SUSTAINABLE BIOENERGY AND ENVIRONMENTAL PROCESS TECHNOLOGIES

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Alok Kumar Shrivastav

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PREFACE

This book brings together innovative research addressing some of the most pressing challenges in sustainable energy production and environmental management. The chapters collectively emphasize the role of advanced engineering and biotechnological approaches in supporting the global transition toward cleaner energy systems and more efficient resource utilization.

The chapter Enhancement of Anaerobic Digestion and Biogas Production: A Sustainable Solution to Global Energy Challenges explores strategies to improve renewable energy generation from organic waste, highlighting anaerobic digestion as a viable and scalable solution. Complementing this, Integrated Process Technologies: From Advanced Oxidation to Engineered Bioremediation presents a holistic view of treatment technologies that combine chemical and biological processes to effectively address complex environmental pollutants.

The final chapter, Circular Economy Strategies for the Valorization of Dairy Sludge, focuses on transforming industrial waste into valuable resources, reinforcing the principles of circular economy and sustainability. Together, these chapters provide readers with a concise yet comprehensive perspective on sustainable process technologies that contribute to environmental protection, energy security, and resource recovery.

Editorial Team
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CHAPTER 1
ENHANCEMENT OF ANAEROBIC DIGESTION AND BIOGAS PRODUCTION: A SUSTAINABLE SOLUTION TO GLOBAL ENERGY CHALLENGES

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INTRODUCTION

The growing global energy demand rising to over 8 billion population and industrialization is coupled with the dominance of fossil fuels (82 - 84% of supply) and their high environmental cost, 37 Gt CO_2eq emissions each year, and 7 million number of deaths as a result of air pollution which demands an immediate alternative to renewable energy resources in accordance with the Paris Agreement and the net-zero targets. This comprehensive review position anaerobic digestion (AD) as a key, and sustainable solution to energy crises integrating organic waste by means of waste-to-biogas. Systematic literature synthesis highlights advancements enhancing AD the progress that improves the efficiency of AD: co- digestion of food waste (1.3 billion tons/year) with cattle rumen content provides 20-40% more biogas without pre-treatment costs, utilizing microbial inoculum (CRC) and optimal C/N ratio (25-35:1); diverse feedstocks (sewage sludge, 0.45-0.70 m^3 CH_4/kg VS; algae) increase their applicability due to nutrient. Life-cycle analysis confirms that AD biogas is better than fossil fuels, 80 - 95% of the global warming potential (GWP), acidic, and resource depletion are lower, and drop-in biomethane can be used in the grids and transport. Scaled AD helps to achieve worldwide objectives of the UN SDGs, and reduces 22 -67 Mt CO_2eq/year of emissions; embraces circular economies through digestate biofertilizers. In spite of such obstacles as inhibitor control, scaling challenges, policy incentives, hybrid system, and modular designs put AD in a strong position as a pillar of energy security, waste valorization and decarbonization in 9.7 billion worldwide by 2050. This review article provides the scientific basis to the massive implementation of AD, which calls upon concerted international actions to exploit its radical potential.

The Global Energy Challenge

The modern world is experiencing a historic energy paradox that is rapidly growing energy demand and at the same time there is an urgent need to decarbonize the energy systems. The International Energy Agency (IEA) reports that in the last twenty years, primary energy consumption in the world rise approximately 2% per year, and the dominant economic force was the population growth and the rise in per capita energy demand in developed and undeveloped countries (Al-Yasiri, 2022; IEA, 2025).

The current globalized population have it at 8 billion, and it is expected to rise to 9.7 billion by 2050. This demographic growth is directly proportional to the growth of natural resources consumption (especially fossil fuels used in industrial sectors, residential and transport), as well as the growth of industrial production (Jain *et al.,* 2023).

Even though renewable energy sources can only constitute 14-16 percent of the total primary energy supply in the world, the quantity is not enough to handle the rising demand. The current fossil energy contributes 82-84% of the world energy production, as it remains dominant due to the current infrastructure and economic inertia and scale to switch to renewable energy sources (Al Kez *et al.,* 2024; Igini, 2024; Holechek *et al.,* 2021).

Geopolitical instability, market volatility, and supply chain vulnerability also put increasing pressure on the global energy system. The COVID-19 crisis and regional crises have demonstrated how easily the fossil fuel chains can be broken, leading to price spikes and energy insecurity in most economies (Setyadi *et al.,* 2024). They demonstrate the importance of diversified energy portfolios on the basis of resilient, locally sourced, and renewable energy systems that will be able to provide stability on a long-term basis and national energy independence. With technological innovation, the key to conquering these structural challenges (Aljohani *et al.,* 2024; Yang and Fu, 2025).

