



MICRO-CREDENTIAL

CIRCULAR ECONOMY FOR LAND AND WASTE MANAGEMENT

9.- Circular Economy in Agriculture and Rural Areas

Manure and biomass utilization

CELWS-W09-V02

From Waste to Wealth: The Circular Economy of Manure and Biomass in Agriculture

A deep dive into how agricultural waste streams — manure, digestate, and biomass — can be transformed into renewable energy, recycled nutrients, and sustainable fertilizers, closing the loop on one of farming's greatest challenges.



The Challenge: A Growing Problem



Global livestock production generates staggering volumes of organic waste every year. Without strategic intervention, this waste becomes a source of pollution, greenhouse gas emissions, and wasted resources. Understanding the scale and complexity of the problem is the first step toward transformative solutions.

The Scale of Agricultural Waste

These interconnected pressures — volume, pollution, and energy dependency — make agricultural waste management one of the defining sustainability challenges of our time.

1 Billion+ Tons

Livestock production generates over one billion tons of digestate annually across the globe — a figure that continues to rise with growing food demand.

Transport & Pollution

Raw manure presents significant logistical challenges: high transport energy costs, environmental pollution of waterways, and serious public health risks from pathogens and nitrates.

Energy-Intensive Alternatives

Traditional nitrogen fertilizer production via the Haber-Bosch process is highly energy-intensive and a major contributor to global greenhouse gas emissions.

The Environmental Burden of Conventional Fertilizers

Why This Matters

The Haber-Bosch process, while revolutionary for global food production, remains almost entirely dependent on fossil fuels for ammonia synthesis. Natural gas serves as both the feedstock and the energy source, making synthetic nitrogen fertilizer one of the most carbon-intensive agricultural inputs in use today.

Every ton of nitrogen produced via this route carries a heavy carbon footprint — underscoring the urgent need for circular, manure-derived alternatives that recover and recycle nitrogen already present in agricultural systems.

A Resource, Not a Waste



Reframing manure and biomass from liabilities into assets is the foundational shift of the circular agricultural economy. What was once considered a disposal problem is increasingly recognized as a rich source of nutrients, energy, and organic matter — waiting to be unlocked by the right technologies and policy frameworks.

The Solution: Unlocking Value Through Circularity

A suite of complementary technologies — anaerobic digestion, mechanical separation, pyrolysis, and wastewater valorisation — offers a powerful toolkit for transforming agricultural waste streams into valuable inputs for the food and energy systems.





Step 1: Mechanical Separation

Biowastes are mechanically separated into **liquid fractions** (rich in soluble nitrogen and potassium) and **solid fractions** (concentrated in phosphorus and organic matter). This separation allows each fraction to be managed and transported according to its properties and local agronomic needs.



Step 2: Pyrolysis into Biochar

The solid fraction undergoes **pyrolysis** — thermal decomposition at high temperatures in the absence of oxygen — converting it into **biochar**. Biochar is a stable, carbon-rich material that can store phosphorus and improve soil health, making it ideal for long-distance transport as a concentrated nutrient carrier.

What Is Sewage Sludge?

Sewage sludge is the semi-solid by-product of wastewater treatment processes. Although often overlooked, it contains significant concentrations of organic matter, nitrogen, phosphorus, and energy — making it a valuable resource within a circular economy framework.

Globally, wastewater treatment plants generate hundreds of millions of tons of sludge annually, much of which is currently landfilled or incinerated — a waste of both resources and potential.

Sewage sludge valorisation represents one of the most scalable opportunities to integrate urban and rural nutrient cycles into a coherent circular system.

Biogas + Digestate = Renewable Energy + Recycled Nutrients

Anaerobic digestion plants sit at the heart of the circular agricultural economy, simultaneously generating clean energy and recovering nutrients that would otherwise be lost to the environment. Each ton of organic waste processed represents both a reduction in emissions and a step toward fertilizer independence.



Innovations in Nutrient Management

Cutting-edge research is delivering new frameworks, field-validated data, and practical decision tools that enable farmers and policymakers to deploy recycled nutrients safely, efficiently, and with measurable agronomic and environmental benefit.



Performance-Based Criteria for Digestate Use

The Research Breakthrough (2025)

New research published in 2025 proposes a **performance-based criteria framework** for the safe and circular use of digestate in agriculture. Rather than relying solely on source-based restrictions, this approach evaluates digestate quality by its measurable effects on crops and soil.

