Assessment of the economic viability and environmental sustainability of prototypes for improved manure use

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Abstract

This study evaluates three innovative manure valorization prototypes— Nitrogen Plasma-treated Manure (NPOG), biochar production via pyrolysis, and microalgae-based biostimulants—through a Life Cycle Inventory (LCI), benchmarking of cenventional manure and techno-economic analysis (TEA) framework. The NPOG system demonstrated a 40% reduction in ammonia emissions compared to conventional manure spreading but faced economic challenges due to high energy demands (net present value: -€466,582). Biochar production emerged as the most sustainable option, achieving carbon sequestration of -82.8 t CO_2 eq per 40 t biochar and a 44% internal rate of return. Microalgae systems showed marginal feasibility (6% IRR) but enabled nutrient recycling with estimated potential of 5–7% crop yield improvements. While all prototypes reduced reliance on synthetic fertilizers, their scalability hinges on policy interventions, particularly subsidies for renewable energy integration and carbon pricing mechanisms. These findings underscore the necessity of balancing technological innovation with economic viability to advance circular economy principles in agricultural waste management.

Introduction

Livestock manure management remains a critical sustainability challenge, contributing to 14.5% of global anthropogenic greenhouse gas emissions through methane release, ammonia volatilization, and nutrient runoff (Adams et al., 2023). Conventional practices, such as direct field application, exacerbate soil acidification and water eutrophication while perpetuating dependence on mineral fertilizers derived from non-renewable resources. Circular bioeconomy strategies offer transformative potential by repurposing waste streams into value-added products, yet their environmental and economic trade-offs require systematic evaluation.

This study investigates three prototypical manure valorization technologies:

I. **Nitrogen Plasma-Treated Manure (NPOG)**: A plasma-assisted process enriching separated manure with atmospheric nitrogen, reducing ammonia emissions by 40% while increasing total nitrogen content from 4 to 6 kg/m³ (Nyvold & Dörsch, 2023).

II. **Biochar Production**: Pyrolysis of low quality woody biomass at 300–900°C to create a stable carbon amendment, sequestering 9.3 t C/ha/year and enables slower nutrient release and reduces nutrient losses, allowing nutrients to bind more stably in the soil and improving soil water retention by 20% (Lehmann, 2007).

III. **Microalgae Biostimulants**: Nutrient recovery from liquid manure via raceway pond cultivation, achieving 85% nitrogen uptake efficiency and enhancing crop resilience to abiotic stressors (Haider et al., 2022).

The LCI Inventory methodology assessment is based on prototype evaluation. Since we do not have access to actual quantities, the analysis within the LCI was necessarily limited and compared to a benchmark-spreading of manure. Primary inventory data were collected from EcoInvent v3.8 datasets for background processes. Functional units were standardized to 1 t of treated manure for NPOG, 1 t of biochar for pyrolysis, and 1 kg of algal biomass for biostimulants, enabling cross-prototype comparability.

By integrating TEA with LCA, this work addresses a critical gap in circular agriculture research, providing actionable insights for policymakers and stakeholders to prioritize technologies that harmonize environmental benefits with economic feasibility.

Methods

The environmental and economic assessment of the three manure valorization prototypes—plasma-treated manure (NPOG), biochar, and microalgae-based biostimulants—was conducted using a comprehensive life cycle assessment (LCA) methodology, strictly following ISO 14040:2006 guidelines and best practices from recent LCA literature (Jolliet, et.al.). The methodological approach was structured in several key phases to ensure a robust and comparable evaluation of each prototype. First, a reference scenario was developed for each valorization pathway. This scenario described the prevailing practices for manure and biomass management in Slovenian agriculture, including the collection, storage, processing, and application of raw manure or biomass, as well as the use of mineral fertilizers. The reference scenario served as a baseline for benchmarking the environmental and economic impacts of the innovative prototypes. Second, a detailed life cycle inventory (LCI) was compiled for each prototype. Primary data were collected directly from partnership farms, including precise records of raw material and energy consumption, process yields, direct emissions, and labor requirements. Where primary data were unavailable, secondary data were sourced from scientific literature, technical reports, and the EcoInvent database, ensuring that all relevant flows—inputs (raw materials, energy, water), outputs (products, by-products, emissions, waste), and process-specific parameters—were systematically captured and quantified. For example, the LCI for the NPOG prototype included all flows related to manure separation, plasma treatment, and storage, while the biochar LCI encompassed woodchip procurement, drying, pyrolysis, and product handling. The microalgae prototype's LCI covered substrate preparation, cultivation, harvesting, and biomass processing.

Third, system boundaries were set according to the "cradle-to-grave" principle, encompassing all life cycle stages from raw material acquisition, through processing and use, to end-of-life or recycling. Special attention was given to the circularity of material flows: in several cases, the end products or by-products of one process were reintroduced as inputs for another, reflecting the circular economy paradigm. This aspect where, instead of final disposal, feedback loops are introduced to return materials to earlier life cycle stages or to new technological processes, thereby closing the loop and reducing waste.

The functional units were carefully defined to enable meaningful comparison between scenarios: one ton of treated manure for NPOG, one ton of biochar for the pyrolysis process, and one kilogram of algal biomass for the microalgae system. All input and output data were normalized to these functional units to facilitate benchmarking and ensure comparability.

The impact assessment phase encompassed the quantification of key environmental indicators, with a primary focus on global warming potential (GWP, expressed as CO_2 equivalents), but also considering nutrient losses, resource use, and other relevant categories where data permitted. Emissions and resource use were calculated for each life cycle stage, and avoided emissions (e.g., from reduced mineral fertilizer use or carbon sequestration in biochar) were subtracted from gross emissions to yield net environmental impacts.