Finally, the energy crisis around the globe is not only a technical crisis, but a socio-economic transformation, which needs a systemic change. The future of sustainable energy implies the redesign of the patterns of production and consumption, the principles of a circular economy, and the alignment of the national energy policies with the objectives of the Paris agreement (Eelager *et al.,* 2025; Khan *et al.,* 2025; Lv *et al.,* 2023).

Environmental and Health Impact of Fossil Fuel Reliance

Combustion of fossil fuels emits an average of 37 gigatons of carbon dioxide $(CO_2)^-$ equivalent number of greenhouse gases each year, or some 75 percent of the anthropogenic greenhouse gases worldwide. Climate change is mainly caused by these emissions, and it has escalated to threatening levels with the levels of CO_2 in the atmosphere rising to 421 ppm in 2024, nearly 50 times more than before the industrial revolution.

The implications of these increasing levels are manifold. Mean surface temperature on earth has risen 1.1°C over pre-industrial times and the current warming is greater than 0.18 °C per decade. This warming promotes the decline of the ecosystem, such as the loss of biodiversity, acidification of oceans, and disrupted precipitation patterns, all of which endanger food security on the planet (Bertrand, 2021; Hansen *et al.,* 2025). In addition, fossil fuel burning is a major contributor to air pollution, resulting in 7 million estimated premature deaths annually, mostly due to respiratory and cardiovascular illness. The economic impacts are also tough, where climate-related losses are estimated to cut global GDP by 5-20 percent by 2100 unless some serious mitigation measures are implemented. The above interrelated and growing problems highlight the critical nature of the development and introduction of renewable energy technologies that have the potential to replace fossil fuels and provide stable and economically viable energy services.

Net-Zero Targets, SDGs, and Anaerobic Digestion

Anaerobic digestion (AD) is currently being understood as a cross-cutting technology that directly aligns with some of the United Nations Sustainable Development Goals (SDGs), in particular, SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). AD can address energy accessibility, urban waste issues, and soil fertility simultaneously, thereby aligning with circular economy principles in national and local development policies by converting municipal solid waste, agro-industrial effluents, and agricultural residues into biogas and nutrient-rich digestate. The application of AD in combined waste and energy systems minimizes the use of open dumps and non-controlled landfills, the two largest contributors to fugitive methane, and also an alternative to fossil fuels in electricity, heat, and transportation industries (Piadeh *et al.,* 2024; Parra-Orobio *et al.,* 2025; Tamasiga *et al.,* 2025). In a climate sense, AD has a significant mitigation potential of up to 50 Mt of methane emissions unlocked by untreated organic waste, as well as 100,000 tonne/km^2 of nitrous oxide emissions by synthetic fertilizer replacement, and 100,000 tonne/km^2 of fossil-based energy carrier replacement by biomethane.

Scenario analysis: Scale up of AD and biogas around the world would add tens of mega-tonnes of CO_2^- equivalent cuts annually, which can be added to national efforts to mitigate carbon emissions at the Paris Agreement and long-term decarbonization trajectories. In regional studies, including the one commissioned by Europe and the UK, extended biogas implementation has been estimated to provide substantial cost-saving in reaching net-zero greenhouse gas emissions by 2050, by reducing the requirement to deploy more costly abatement technologies (Daniel-Gromke *et al.,* 2015; Korbag *et al.,* 2021). AD is therefore no longer a waste treatment or agricultural technology; it is a fundamental part of net-zero plans, particularly with the inclusion of renewable electricity, green hydrogen, and carbon capture plans.

Renewable Energy as a Solution: The State and Limitations

Currently, renewable sources of energy such as solar, wind, hydroelectric, geothermal and biomass are considered as the fastest-growing energy source in the world with an average growth rate of 30 percent over the past years. With this trend, there are major constraints that limit their capacity to completely replace fossil fuels, such as the intermittency of solar and wind energy, geographical restrictions on hydroelectric plants, and high capital requirements, which limit their ability to scale quickly. Among these, biomass-based renewable energy, specifically, the conversion of organic waste into renewable energy through anaerobic digestion (AD), is an opportunity to counteract these disadvantages, providing a year-round supply at the cost of processing organic waste feedstock regardless of weather and seasonal factors (Adeshina *et al.,* 2023; Alex-Oke *et al.,* 2025; Kaseem and Moscariello, 2025).