The framework focuses on three key chemical thresholds that reliably predict phytotoxicity risk:

- **Total Ammonia Nitrogen (TAN)** — the primary driver of plant toxicity at high concentrations
- **Potassium (K)** — linked to osmotic stress in sensitive crops
- **Boron (B)** — a micronutrient that becomes toxic at elevated levels

Decision-Ready Framework

The framework provides farmers and agronomists with clear, actionable guidance on when and how to apply digestate safely. It incorporates mitigation strategies — such as dilution, incorporation timing, and crop rotation — to maintain nitrogen use efficiency while protecting crop establishment.

The Promise

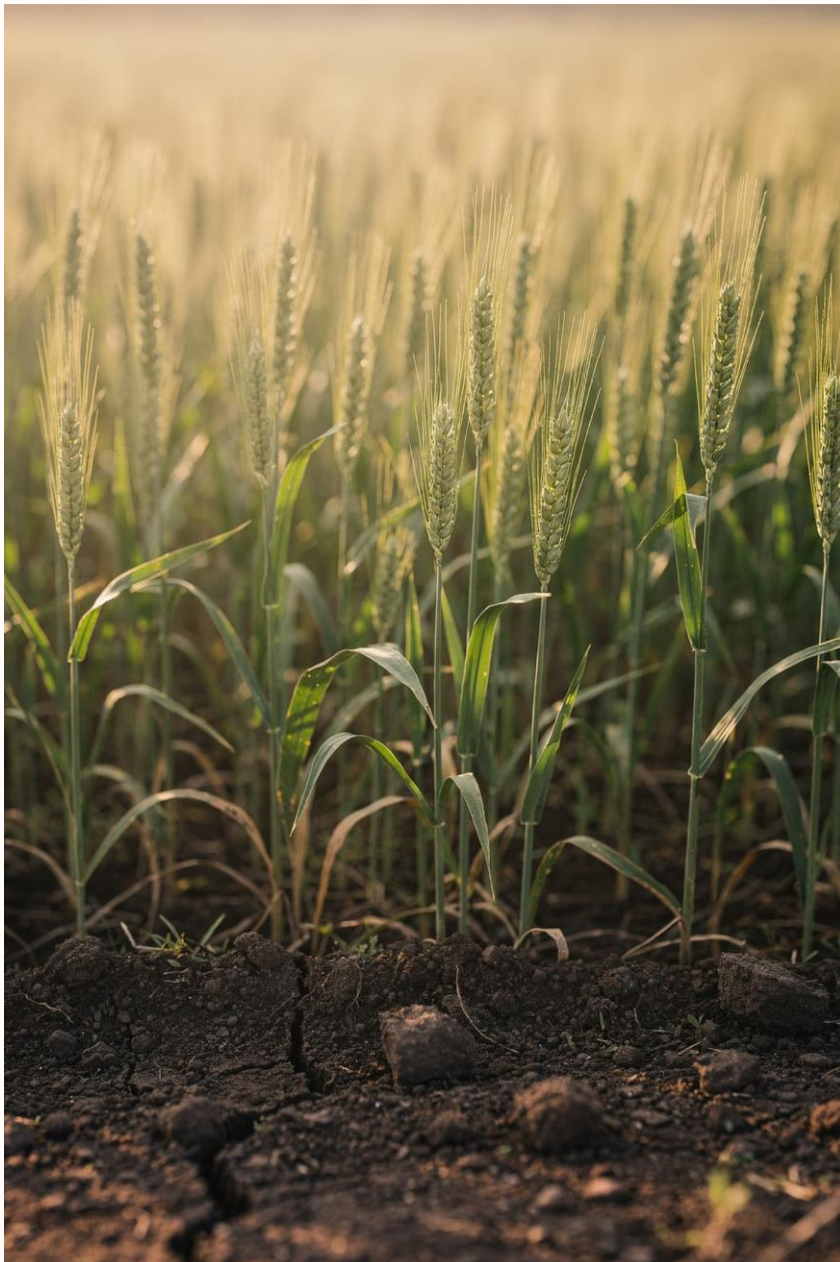
Biochars produced from the solid fractions of separated slurries and digestates offer a novel pathway for **long-distance phosphorus transport**. By concentrating phosphorus into a stable, low-weight, high-value material, biochar enables nutrient redistribution from phosphorus-surplus regions to phosphorus-deficient agricultural areas — a key goal of circular nutrient management.

The Caveats

Early field trials conducted in 2026, however, reveal important nuances. No immediate agronomic benefits — including yield improvements or nitrous oxide (N₂O) mitigation — were observed in the first growing season after biochar application. More critically, some biochars actually **reduced crop yield**, pointing to feedstock-dependent effects that require careful characterization and selection before field use.

