

Phosphogypsum Valorisation in Anaerobic Digestion Enhances Digestate Nutrient Quality and Seedling Vigor

AbdulAzeez Shobajo¹, Viktoriia Chubur¹, Chernysh Yelizaveta^{2,3}, Stacy Hammond¹, Pavel Míchal⁴, Filip Mercl⁴, Taisheva Altyn⁴, Hynek Roubík¹

¹ Department of Sustainable Technologies, Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague, Kamýcká 129, 165 00 Prague, Czech Republic

² Sumy State University, Kharkivska st. 116, Sumy, 40007, Ukraine.

³ Environmental Problems Research and Application Center, Muğla Sıtkı Koçman University, Kötekli Yerleşkesi - 48050 Menteşe/Muğla, Turkey

⁴ Faculty of Agrobiological Sciences, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129, 165 00 Prague, Czech Republic;

Corresponding author: roubik@ftz.czu.cz

Introduction: Phosphogypsum (PG), a calcium sulfate dihydrate byproduct of wet-process phosphoric acid production, is generated in excess of 200 million tonnes annually worldwide, with cumulative stockpiles exceeding 7 billion tonnes (Seraya et al., 2023). Due to residual acidity and trace contaminants, large-scale PG accumulation poses long-term environmental management challenges (El-Didamony et al., 2012). Anaerobic digestion (AD) is a key circular bioeconomy technology for converting agricultural residues such as sugarcane bagasse into renewable energy and nutrient-rich biofertilizers (Alengebawy et al., 2022). However, lignocellulosic substrates often yield digestates with relatively lower nutrient density due to high C/N ratios and limited intrinsic nitrogen and phosphorus. Mineral supplementation has therefore been explored as a strategy to enhance process performance and digestate quality. Recent studies indicate that PG addition can enrich digestates with calcium and sulfur, although excessive sulfate loading may stimulate sulfate-reducing bacteria and increase hydrogen sulfide formation, potentially competing with methanogenesis (Chubur et al., 2022). This study evaluates the addition of low-dose PG during anaerobic digestion of sugarcane bagasse to improve biogas quality and digestate nutrient composition, while identifying a biologically tolerable dosage range and associated sulfate-driven limitations.

Materials and Methods: PG sourced from Sumy region (Ukraine) was air-dried and homogenized to a powder form. An initial bioindication assay using *Lepidium sativum* L. (garden cress) was performed on 1.5% (w/v) water-agar medium. Molten agar (25 mL per 90 mm Petri dish) was amended with PG at final concentrations ranging from 0.1 to 5 g/L before solidification. Seedling vigor index (SVI) was calculated from germination percentage and shoot elongation. Batch AD trials were conducted in 1 L reactors under mesophilic conditions (38 ± 1 °C) for a 22-day retention period. Sugarcane bagasse (SB) was the primary biomass with a substrate-to-inoculum ratio of 0.5:1 (VS basis). Three treatments were established: SB (0 g PG, control), SBPGa (0.25 g PG), SBPGb (0.5 g PG) and inoculum (IN) as blank. All treatments were setup in triplicates. Biogas composition (CH₄, CO₂, H₂S, O₂, CO) was measured with a portable infrared and electrochemical analyzer (Biogas 5000, Geotech/QED Environmental Systems, USA). Post-digestion, the elemental composition (Ca, S, P, K and trace metals) of the digestate was determined by ICP-OES following microwave-assisted acid digestion. Statistical significance was done via one-way ANOVA and Tukey's HSD ($p < 0.05$).

Results and Discussion: The seedling bioindication test revealed a clear PG dose–response relationship. The SBPGa (0.25g PG, 10 g/L equivalent) produced the maximum Seedling Vigor Index (SVI), significantly outperforming the standard Murashige–Skoog (MS) nutrient control ($p < 0.05$). This indicates a stimulatory effect of Ca²⁺ and SO₄²⁻ on early plant development. Conversely, higher dosages (≥ 3 g) severely inhibited germination and growth, likely due to osmotic stress and elevated salinity.

During anaerobic digestion of sugarcane bagasse, SBPGa maintained cumulative methane production comparable to the control while increasing the percentage of methane from about 33% to 40%. This thereby improved the calorific value of the biogas. However, PG amendment resulted in a dose-dependent rise in hydrogen sulfide (H₂S) concentrations in the biogas, reaching approximately 3000 ppm in SBPGa and 4400 ppm in SBPGb. This rise is attributed to sulfate reduction by sulfate-reducing bacteria (SRB), which competitively diverted electron donors from methanogenic pathways. A similar pattern has been reported in PG-amended digestion studies, where low PG amendment yielded neutral to positive effects on methane composition, but higher PG additions reduced performance due to sulfate stress and microbial competition. For example, Chubur et al. (2022) reported that biogas volume remained comparable to the control at low PG addition rates of approximately 5%, whereas increasing the PG concentration to 15% resulted in reduced biogas production. Similarly, Zhang et al. (2025) demonstrated that adding 1% PG during electrochemically enhanced anaerobic fermentation of pig manure increased the gas production rate by 16% and methane content by 15.65%, while higher doses (>5%) significantly inhibited digestion performance.