This technology has been of two advantages in managing waste materials and also producing energy at the same time thus decreasing the use of landfills and production of methane. AD also improves the economic aspect because operating costs decline when waste feedstock is used, which would otherwise cause disposal costs. Moreover, geographic flexibility enables units to be spread throughout areas with organic wastes produced, with decentralized deployment without site-specific deployment of other renewables (Abedin *et al.,* 2025; Un, 2022).

1. ANAEROBIC DIGESTION: BASICS AND BIOCHEMISTRY

1.1 Introduction and Major Postulates

Anaerobic digestion (AD) is an established and ecologically friendly biotechnological process of treating organic waste and recovery of renewable energy, which can be done by biologically degrading the biomass in the absence of oxygen. This natural operation consists of converting complex organic matter into biogas, a renewable fuel, which mainly comprises of methane (CH4) at a concentration that is usually more than 65 percent, carbon dioxide (CO2) and small pollutants like hydrogen sulfide (H2S) and water vapor (Harirchi *et al.,* 2022; Prasanna Kumar *et al.,* 2023; Sevillano et al., 2021). The general simplified chemical reaction may be shown as:

$$(C_6H_{10}O_4)_n + nH_2O \rightarrow 3nCH_4 + 3nCO_2$$

This equation demonstrates how polymeric carbohydrates (estimated as cellulose or starch) are converted to methane and carbon dioxide in a net reaction, but several intermediates are in reality involved.

Fundamentally, the biochemistry of AD relies on syntrophic relationships among various microbial communities, which sequentially decompose the substrates through four interlinked steps, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Complex organics such as polysaccharides, proteins and lipids are broken down to soluble monomers (e.g. sugars, amino acids and fatty acids) by excreted hydrolytic bacterial enzymes. This is followed by acidogenesis where the fermentative microorganisms transform these monomers into volatile fatty acids (VFAs) like acetate, propionate, and butyrate in addition to hydrogen (H_2), CO_2 and alcohols. The longer-chain VFAs and alcohols are then further metabolized by acetogenic bacteria producing acetate, H_2 and CO_2 which keeps the hydrogen partial pressures low and supports syntrophy (Cao, 2025; Fanfoni *et al.,* 2024; Venkiteshwaran *et al.,* 2016). Lastly, strict anaerobes, found in methanogenic archaea, generate CH_4 through the reduction of CO_2 by H_2 (hydrogenotrophic methanogenesis:

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$), or by the cleavage of acetate (acetoclastic methanogenesis:

$CH_3COOH \rightarrow CH_4 + CO_2$), which contributes to about 70 percent of biogas methane.

Active digester systems are usually colonized with 10^{10} to 10^{11} microbial cells per gram comprising both hydrolytic and fermentative bacteria and specialized methanogen, the synergistic interaction of which results in the stability of the process and the high biogas productivity. It is not only based on this microbial synergy that AD can be viewed as a cornerstone technology in the shift toward circular bioeconomies, but also its flexibility to accept an expansive range of feedstocks (Arowolo & He, 2018; Carlos *et al.,* 2025; Harirchi *et al.,* 2022).

1.2 Biochemical Process: Four Sequential Phases

Four separate, interdependent biochemical steps in anaerobic digestion, including hydrolysis, acidogenesis, acetogenesis and methanogenesis, are catalyzed by distinct microbial communities, which convert collectively complex organic matter into biogas. These steps constitute a cascade of events whereby the product of one process will be the substrate of the other, and the efficiency of the process depends on harmonized microbial syntrophy and environmental stability. The failures may be caused by disruption at any part of the chain, which explains why operational conditions have to be optimized in real-life scenarios (Harirchi *et al.,* 2022; Westerholm and Schnurer, 2019). The most important chemical reactions at the AD stages are addressed in Table 2.1.

Table 1. Chemical Reactions during Anaerobic Digestion (Anukam *et al.* (2019)

Stage	Substrate → Products	Chemical Equation	Key Microbes
Hydrolysis	Cellulose → Glucose	$(C6H10O5)_n + nH2O \rightarrow nC6H12O6$	Hydrolytic bacteria
	Proteins → Amino acids	$(Protein)\_n + H2O \rightarrow Amino"$	
	Lipids → Fatty acids + Glycerol	$Triglycerides + 3H2O \rightarrow Glycerol + 3Fatty$	

