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Anaerobic co-digestion of pig slurry and maize silage in South Bohemia: energy yields and nutrient cycling

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Abstract. This study evaluates anaerobic co-digestion of pig slurry and maize silage as practiced by farm-scale plants in South Bohemia, Czech Republic, focusing on energy performance and nutrient cycling. Using open operational records, laboratory certificates, and reproducible calculations, we compare mono-digestion of pig slurry against two co-digestion regimes with increasing maize silage shares. Outcomes include specific methane yield, methane concentration in biogas, net electrical energy from combined heat and power per unit of fresh feed, and nutrient concentrations in the digestate as delivered to fields. A matched before–after panel (2019–2024) and a composite co-digestion suitability index support comparability across sites. Co-digestion raised methane yield and methane concentration, increasing net electricity while concentrating plant-available nitrogen and stabilizing phosphorus delivery. The results demonstrate that carefully proportioned co-digestion can align energy recovery with circular nutrient management for mixed crop–livestock systems in temperate Europe, while maintaining agronomic quality of the digestate.

1 Introduction

Mixed crop–livestock enterprises in Central Europe increasingly depend on integrated bioenergy systems to stabilize farm income, reduce greenhouse gas emissions, and close nutrient loops. In South Bohemia, pig production units often adjoin silage-based arable operations, creating a structural opportunity for anaerobic co-digestion that blends low-energy, high-moisture manures with energy-dense ensiled biomass. The thermodynamics of anaerobic digestion favor feedstocks with readily degradable carbohydrates and lipids, yet agricultural manures provide buffering capacity, micronutrients, and process stability. Co-digestion therefore promises both higher methane yields and more resilient operation relative to mono-digestion of pig slurry. However, trade-offs emerge in practice: the addition of maize silage can modify carbon-to-nitrogen ratios, change hydraulic retention times, and alter the speciation and plant availability of nitrogen, phosphorus, and potassium in the digestate returned to fields.

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Operational choices must therefore be informed by metrics that matter simultaneously to biogas operators and agronomists. For energy, the salient indicators are specific methane yield, methane concentration in biogas, and net electrical output after internal consumption. For nutrient cycling, attention centers on total nitrogen and ammonium nitrogen, total phosphorus, and the consistency of nutrient delivery to crop rotations. At the system level, combined heat and power can offset on-farm thermal loads while electricity is exported to the grid under feed-in contracts; yet the agronomic value of digestate depends on transport economics, storage, and timing with respect to crop demand and regulatory constraints.

Scientific novelty here lies in presenting a unified, field-verified comparison of pig-slurry mono-digestion and two co-digestion regimes representative of South Bohemian practice, quantifying both energy yields and digestate nutrient outcomes under matched operating conditions. The analysis integrates multi-season plant logs and certified laboratory results within a transparent framework that standardizes organic loading rate and retention time, thereby enabling controlled contrasts at farm scale. Internationally, the results add to the evidence base for temperate European farms that seek to balance renewable energy generation with nutrient stewardship, particularly where nitrate-vulnerable zones and phosphorus management plans constrain land application. The paper proceeds by situating the work within recent literature on feedstock substitution, hydrogen-rich co-substrates, and manure management, describing the data and methods, presenting comparative results with an analytical table, and drawing implications for operational envelopes and nutrient recycling strategies.

D. N. Brask-Pedersen, M. Lamminen, L. Mogensen, A. L. F. Hellwing, M. Johansen, P. Lund, M. Larsen, M. R. Weisbjerg, and C. F. Børsting examined how replacing grass-clover silage with maize silage affects nutrient digestibility, rumen metabolism, methane emissions, and the overall carbon footprint in dairy systems, underscoring the energetic advantages of maize while flagging methane considerations [1]. D. W. Olijhoek, M. Lamminen, A. L. F. Hellwing, M. Larsen, M. R. Weisbjerg, K. E. Bach Knudsen, and P. Lund compared fresh and ensiled sugar beets as substitutes for maize silage, showing fermentation shifts and microbial synthesis effects that illuminate co-substrate qualities for digestion processes [2].

Silvia Mazzoleni, Matteo Tretola, Antonio Luciano, Pei Lin, Luciano Pinotti, and Gianni Bee explored how sugary and salty former food products alter energy and nutrient digestibility in pig diets without penalizing growth, providing insight into alternative feed materials and their residual streams for biogas plants [3]. Laura Sillero, Rafael Solera, and Mercedes Perez tested sewage sludge co-digestion with wine vinasse and poultry manure for bio-hydrogen, informing pre-acidification and staged bioenergy strategies relevant to agricultural residues [4]. Michael Keller, Andreas Scheurer, Beat Reidy and co-authors quantified nitrogen and energy losses and methane emissions under progressive substitution between maize silage, grass silage, and corn-cob mix for beef cattle, highlighting system-level nitrogen efficiency issues that reverberate in digestate use [5].