Closing the Loop: From Field to Farm and Back

The vision of truly circular agriculture is one where every nutrient extracted from the soil by a crop is ultimately returned to that soil — processed, refined, and made more efficient through technology. Manure, digestate, and biomass are not endpoints. They are waypoints in a continuous cycle of renewal.



Energy Efficiency and Cost Reduction Reduction

Beyond nutrient recovery, circular manure management delivers substantial energy savings and cost reductions across the agricultural value chain — making the economic case for transition as compelling as the environmental one.



Across all these technologies, manure processing **significantly reduces energy demand** for fertilizer application and transport compared to handling raw manure, delivering both economic savings and a lower carbon footprint per unit of nutrient delivered to the field.

Struvite Precipitation

A crystallization process that recovers phosphorus and nitrogen from liquid manure fractions as **struvite** (magnesium ammonium phosphate) — a slow-release fertilizer with low transport costs and minimal processing energy requirements.

Ammonia Stripping

Volatilizes ammonia from liquid digestate under controlled conditions, concentrating nitrogen into an ammonium sulfate solution that can be applied directly as a fertilizer or further refined — with significantly lower handling costs than raw slurry.

Reverse Osmosis Concentration

Membrane-based technology that concentrates nutrients in the liquid fraction, reducing volume — and thus transport costs — while producing a high-quality, stable nutrient product with low energy inputs relative to synthetic fertilizer production.

The Opportunity

Every kilogram of nitrogen recovered from manure and converted into a plant-available fertilizer is a kilogram that does not need to be synthesized via the Haber-Bosch process. At scale, this displacement represents a **substantial reduction** in both energy consumption and greenhouse gas emissions associated with ammonia synthesis.

The global potential is significant: if just 50% of recoverable nitrogen in agricultural waste streams were captured and recycled, it could offset tens of millions of tons of synthetic nitrogen production annually.

Climate and Energy Benefits

- Reduces fossil fuel demand for fertilizer manufacturing
- Lowers direct CO₂ and N₂O emissions from agricultural systems
- Decreases nitrate leaching and eutrophication of waterways
- Improves national nutrient self-sufficiency and food security
- Supports EU Green Deal and Farm-to-Fork Strategy targets for sustainable fertilizer use

A Greener Path to Fertilization



The contrast between conventional and circular fertilizer production pathways could not be starker. Where the Haber-Bosch route demands vast quantities of fossil energy and emits large volumes of CO₂, manure-based systems recover nutrients already cycling within the food system — with a fraction of the energy cost and a net positive impact on soil health and climate.

Overcoming Challenges and Fostering Acceptance

Technology alone is not sufficient. Widespread adoption of circular nutrient management requires addressing real concerns about safety and contamination, building farmer confidence through transparent evidence, and creating the social and regulatory conditions for a just and effective transition.





Heavy Metals

Cadmium, lead, mercury, and other heavy metals can accumulate in sewage sludge from industrial and household sources. Long-term soil accumulation poses risks to food safety and ecosystem health, requiring strict monitoring protocols.



Emerging Contaminants

Microplastics, pharmaceuticals, PFAS, and endocrine-disrupting compounds are increasingly detected in sludge. Current EU regulations do not fully address these substances, highlighting an urgent need for updated, science-based standards.

Pathogens

Inadequately treated sludge may harbor bacteria, viruses, and parasites harmful to human and animal health. Advanced treatment processes — including pasteurization and anaerobic digestion — are critical to pathogen reduction before land application.

Trust Through Transparency

Transitioning farmers from synthetic fertilizers to recycled organic materials requires more than technical evidence — it requires trust.

Performance-based thresholds and **transparent certification systems** provide farmers with clear, verifiable quality assurances that recycled nutrient products are safe and effective for their crops and soils.