Acidogenesis	Glucose → Acetate pathway	$C6H12O6 + 2H2O \rightarrow 2CH3COOH + 2CO2 + 4H2$	Fermentative bacteria
	Glucose → Propionate	$C6H12O6 + 2H2 \rightarrow 2CH3CH2COOH + 2H2O$	
	Glucose → Butyrate	$C6H12O6 \rightarrow CH3(CH2)2COOH + 2CO2 + 2H2$	
Acetogenesis	Propionate → Acetate	$CH3CH2COOH + 2H2O \rightarrow CH3COOH + CO2 + 3H2$	Syntrophic acetogens
	Butyrate → Acetate	$CH3(CH2)2COOH + 2H2O \rightarrow 2CH3COOH + 2CO2 + 2H2$	
	Ethanol → Acetate	$CH3CH2OH + H2O \rightarrow CH3COOH + 2H2$	
Methanogenesis	Acetate (70%)	$CH3COOH \rightarrow CH4 + CO2$	Methanogenic archaea
	H_2/CO_2 (30%)	$CO2 + 4H2 \rightarrow CH4 + 2H2O$	

Hydrolysis

Hydrolysis is the rate limiting step in the anaerobic digestion where hydrolytic bacteria extracellularly release enzymes that break down complex organic matter into soluble monomers. This hydrolysis is slow especially when dealing with recalcitrant lignocellulosic feast, structural lignin forms bottlenecks which determine the overall digestion rate and biogas yield potential. The best pretreatment methods therefore aim at improving the hydrolysis rates to overcome this shortcoming (Cao *et al.,* 2025; Kasulla *et al.,* 2024; Menzel *et al.,* 2019).

Acidogenesis

Fermentative bacteria are used in acidogenesis to quickly break down the monomers formed by hydrolysis and then convert them into methanogen-precursor intermediates. The hydrogen partial pressure has a drastic influence on product spectra: low H_2 concentrations select acetate-dominated products (70 percent of products) that are useful in the process of methanogenesis, but high concentrations favor reduced products such as propionate and butyrate (30 percent), which may render the process unstable.

The versatility of its metabolism makes it adaptable to a variety of feedstocks, but it needs close observation to avoid the development of VFA (Detman *et al.,* 2021; Nagarajan *et al.,* 2022).

Acetogenesis

The acetogenesis process further perfects the acidogenic intermediates, and obligate proton-reducing acetogenic bacteria oxidize longer-chain volatile fatty acids to acetate, H_2, and CO_2. Such reactions are thermodynamically unfavourable at standard temperatures (DG°C > 0) and can only take place when chain elongation reactions are exergonic, as the methanogens keep ultralow levels of hydrogen (<10-4 atm) in interspecies hydrogen transfer. Vulnerability to environmental changes, therefore, makes acetogenesis a pivotal control point on digester stability (Detman *et al.,* 2021; Karekar *et al.,* 2022; Pavan *et al.,* 2022).

Methanogenesis

The process is culminated by methanogenesis, which is the rate limiting step and catalyzed solely by methanogenic archea. Although it constitutes only 5-20% of the biomass of microbes, methanogens are highly sensitive to disturbances, such as changes in pH (best 6.8-7.2), temperatures, exposure to oxygen, and inhibitors such as ammonia, sulfides, or excessive VFAs or which will stop the production of methane. Strong process management, therefore focuses on the welfare of methanogen in order to recover the maximum amount of energy (Jung *et al.,* 2019; Lyu *et al.,* 2018; Maric *et al.,* 2023).

1.3 Substrates for Anaerobic Digestion

Food Waste as High-Value Feedstock

Food waste has become a very promising raw material to undergo anaerobic digestion (AD) because it possesses several beneficial traits that make it efficient in the processes and biogas output (Ngabala & Emmanuel, 2024). With a high biodegraded percentage of 80-90, most elements of food waste can easily be converted to biogas, which is much greater in comparison with other less biodegradable products.

This feedstock provides some of the highest rates of methane of any organic waste, with its rapid biodegradation as a feature in comparison to lignocellulose-based feedstocks, and high initial potentials, 200-600 L CH_4 per kilogram of volatile solids, resulting in the hydraulic retention times being reduced considerably (Tomczak *et al.,* 2023). This naturally elevated moisture content (70-85%) also contributes to easing microbial processes because it does not require the addition of external water, making food waste a high-quality, locally accessible resource of decentralized AD systems (Ngabala *et al.,* 2024; Negri *et al.,* 2020; Tomczak *et al.,* 2023).

Food Waste Challenges and Co-Digestion Solutions

All these properties help food waste to facilitate high-rate digestion and ideal energy recovery, so it is specifically attractive to urban waste management combined with renewable energy generation (Tomczak *et al.,* 2023). Nevertheless, there are operational issues in mono-digestion of food waste that limit its adoption on a large scale in industry in the past. First of all, it is the inefficient carbon-to-nitrogen (C/N) ratio, which is between 15:1 and 25:1 as opposed to 20:1 to 30:1 ratio which is optimal in the balanced microbial nutrition and stable process functionality (Nleya *et al.,* 2023; Tomczak *et al.,* 2023).