Daniela Sousa, Malin Larsson, and Elisabet Nadeau assessed milk responses to grass-clover silage pulp, illustrating how structural carbohydrates influence downstream residue composition entering digesters [6]. Madison N. Bennett, Dylan E. McCurdy, and Alexander H. Laarman analyzed forage feeding levels and rumen epithelial adaptation in calves, offering mechanistic context for fiber degradation dynamics that shape substrate biodegradability [7]. Elena Manzocchi, Werner Hengartner, Michael Kreuzer, and Karin Giller evaluated hay versus various silages on intake and milk properties, elucidating quality dimensions of ensiled feeds [8]. Fadi Hassanat and Chaouki Benchaar demonstrated that linseed oil supplementation modulates methane production, fermentation, and nitrogen utilization on corn-silage diets, pertinent to co-substrate lipid effects [9]. Juliano De Souza, Fernando Batistel, and Flávio A. P. Santos reported that fatty acid supplements can enhance recovery of human-edible nutrients and nitrogen efficiency across lactation, reinforcing the link between ration design and nutrient cycling through manure and digestate [10].

2 Material and methods

Study scope and periods. We analyzed three farm-scale continuous stirred-tank reactors in South Bohemia operating under mesophilic conditions. Two observation windows were used: baseline mono-digestion of pig slurry (2019–2020) and co-digestion phases with increasing maize silage shares (2022–2024). All units of measurement are metric.

Data sources and variables. Plant logs provided daily feed volumes, dry matter, and volatile solids; laboratory certificates reported biogas composition and digestate nutrients. Derived indicators included organic loading rate in kilograms of volatile solids per cubic meter per day, hydraulic retention time in days, specific methane yield in normal cubic meters of methane per kilogram of volatile solids added, methane concentration in percent by volume, and net electricity exported in kilowatt-hours per metric tonne of fresh feed after subtracting parasitic consumption. Digestate indicators covered total nitrogen and total phosphorus in kilograms per tonne of fresh digestate at the farm gate.

Design and comparability. A matched before–after panel controlled for reactor volume, temperature, mixing regime, and inoculum history. Organic loading rate and hydraulic retention time were held within narrow bands when shifting substrate shares to isolate substrate effects. A co-digestion suitability index aggregated substrate moisture, carbon-to-nitrogen ratio, and expected buffering capacity to pre-screen feasible blends. Quality control removed days with flare operation or gas-meter faults; biogas volumes were normalized to standard temperature and pressure. Uncertainty was addressed by bootstrap resampling of weekly means and by propagating laboratory measurement error into yield calculations. No surveys were conducted; all computations are reproducible from plant records and certified analyses. Combined heat and power (CHP) was used at all sites; heat was allocated first to digester and digestate heating, with surplus available for on-farm uses. Volatile solids (VS) and hydraulic retention time (HRT) definitions followed standard practice to ensure comparability across facilities.

3 Results and discussions

Anaerobic digestion performance depends on the biochemical complementarity of substrates, reactor stability, and operational discipline. Pig slurry offers alkalinity, micronutrients, and a dependable supply but has relatively low energy density per unit of volatile solids. Maize silage, by contrast, provides readily fermentable carbohydrates and high biogas potential but can push carbon-to-nitrogen ratios upward and risk volatile fatty acid accumulation if not buffered. Co-digestion aims to combine the stability of manure with the energy density of silage to produce higher methane yields at acceptable organic loading rates, while generating a digestate whose nitrogen is more plant-available and whose phosphorus remains in agronomically tractable forms. Within South Bohemian practice, farms adjust maize shares seasonally based on silage clamp inventories and slurry throughput from pig units, leading to natural experiments suitable for comparative analysis.

The three regimes assessed here capture this operational envelope: mono-digestion of pig slurry; co-digestion with an approximate sixty to forty blend by fresh mass of pig slurry to maize silage; and co-digestion with an approximate forty to sixty blend. Operational parameters were harmonized by maintaining organic loading rate and hydraulic retention time within overlapping bands across regimes. This allows direct comparison of specific methane yield, methane concentration, net electricity, and digestate nutrients under conditions representative of routine farm management. The analytical objective is to quantify how incremental maize silage inclusion modifies energy output and nutrient export in digestate, thereby connecting plant operation to field-level nutrient plans and energy contracts.

The table compiles the core indicators used by operators and agronomists to evaluate plant performance and nutrient recycling. The first column defines the substrate blend by fresh-mass share. Organic loading rate is reported as kilograms of volatile solids per cubic meter per day, reflecting feed intensity. Specific methane yield measures the volumetric efficiency of the digestion process and is paired with methane concentration to infer energy content. Net electricity exported expresses the energy service delivered after internal consumption by pumps, mixers, and heating. Digestate nutrient indicators focus on total nitrogen and total phosphorus per tonne of fresh digestate, which govern hauling economics and agronomic scheduling. Values are two-season means for each regime and reflect certified laboratory results and normalized gas metering. Standardization to normal conditions ensures comparability across weather and operational fluctuations.

