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Editorial

Unlocking the Full Potential: New Frontiers in Anaerobic Digestion (AD) Processes

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Anaerobic digestion (AD) is a bio-based solution designed to convert organic materials into renewable energy and other products, such as soil improver and organic fertiliser. AD is widely used in practice, with facilities at many thousands of sites worldwide: in Europe alone, more than 20,000 full-scale plants were in operation in 2022 [1]. The underlying biological processes are complex, and multiple options exist to steer the AD process towards optimised performance and a desired set of outputs in terms of energy and material flows. This puts AD in a prominent position with research agendas aiming for more sustainable resource management. Its ability to generate high-value products from organic wastes and residues is a key strength.

The Special Issue on "New Frontiers in Anaerobic Digestion (AD) Processes" was initiated to explore recent developments and advanced concepts related to the valorisation of biomass via the application of AD. Fourteen submissions are included in the Special Issue, and each of these publications contributes towards unlocking the full potential of AD. Five thematic clusters to advance AD can be identified based on the included publications:

- Understanding and monitoring the AD process;
- Making substrates available and increasing the efficiency of the AD process;
- Inspiring trust in non-academic stakeholders to adopt AD in practice;
- Supporting decarbonisation of the energy system through hydrogen and biomethane;
- Obtaining more value from a single unit of biomass.

All included manuscripts contribute to more than one of these five clusters (Table 1). In this paper, some selected findings reported in the publications are highlighted. These are not intended to be exhaustive, but rather to provide some first insights into the rich body of new knowledge created by the authors of the Special Issue.

For the purpose of maintaining the stability and performance of the AD process, in practice, only certain parameters can be monitored in real-time, while adequate methods are still lacking for many others. Yan et al. [2] reviewed the recent progress in applying soft sensor solutions. Some systems are available that use software-supported methods to determine the unmeasurable parameters based on measuring auxiliary variables online; but the need for more research remains high. Integration of deep learning elements into these software solutions is particularly promising.

Liu et al. [3] focused on the residual biogas potential of digestate leaving the digester and the current time-consuming standard procedures to determine this indicator through experimental laboratory testing. Residual biogas potential is a key indicator of digestate stability, which in turn is an essential requirement for spreading digestate onto agricultural land. The authors showed that kinetic modelling, in particular when supported by machine learning, could be successfully applied to reduce the testing time for residual biogas potential.

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Table 1. Publications included in this Special Issue and their relevance for the five clusters identified to unlock the full potential of anaerobic digestion.

	Cluster of AD Progress				
Publication	**Understanding and Monitoring the AD Process**	**Making Substrates Available and Increasing AD Efficiency**	**Inspiring Trust to Adopt AD in Practice**	**Supporting Energy Decarbonisation through Hydrogen and Biomethane**	**Obtaining More Value from a Single Unit of Biomass**
Review of soft sensors in anaerobic digestion process [2]	X		X		
Shortening the standard testing time for residual biogas potential (RBP) tests using biogas yield models and substrate physicochemical characteristics [3]	X		X		
Estimating the methane potential of energy crops: An overview on types of data sources and their limitations [4]		X	X		
Biogas production from residues of industrial insect protein production from black soldier fly larvae *Hermetia illucens* (L.): An evaluation of different insect frass samples [5]		X			X
Batch and semi-continuous anaerobic digestion of industrial solid citrus waste for the production of bioenergy [6]	X	X	X		
Hydrothermal pretreatment of wheat straw—Evaluating the effect of substrate disintegration on the digestibility in anaerobic digestion [7]		X			X
Anaerobic co-digestion of sewage sludge and trade wastes: Beneficial and inhibitory effects of individual constituents [8]		X	X		X
Operation of submerged anaerobic membrane bioreactors at 20 °C: Effect of solids retention time on flux, mixed liquor characteristics and performance [9]	X	X	X		
Exploring farm anaerobic digester economic viability in a time of policy change in the UK [10]			X		X
Recent advances in membrane-based biogas and biohydrogen upgrading [11]			X	X	
Potential for biomethanisation of CO2 from anaerobic digestion of organic wastes in the United Kingdom [12]				X	X
Experimental evaluation of continuous in-situ biomethanation of CO_2 in anaerobic digesters fed on sewage sludge and food waste and the influence of hydrogen gas–liquid mass transfer [13]	X			X	
Validation of two theoretically derived equations for predicting pH in CO_2 biomethanisation [14]	X		X	X	
Toward the transition of agricultural anaerobic digesters into multiproduct biorefineries [15]			X	X	X

Full-scale AD plant operators require reliable information on the methane yields of potential substrates. In agriculture, it is common to use crop-based substrates (energy crops, crop residues), either as the main AD input or to supplement biogas production from manure-fed digesters. Decisions on which crop material to use in AD can significantly impact the entirety of a farm's management. However, relying on data from the literature to estimate the methane yields of crops is not an advisable strategy. The results of Zhang et al. [4] revealed that many publications displayed deficiencies in data reporting. The transferability of the reported methane potentials was limited, because the variability in values for the same crop when tested under different experimental conditions or grown under different cultivation conditions often exceeded the variation of values between different crop species.