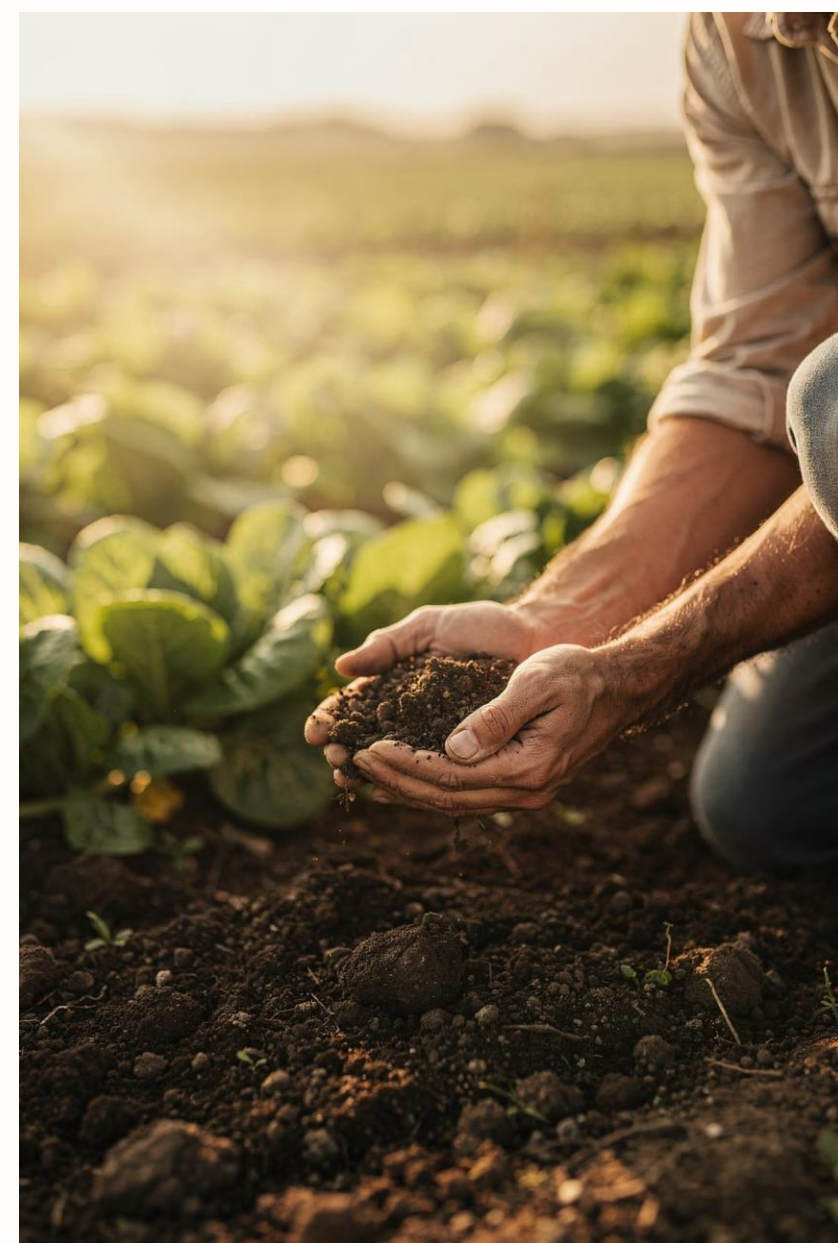
Third-party certification, standardized labeling, and publicly accessible testing data are all essential components of a trustworthy circular nutrient supply chain.

- ❏ Integrated emission mitigation strategies — covering ammonia, methane, and nitrous oxide — are crucial for ensuring that circular systems deliver genuine, measurable climate benefits alongside nutrient efficiency gains.

Demonstrating tangible economic benefits — reduced fertilizer purchase costs, lower waste disposal fees, and access to premium markets for sustainably produced crops — is key to driving voluntary adoption. Equally important is communicating the **environmental co-benefits**: reduced nitrate leaching, lower greenhouse gas emissions, and improved soil organic matter over time.

The Future of Agriculture is Circular

A circular agricultural economy is not a distant aspiration — it is a practical, technologically achievable transition that is already underway on farms across Europe and beyond. Every farmer who adopts recycled nutrient management is not just reducing costs; they are becoming a steward of the planetary resource cycles that sustain all life on Earth.



The Vision: A Resilient and Sustainable Future

Circular manure and biomass utilization is not merely an agricultural innovation — it is a systemic response to the converging crises of climate change, resource depletion, and food insecurity. The vision is bold, the technologies are proven, and the moment to act is now.





Stronger Nitrogen Use Efficiency

Manure and biomass utilization strengthens nitrogen use efficiency across the agricultural system, reducing losses to the atmosphere and waterways while maximizing the agronomic value of every kilogram of recovered nutrient.



Food System Resilience

By reducing dependence on imported synthetic fertilizers, circular nutrient systems strengthen the resilience of national food systems against geopolitical shocks, price volatility, and supply chain disruptions.



A Global Lever for Climate Action

Positioning digestate reuse as a global strategy for climate mitigation can curb agriculture's contribution to greenhouse gas emissions — one of the sector's most urgent responsibilities under international climate agreements.