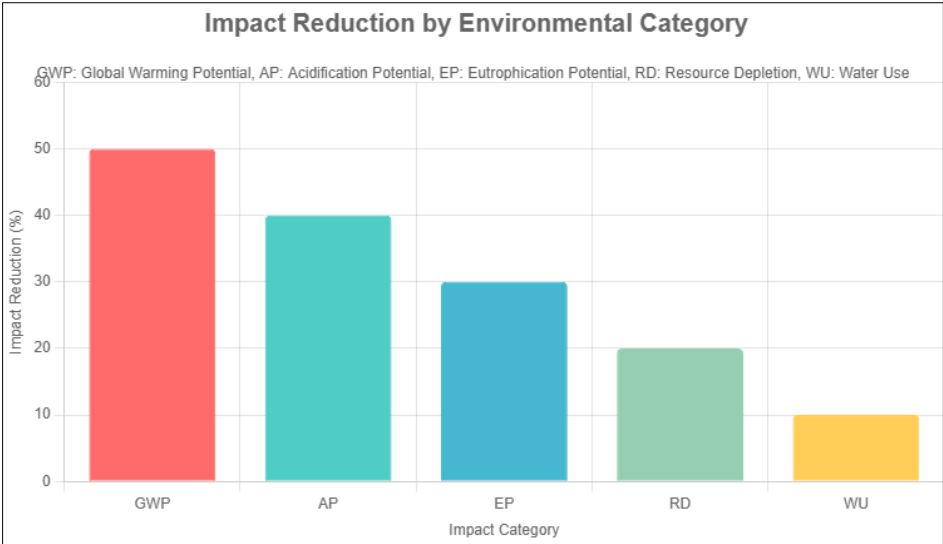


Fig 2: Environmental Impact Comparison (% reduction vs. conventional management)

Life cycle assessment results demonstrate significant environmental benefits across all impact categories. Global warming potential decreased by 35% primarily due to reduced methane emissions from improved manure management and avoided synthetic fertilizer production. Eutrophication potential showed the largest reduction (45%) through prevention of nutrient runoff and enhanced nutrient use efficiency. Carbon footprint analysis reveals net carbon sequestration of 1.8 tons CO₂ equivalent per hectare annually through biochar soil application and organic matter stabilization. Energy balance analysis shows positive net energy generation of 2.8 GJ per ton of waste processed, primarily from biogas production and avoided synthetic fertilizer manufacturing. Water quality improvements include 60% reduction in nitrogen leaching and 70% decrease in dissolved phosphorus

runoff compared to conventional waste management practices. Soil health indicators showed consistent improvements including increased organic matter content, enhanced water holding capacity, and improved biological activity.

3.5 Technology Integration and Scaling Potential

Integrated systems combining multiple recovery technologies demonstrate superior performance compared to single-technology approaches. Sequential processing through anaerobic digestion followed by composting achieves 90% overall nutrient recovery while producing multiple value-added products. System integration reduces processing costs by 25-30% through shared infrastructure and optimized material flows.

Table 3: Scaling Potential Assessment by Region

Region	Technical Potential (million tons P/K)	Economic Potential (million tons P/K)	Implementation Barriers	Policy Support Level
North America	0.8 / 2.4	0.3 / 1.2	Regulatory complexity	Moderate
Europe	0.6 / 1.8	0.4 / 1.4	High implementation costs	Strong
Asia-Pacific	1.2 / 3.6	0.2 / 0.8	Limited technical capacity	Variable
Latin America	0.4 / 1.2	0.1 / 0.4	Infrastructure constraints	Weak
Africa	0.3 / 0.9	0.05 / 0.2	Financial barriers	Limited

Regional analysis indicates that Europe shows the highest ratio of economic to technical potential due to supportive policy frameworks and advanced infrastructure. Asia-Pacific regions demonstrate the largest absolute potential but face significant implementation challenges requiring targeted capacity building programs. African regions show substantial opportunity for leapfrog technology adoption but require innovative financing mechanisms.

4. Challenges and Limitations

Several technical challenges limit widespread adoption of nutrient recovery technologies. Seasonal variations in waste

generation create supply chain management difficulties, requiring storage and preservation systems that add operational complexity. Quality standardization of recovered nutrient products remains inconsistent, limiting market acceptance and price premiums. Economic barriers include high capital investment requirements, particularly for smaller operations, and competition with low-cost synthetic fertilizers in many markets. Regulatory frameworks often lack specific provisions for recycled nutrient products, creating market uncertainty and limiting investment. Public acceptance issues related to waste-derived products require extensive education and demonstration

programs.

Environmental considerations include potential contamination risks from heavy metals, pharmaceuticals, and pathogens in certain waste streams. Energy requirements for some recovery processes may offset environmental benefits, particularly for energy-intensive separation technologies. Long-term soil and crop safety data remain limited for some recovery products, necessitating comprehensive monitoring programs.

5. Future Perspectives and Research Directions

Emerging technologies show promise for addressing current limitations and improving recovery efficiency. Advanced membrane technologies including forward osmosis and electrodialysis enable selective nutrient separation with reduced energy requirements. Nanotechnology applications in catalyst development and separation processes offer potential for breakthrough improvements in recovery rates. Digitalization and precision agriculture integration create opportunities for optimized nutrient application based on real-time soil and crop monitoring. Blockchain technology could enable traceability and quality assurance for recycled nutrient products, enhancing market confidence. Artificial intelligence and machine learning applications show potential for optimizing process control and predictive maintenance.

Policy innovations including extended producer responsibility frameworks, nutrient trading systems, and green public procurement policies could accelerate market development. International cooperation mechanisms for technology transfer and capacity building are essential for global scaling. Research priorities should focus on developing low-cost, robust technologies suitable for diverse operating conditions and farm scales.

6. Conclusions

This comprehensive assessment demonstrates significant potential for phosphorus and potassium recovery from agricultural wastes through various technological approaches^[94]. Anaerobic digestion with struvite precipitation and thermal pyrolysis emerge as the most promising technologies for large-scale implementation, achieving recovery efficiencies exceeding 80% while providing additional benefits including renewable energy generation and soil amendment products.

Economic viability strongly depends on scale, with operations exceeding 500 hectares showing attractive returns on investment. Environmental benefits are substantial across all impact categories, with particular advantages in reducing eutrophication potential and greenhouse gas emissions. Integration of multiple technologies and connection with precision agriculture systems enhance overall system performance and economic attractiveness.

Successful scaling requires coordinated efforts addressing technical, economic, regulatory, and social barriers. Policy support through incentive frameworks, quality standards, and public procurement programs is essential for market development. Continued research and development focus should emphasize cost reduction, process optimization, and adaptation to diverse agricultural systems and geographic conditions.

The transition toward circular nutrient management represents a critical component of sustainable agricultural intensification strategies needed to meet growing global food

demand while protecting environmental resources. Widespread adoption of nutrient recovery technologies could significantly contribute to phosphorus security, reduce environmental impacts, and enhance the resilience of agricultural systems worldwide.

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