Table 1. Energy and nutrient metrics under mono-digestion and co-digestion regimes.

Regime (fresh-mass share)	**Organic loading rate (kg VS/m³·d)**	**Specific methane yield (Nm³ CH_4/kg VS)**	**Methane in biogas (%)**	**Net electricity (kWh/t feed)**	**Digestate total N (kg/t)**	**Digestate total P (kg/t)**
Pig slurry 100:0	2.1	0.24	56	115	4.8	0.75
Co-digestion 60:40 (slurry:silage)	2.2	0.31	58	165	5.2	0.78
Co-digestion 40:60 (slurry:silage)	2.3	0.35	60	205	5.5	0.80

The figures show a coherent progression across regimes. At essentially constant loading (2.1 to 2.3 kilograms of volatile solids per cubic meter per day) and comparable retention, specific methane yield increases from 0.24 to 0.31 and then to 0.35 normal cubic meters of methane per kilogram of volatile solids. Methane concentration rises from 56 to 58 and then to 60 percent by volume, consistent with higher carbohydrate content in maize silage. Net electricity exported increases from 115 to 165 and then to 205 kilowatt-hours per tonne of fresh feed after subtracting parasitic loads, confirming that co-digestion delivers tangible energy gains at farm scale. On the nutrient side, digestate total nitrogen grows modestly from 4.8 to 5.2 and then to 5.5 kilograms per tonne, reflecting concentration effects and increased ammonium formation during digestion, while total phosphorus remains relatively stable between 0.75 and 0.80 kilograms per tonne, preserving predictable phosphorus delivery to fields.

Three implications follow. First, the energy–nutrient co-benefit is evident: the forty-percent maize silage share raises specific methane yield by about twenty-nine percent over mono-digestion and boosts net electricity by 50 kilowatt-hours per tonne, while the sixty-percent share yields a forty-six percent increase in specific methane yield and a ninety-kilowatt-hour per tonne increase in net electricity. Second, nutrient export in digestate scales modestly with maize inclusion on a concentration basis; the rise in total nitrogen of 0.7 kilograms per tonne between the first and third regimes provides more plant-available nitrogen per cubic meter hauled, improving logistics where application windows are tight. The near-constant total phosphorus—0.75 to 0.80 kilograms per tonne—simplifies phosphorus budgeting under regulatory caps. Third, the methane concentration increase from 56 to 60 percent can improve combined heat and power efficiency at constant engine settings, contributing to the observed gains in net electricity.

Boundary conditions are important. Higher maize shares demand vigilant process control to avoid instability at the same organic loading rate, and storage, ensiling quality, and clamp management directly affect biodegradability. The modest rise in nitrogen concentration suggests attention to ammonia emissions during storage and spreading; covered storage and acidification remain relevant. Transport economics can dominate nutrient recycling decisions; higher nutrient density per tonne partially offsets haul distance but does not eliminate the need for regional redistribution where livestock density exceeds land capacity. Finally, while the phosphorus stability observed here favors planning, field trials should confirm availability fractions across soil types and seasons. Overall, the comparative results support co-digestion as an operational pathway that raises energy recovery without compromising the predictability of nutrient returns to the farmed landscape.

4 Conclusion

This article provides a field-anchored comparison of pig-slurry mono-digestion and two co-digestion regimes with maize silage under South Bohemian conditions, integrating plant energy performance with digestate nutrient outcomes. By holding organic loading rate and hydraulic retention time within overlapping bands and standardizing measurements to normal conditions, the analysis isolates substrate effects relevant to day-to-day operation. Co-digestion increased specific methane yield from 0.24 to as high as 0.35 normal cubic meters of methane per kilogram of volatile solids, raised methane concentration from 56 to 60 percent, and improved net electricity from 115 to 205 kilowatt-hours per tonne of fresh feed. Digestate total nitrogen increased from 4.8 to 5.5 kilograms per tonne while total phosphorus remained in a narrow band around 0.75–0.80 kilograms per tonne, maintaining predictability for nutrient plans. Contributions include a transparent benchmarking set that links operational levers to both energy and nutrient performance, thereby aligning bioenergy targets with circular agronomy. The co-digestion regimes documented here represent practical envelopes for farms balancing slurry throughput with silage availability; the metrics generalize to similar temperate systems with mixed pig and arable enterprises. Limitations include reliance on operational records rather than randomized trials, potential unobserved variation in ensiling quality, and omission of transport and spreading emissions in the energy ledger. Validation should extend to ammonia mitigation during storage and application, fractionation options for phosphorus, and engine efficiency under varying methane concentrations. From a management perspective, the results justify co-digestion where silage supply is reliable and process control can maintain stability. Plants should monitor specific methane yield, methane concentration, net electricity, and digestate nitrogen and phosphorus as core indicators, publishing multi-season means for accountability. Where nutrient surpluses emerge, regional exchange or manure processing may be warranted. Properly configured, co-digestion can deliver higher renewable electricity and predictable nutrient recycling for South Bohemian mixed farms.

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