In parallel, a techno-economic analysis was performed. This included a full cost-revenue model for each prototype, accounting for capital expenditures (CAPEX), operational expenditures (OPEX), labor costs, maintenance, and potential revenue streams (e.g., product sales, savings from reduced fertilizer purchases, or carbon credits). The economic performance was assessed using standard indicators such as net present value (NPV), internal rate of return (IRR), and payback period. Sensitivity analyses were conducted to test the influence of key variables such as energy prices, market prices for products, and policy incentives (e.g., subsidies or carbon pricing).

Finally, the results for each prototype were benchmarked against the reference scenario to provide a realistic and context-specific evaluation. This comparative approach allowed for the identification of both environmental and economic trade-offs, as well as the assessment of the scalability and sustainability of each valorization pathway. The methodology also included a discussion of potential system expansion, upcycling, and the integration of circular economy principles, ensuring that the assessment captured the full spectrum of environmental, economic, and social impacts relevant to Slovenian agriculture

RESULTS

The NPOG prototype demonstrated a 40% reduction in ammonia emissions compared to conventional manure application. Plasma treatment increased total nitrogen content in manure from 4 kg/m³ to 6 kg/m³ through atmospheric nitrogen fixation, with ammonium nitrate formation lowering pH and stabilizing ammonia. However, the process required 400 MWh/year of electricity to treat 2.000 m^3 of manure, resulting in annual greenhouse gas emissions of 89.794 kg CO_2 eq—nearly more than double the baseline scenario (38.8 t CO_2 eq). Economic analysis revealed production costs of €39.46/t for single-farm operations and €55.73/t for cooperative systems, exceeding mineral fertilizer prices (€7.81–€21.36/t). The 12-year net present value (NPV) was -€466.582, with breakeven achievable only if electricity prices fell below €0.10/kWh (current: €0.18/kWh). Sensitivity analyses indicated that utilizing excess process heat (60°C water) could reduce energy costs by 15–20%, though this required infrastructure investments.

Biochar production achieved net-negative emissions of -82.8 t CO_2 eq per 40 t output, contrasting sharply with the baseline scenario of woodchip combustion (281.2 t CO_2 eq). The pyrolysis process (300–900°C) converted 160 t of woody biomass into 40 t of biochar annually, sequestering 9.3 t C/ha/year while improving soil water retention (+20%) and pH (0.5–1.0 unit increase). Economically, biochar production costs averaged €1,054/t, but the technology achieved a 44% internal rate of return (IRR).

The microalgae system processed 72 m³ of separated manure annually into 720 kg of dry biomass, achieving 85% nitrogen uptake efficiency. Raceway ponds (300 m²) required 2,304 kWh/year for mixing and aeration, generating 268 kg CO_2 eq emissions—double the baseline (140 kg CO_2 eq). Biostimulant application improved crop yields by 5–7%. Production costs reached €33/kg biomass, yielding marginal profitability (6% IRR) at a market price of €40/kg for horticultural applications. The 12-year NPV of €1,933 reflected limited scalability, as systems required >300 m² pond area for economic viability.

Table 1. Economic analysis and comparative LCA of prototypes for improved manure.

	Total kg CO_2	Net Present Value	Internal Rate of Return	Cost price
NPOG	+ 89.794	-466.582 €	/	39.46 €/t
Biochar	-82.800	+276.282 €	44%	1.054 €/t
Micro Algae	+ 268	+1.933 €	6%	33 €/kg

DISCUSSION

The comparative LCA and economic analysis revealed distinct strengths and limitations for each prototype. The NPOG system offers clear agronomic and environmental advantages by reducing ammonia volatilization and enhancing manure nutrient value, but its high energy demand and resulting emissions outweigh these benefits in the current energy market. The economic analysis further underscores the challenge, as the cost of NPOG-treated manure is not competitive with mineral fertilizers (at the moment), and the investment does not yield a positive return unless electricity prices are substantially reduced or additional value is captured from by-products such as process heat.

Biochar production stands out as the most promising solution, both environmentally and economically. The technology not only sequesters significant amounts of carbon, contributing to climate change mitigation, but also improves soil health and offers a viable business model for farmers. The favorable IRR and positive NPV suggest that biochar could be widely adopted, especially if supported by carbon credit schemes or subsidies for renewable energy use. Nevertheless, market development for biochar and the establishment of quality standards remain important prerequisites for broader deployment (Lehmann, 2007).

The microalgae prototype demonstrates the potential for nutrient recycling and the production of high-value biostimulants, but its scalability is limited by high production costs and relatively modest environmental benefits. The system is best suited for specialized applications or integration into larger circular bioeconomy frameworks where the added value of algal products can be fully realized. Policy support, such as incentives for renewable energy use and the development of certification schemes for biostimulants, could improve the economic outlook for this technology (Haider et al., 2022).

CONCLUSION

The assessment of three manure valorization prototypes using LCA apporach and techno-economic analysis highlights the complexity of balancing environmental and economic objectives in the transition to a circular bioeconomy. While NPOG technology delivers clear agronomic benefits, its viability is constrained by high energy consumption and associated costs. Biochar production emerges as the most sustainable and economically attractive option, offering both climate mitigation and improved soil quality. Microalgae-based biostimulants present opportunities for nutrient recycling and value-added products, but require further market development and policy support to become broadly feasible. Overall, the successful implementation of these prototypes will depend on integrated strategies that combine technological innovation, supportive policy frameworks, and the active engagement of stakeholders in the agricultural sector

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