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Editorial

Editorial: Special Issue "From Waste to Energy: Anaerobic Digestion Technologies"

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Anaerobic digestion (AD) has become a cornerstone in the global pursuit of sustainable energy solutions and effective waste management. This Special Issue, "From Waste to Energy: Anaerobic Digestion Technologies," highlights significant progress and innovative approaches aimed at addressing critical challenges in the AD process, including enhancing methane production, optimizing feedstocks, and integrating emerging technologies to increase efficiency and sustainability.

The articles in this collection explore a wide array of innovations in AD, focusing on improving biogas production, effective feedstock management, the role of biochar as a process enhancer, and nutrient recovery strategies. Together, they offer valuable insights into how anaerobic digestion is evolving to meet the demands of a cleaner, greener energy future while simultaneously mitigating environmental issues.

Progress in Co-Digestion and Feedstock Optimization: The study conducted by Dębowski et al. [1] explores the impact of co-digestion on anaerobic digestion, specifically by combining pre-hydrodynamically cavitated aerobic granular sludge (AGS) with waste fats. Their findings reveal that the addition of waste fats to the mix improves the C/N ratio, leading to substantial increases in both biogas and methane yields, particularly in thermophilic conditions. Impressively, under these conditions, methane yields increased by 40.1% with a 15% addition of waste fats, demonstrating the transformative potential of optimizing feedstock mixtures. This study stresses the importance of further research in continuous reactor setups to better understand the full energy and economic benefits. In a related exploration, Zieliński et al. [2] investigated the application of hydrodynamic cavitation (HC) as a pretreatment technique for AGS. By mechanically disrupting the sludge structure, cavitation enhances the solubilization of organic compounds, boosting methane production by 19.6% compared to untreated sludge. The research highlights the importance of improving feedstock properties to increase AD efficiency and demonstrates how hydrodynamic cavitation can enhance AD performance without significantly increasing energy consumption and showing no influence on the CH4 content in biogas, particularly with optimal cavitation times between 15 and 50 min. Both studies emphasize the vital role that feedstock optimization and pretreatment technologies play in maximizing the efficiency of anaerobic digestion. These innovations are particularly important for industries looking to achieve higher biogas yields from diverse and challenging feedstocks, such as wastewater sludge.

Energy Crops as Renewable Feedstock: Sweet Sorghum's Potential: Mathias et al. [3] take a novel approach by assessing the use of sweet sorghum as a renewable energy crop that can be grown during the fallow periods of sugarcane cultivation in Queensland, Australia. Sweet sorghum is known for its high biomass yield and sugar content, which presents a promising opportunity for biogas production without competing with food

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crops. The study revealed significant methane yield differences across the nine cultivars tested, with SE-81 emerging as the most promising, delivering 3059.18 nm^3 CH4/ha. This represents an impressive gross energy value of 761.74 MWh/year. While the potential of sweet sorghum as an energy crop is evident, Mathias et al. [3] emphasize the need for further research into pretreatment methods and co-digestion with animal manure to optimize methane yields and ensure a more balanced C/N ratio. This research highlights the possibility of utilizing energy crops to complement biogas production systems in agricultural regions. By growing crops like sweet sorghum during off-seasons, farmers can contribute to renewable energy initiatives while maintaining agricultural productivity, offering a win–win situation for both energy and food production sectors.

Biochar: A Game-Changer for Anaerobic Digestion Efficiency: Some articles in this Special Issue focused on the increasingly popular role of biochar as a process enhancer in anaerobic digestion. Quintana-Najera et al. [4] applied Principal Component Analysis (PCA) to evaluate the effects of biochar produced from woody feedstocks under slow pyrolysis (450–550 °C). Their results suggest that biochar significantly enhances methane production, with optimal biochar loads between 0.4% and 0.6% (w/v) proving effective at improving methane yields. Higher loads, however, can be detrimental, reinforcing the need for precise application. This study also highlights the potential of biochar to facilitate direct interspecies electron transfer (DIET), thereby improving methane production, particularly in suboptimal conditions. By using PCA to analyze biochar's influence, Quintana-Najera et al. [4] provide an essential framework for standardizing biochar use in anaerobic digestion, helping operators achieve more consistent and reliable outcomes. In a broader analysis, Manga et al. [5] present a critical review of biochar's multiple benefits for AD, emphasizing the importance of selecting biochar with appropriate properties, such as a high surface area, pore structure, and functional groups, to maximize its positive impact. The review also highlights biochar's ability to address common AD challenges, including substrate inefficiencies, poor-quality digestate, and poor management of effluent, while noting the need for more research on biochar integration into large-scale AD systems. Biochar's potential as a process enhancer for anaerobic digestion holds immense promise, particularly for improving methane yields and stabilizing digestion processes in industrial settings. The insights provided by these papers offer valuable guidance for practitioners and researchers alike, enabling them to better harness biochar's capabilities.

Innovative Approaches to Nutrient Recovery and Process Efficiency: In addition to energy production, nutrient recovery is another key benefit of anaerobic digestion, particularly in agricultural systems where excess nitrogen can cause environmental harm. Abbà et al. [6] contribute to this research area by presenting an innovative approach to ammonia recovery from livestock manure digestate using an air-bubble stripping reactor. Their study demonstrated ammonia removal rates of up to 81%, achieved under optimized conditions without the need for alkaline reagents, making it both cost-effective and environmentally friendly. The energy needed for this process was supplied by a CHP unit powered by the biogas produced during digestion, further enhancing the system's sustainability. This integration of energy production and nutrient recovery highlights the potential for anaerobic digestion to support sustainable agricultural practices while simultaneously reducing nitrogen pollution. This research shows the importance of innovative nutrient recovery solutions in AD systems, particularly as regulatory pressure increases for agricultural producers to manage nutrient runoff and reduce environmental impacts. Abbà et al.'s approach offers a scalable solution that can improve both the efficiency and sustainability of anaerobic digestion in livestock operations.

The research presented in this Special Issue highlights the growing potential of anaerobic digestion technologies to tackle critical energy and environmental challenges. From optimizing feedstock mixtures and developing pretreatment techniques to integrating biochar and nutrient recovery systems, these advancements are paving the way for more sustainable and efficient anaerobic digestion processes.

As anaerobic digestion continues to evolve, innovations in feedstock management, methane production optimization, and nutrient recovery will play an essential role in ensuring that AD systems are both economically viable and environmentally sustainable. The findings presented in this issue represent important steps toward achieving these goals, with significant implications for industries ranging from waste management and agriculture to renewable energy production.

We would like to extend our sincere gratitude to the authors and reviewers who have contributed their expertise to this Special Issue. Their research pushes the boundaries of the possibilities of anaerobic digestion technologies, opening new opportunities for their application across diverse sectors and industries.

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