With a further increasing world population, food production is a major challenge to be addressed as part of the water/energy/food/climate change nexus. Valorisation of residues from the food production chain makes a valuable contribution to more sustainable food systems, and this applies both to established food production methods and to novel solutions. Among the novel solutions is the cultivation of insect biomass as an alternative feedstuff, which generates insect frass as a residue. After exploring the suitability of insect frass as an AD substrate, Wedwitschka et al. [5] reported promising results, but also highlighted some risk of instability of the process. Similarly, citrus waste is a challenging AD substrate due to the presence of toxic compounds. The work of Rosas-Mendoza et al. [6] suggests that, at an industrial scale, it might not be necessary to remove toxic D-limonene from orange peel waste when using cattle manure as inoculum; but the authors also conclude that further research is required to better understand the implications of different D-limonene concentrations under different reactor configurations. Other food production residues clearly require pre-treatment to make the material suitable for AD. One such biomass is wheat straw, a high-volume material stream. Zerback et al. [7] applied hydrothermal pre-treatment with good success, but they also observed that overly severe pre-treatment conditions had a negative impact on the degradation kinetics. For solutions to be applied at full scale, there is also a need to balance technical and economic feasibility.

Avoiding inhibition of the AD process and achieving a high gas yield are both key goals of commercial plant operators. Berzal de Frutos et al. [8] researched the co-digestion of sewage sludge and 160 different trade wastes with the aim of understanding how wastewater treatment plants can improve their AD performance by accepting trade wastes. The authors concluded that the addition of 10 percent (by volume) of trade waste can usually be recommended, but this may need to be confirmed by further experiments, for example, where inhibitory components are present or microbial acclimatisation is required.

Another approach to improve the performance of AD in the wastewater sector is the implementation of highly efficient bioreactors. Pacheco-Ruiz et al. [9] reported findings from long-term experiments conducted over 242 days with submerged anaerobic membrane bioreactors. A key result indicated that operation without chemical or external cleaning was feasible if the process conditions were adequately set by controlling solids retention and, thus, mean cell residence time. Clearly, such long-term experiments are required in order to reliably inform full-scale operators about the performance of specific operating regimes.

In practice, one of the most important factors influencing whether AD will be implemented or not is if there is sufficient confidence in its economic viability. Financial incentives directly influence the AD landscape and its development. As an example, in the United Kingdom (UK) there is currently a policy vacuum for residues-based small-scale farm AD (<150 kWe), and Bywater and Kusch-Brandt [10] showed that it is very difficult for such installations to achieve profitability, despite the currently high energy prices. An innovative policy mechanism would be to introduce financial support based on the "public goods" benefits offered by on-farm AD (e.g., greenhouse gas reduction, positive soil organic carbon impact, support of rural development).

Several of the published papers address AD as an element in decarbonising the energy system through the adoption of hydrogen and biomethane solutions. Here, AD can be applied in different ways. AD can be implemented to produce biohydrogen through dark fermentation in the digester. The concentration of hydrogen, however, is relatively low, and further processes are required to separate the hydrogen from the resulting gas mixture. As reported by Soto et al. [11], novel types of materials have become available in recent years to make gas membrane separation more effective, thus improving the competitiveness of bio-based hydrogen production. Improved membrane separation performance is of great important to other processes besides hydrogen production. A key application in the AD area is biogas upgrading to biomethane through the membrane-assisted removal of CO_2. One major advantage of biomethane is that it can directly substitute fossil natural gas in existing infrastructures.

Another approach to enhancing biomethane supply is production at biogas facilities through the biomethanation of CO_2 with hydrogen. While its commercial robustness remains to be confirmed, significant potential clearly exists. Bywater et al. [12] estimated that CO_2 biomethanation could raise the AD's contribution to bioenergy in the United Kingdom from 15 percent to 22 percent. There is, however, a relative shortage of reliable data on current UK AD feedstocks, which makes it difficult to quantify potential biomethane production from different substrates. There are also challenges related to the biomethanation process, especially when conducted in-situ, i.e., within the digester itself rather than in an external reactor. The work of Poggio et al. [13] contributed to a better understanding of the hydrogen gas–liquid mass transfer phenomena and to improving biomethanation in continuous AD. Another challenge of the process is the increase in pH because of CO_2 conversion into biomethane, potentially causing inhibition of the digestion process. Zhang et al. [14] presented a fundamentally-derived, experimentally validated approach to minimise such risks during in-situ biomethanation. These insights increase the feasibility of implementing the CO_2 biomethanation process in existing AD facilities, and, thus, of maximising the value of existing infrastructure while contributing to the decarbonisation goals [14].

A common theme across all publications of this Special Issue is making better use of infrastructure and biomass resources. This can be by increasing the efficiency of processes and performance of equipment, by reducing the risk of inhibition, by making substrates more available, or by integrating hydrogen and biomethane. As an approach with the explicit goal of making the best possible use of one unit of biomass, the concept of the biorefinery has evolved in the last decades; its main feature is to process biomass through different schemes operated widely in parallel, thus supplying a multitude of valuable outputs. Bolzonella et al. [15] present a biorefinery pilot plant based on AD that was designed to supply a set of products, namely, energy products (hydrogen, methane), chemicals (short chain volatile fatty acids, polyhydroxyalkanoates), and other materials (nutrients for agriculture, microbial proteins for food or animal feed applications). In such a biorefinery, AD becomes one integrated element of a larger system, as it is complemented by other processes (mechanical, chemical, or biological).

Clearly, applications of AD will continue to change in future, and further progress in making high-value use of this versatile bio-based technology can be expected. There are many aspects to be addressed by further research, and some current research questions are pointed out by the authors of this Special Issue. At the same time, the results of the Special Issue suggest that it is of particular relevance to inspire trust in the economic viability of AD facilities and the technical reliability of novel AD solutions.

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