ICP-OES analysis (Table 1) confirmed substantial mineral enrichment in PG-amended digestates, particularly for calcium (Ca) and sulfur (S). Ca concentrations increased from 20.0 g/kg in SB to 24.7 g/kg in SBPGa and 27.8 in SBPGb. Similarly, sulfur content rose from 8.0 g/kg in the control to 9.0 g/kg (+13%) and 9.7 g/kg (+22%) at 0.25 g and 0.5 g PG, respectively. Moderate increases were also observed for magnesium (Mg), which increased from 10.7 g/kg in the control to 11.7 mg/kg at SBPGa, and for strontium (Sr), which rose markedly from 0.7 g/kg to 0.9 g/kg and 1 g/kg with increasing PG dosage.

Importantly, primary macronutrients remained at agronomically relevant levels across all treatments. Phosphorus (P) showed a slight increase with PG amendment, rising from 12.7 g/kg in SB to 13.3 g/kg in SBPGa, and 12.9 g/kg in SBPGb. In contrast, potassium (K) exhibited a modest dilution effect in the PG-enriched digestates, decreasing from 59,432 mg/kg in the control to 49,933 mg/kg and 53,017 mg/kg in SBPGa and SBPGb respectively. No evidence of heavy metal accumulation was detected. Lead (Pb), nickel (Ni), cadmium (Cd), and chromium (Cr) remained within narrow ranges across treatments, and arsenic (As) was consistently below the limit of quantification (LOQ). These findings indicate that PG addition substantially enriched the digestates without compromising environmental safety, effectively transforming the residue into an enriched organomineral fertilizer.

Table 1. Digestate elemental composition (mg/kg dry weight) following anaerobic digestion of sugarcane bagasse. IN: inoculum-only; SB: 0%PG control; SBPGa: 0.25% PG; SBPGb: 0.5% PG).

Nutrients	IN (control)	SB	SBPGa	SBPGb
K (potassium)	81,786 ± 20,395	59,432 ± 1,772	49,933 ± 2,825	53,017 ± 599
P (phosphorus)	10,436 ± 3,790	12,692 ± 341	13,274 ± 538	12,863 ± 351
Ca (calcium)	19,586 ± 1,065	20,038 ± 267	24,706 ± 826	27,803 ± 195
Mg (magnesium)	9,406 ± 2,082	10,707 ± 300	11,679 ± 475	11,484 ± 122
S (sulfur)	9,189 ± 202	7,962 ± 193	9,020 ± 176	9,721 ± 130
Fe (iron)	5,409 ± 740	5,713 ± 40	5,940 ± 246	5,807 ± 9
Zn (zinc)	702 ± 78	647 ± 21	594 ± 13	605 ± 22
Cu (copper)	110 ± 7	89 ± 3	79 ± 2	81 ± 2
Pb (lead)	2.50 ± 1.97	3.51 ± 0.04	3.24 ± 0.12	3.38 ± 0.06
Sr (strontium)	71.6 ± 2.3	69.9 ± 1.1	86.2 ± 1.7	99.8 ± 1.0

Conclusions: Low-dose PG addition can be effectively integrated into mesophilic batch AD of sugarcane bagasse to improve methane quality and enrich the nutrient profile of the digestate with secondary macronutrients (Ca and S). The increase in H₂S in the biogas requires desulfurization measures in large scale applications. Future research should focus on the long-term agronomic performance of this organomineral digestate and the assessment of radiological safety markers based on specific jurisdictional requirements.

Keywords: Phosphogypsum, Waste Valorisation, Circular Bioeconomy, Anaerobic Digestion, Biofertilizers

References:

- Alengebawy, A., Mohamed, B. A., Jin, K., Liu, T., Ghimire, N., Samer, M., & Ai, P. (2022). A comparative life cycle assessment of biofertilizer production towards sustainable utilization of anaerobic digestate. *Sustainable Production and Consumption*, 33, 875–889. <https://doi.org/10.1016/J.SPC.2022.08.016>
- Chubur, V., Chernysh, Y., Ferchau, E., & Zaffar, N. (2022). Effect of Phosphogypsum Addition on Methane Yield in Biogas and Digestate Properties During Anaerobic Digestion. *Journal of Engineering Sciences*, 9(1), H11–H18. [https://doi.org/10.21272/JES.2022.9\(1\).H2](https://doi.org/10.21272/JES.2022.9(1).H2)
- El-Didamony, H., Ali, M. M., Awwad, N. S., Fawzy, M. M., & Attallah, M. F. (2012). Treatment of phosphogypsum waste using suitable organic extractants. *Journal of Radioanalytical and Nuclear Chemistry*, 291(3), 907–914. <https://doi.org/10.1007/S10967-011-1547-3>
- Seraya, N., Litvinov, V., Daumova, G., Zhusipov, N., Idrisheva, Z., & Aubakirova, R. (2023). Production Waste Management: Qualitative and Quantitative Characteristics and the Calculation of the Hazard Class of Phosphogypsum. *Processes*, 11(10), 3033. <https://doi.org/10.3390/pr11103033>

Acknowledgements:

Funding: Technology Agency of the Czech Republic (TA CR) (Grant Number: TQ17000003). Internal Grant Agency of the Faculty of Tropical AgriSciences, CZU IGA [20263111]. Scientific and Technological Research Council of Türkiye (TÜBİTAK) 2221 Fellowship Program for Visiting Scientists and Scientists on Sabbatical Leave. The research was carried out within the framework of the project “Development of Technological Foundations for Obtaining Complex Mixed Fertilizers with Monodisperse Composition” (State Registration No. 0125U000500), funded by the Ministry of Education and Science of Ukraine.