Compounding this issue, food waste is frequently affected by nutrient imbalances, such as the lack of phosphorus, potassium, and essential trace metals that limit the growth and activity of microbes. The instability of pH caused by high nitrogen content increases the accumulation of ammonia, increasing alkalinity levels and directly preventing the growth of methanogenic archaea, and the rapid degradability of the substrate produces a large amount of volatile fatty acids (VFAs) that are rapidly produced faster than they can be metabolized by downsteam methanogens. This rapid acidification threatens the collapse of processes, which is observed in the form of the sharp decrease of pH, VFA overload, and the total inability to digest (Almaramah *et al.,* 2023; Mia and Zaman, 2025). Co-digestion measures (as the mixing of food waste with carbon-rich agricultural residues, or specific additions of nutrients and pH buffers) are important avenues of leading to the realization of the full potential of food waste.

These optimizations do not only reduce instabilities, but also increase the overall quality of biogas and the stability of the digester, which highlights the importance of food waste as one of the cornerstone feedstocks in the bioenergy system of the future.

Cattle Rumen Content: Novel Co-Digestion Partner

Cattle rumen content (CRC) is a plentiful, unused slaughterhouse by-product that has great potential as a co-substrate in anaerobic digestion (AD) especially in combination with highly-degradable feedstocks such as food waste. These partially digested rumen residues, which are produced on cattle slaughter, are traditionally carbonated as wastes that have to be disposed of at a high cost, but they pose environmental threats when they cause untreated discharge, which leads to water pollution, greenhouse emissions, and land degradation. Repurposing CRC can turn this liability into a strategic asset because it has excellent biological and nutritional properties that can be utilized to increase AD stability, biogas production, and process durability in co-digestion systems (Amoo *et al.,* 2025; Ihoeghian *et al.,* 2022; Ihoeghian *et al.,* 2023).

CRC Advantages, Microbial Inoculum, Nutrient Balance and Synergistic Co-Digestion

The main value of CRC is its highly diverse, pre-developed microbial consortium containing 10^{10} to 10^{11} bacterial cells per gram, various fungi and ciliated protozoa. It is a community of co-evolution between ruminant animals and microbes over millions of years that is the most efficient at degrading lignocellulosic material, recalcitrant plant fibers (cellulose, hemicellulose) that are difficult to degrade by conventional AD microbiomes (Langda *et al.,* 2020; Sha *et al.,* 2020). The inoculation of digesters with CRC enhances the hydrolysis and acidogenesis processes by inoculating with hydrolytic enzymes and the syntrophic bacteria to increase the overall substrate conversion rates and reduce the start-up times of new systems. To supplement its microbial richness, CRC has an ideal nutrient profile that deals with mono-digestion feedstock deficiencies.

It provides a carbon-to-nitrogen (C/N) ratio of 25:1 to 35:1 that is in line with the AD optima with high lignocellulosic carbon and moderate protein levels by rumen microbes and undigested forage (Otite *et al.,* 2024). Natural dietary residues and microbial biomass are rich sources of phosphorus, potassium and essential trace metals (e.g. cobalt, nickel and iron) and support the growth of methanogenic activity. The nutritional completeness counterbalances imbalances, maintains pH through the slow production of volatile fatty acids (VFA), and minimizes ammonia toxicity thus common in protein-rich wastes (Ariunbaatar *et al.,* 2016).

Synergistic pairing of feedstock Co-digestion of CRC and food waste is an example of synergistic feedstock. The high carbon content and microbial inoculum of CRC offset the negative properties of the latter low C/N ratio, rapid acidification, and nutrient deficits, producing 20-40 times more biogas and increasing process stability (Kainthola *et al.,* 2020; Ma *et al.,* 2019). Not only do such pairings make slaughterhouse waste more valorized, but they also bring about circular bioeconomy ideas, where linear waste streams would be converted into renewable energy and fewer environmental footprints would be created by the food and livestock industries (Matwani & Iddphonce, 2025; Oduor *et al.,* 2022; Xu *et al.,* 2022; Yu *et al.,* 2023).

Table 2. Comparison of nutrient content of cattle rumen content and AD requirements (Faccenda *et al.* (2019); Zhang *et al.* (2023).

Nutrient Parameter	Cattle Rumen Content	Recommended Range
Crude Protein (%)	18.52-19.56	15-20
Calcium (%)	0.45-0.68	0.4-0.8
Phosphorus (%)	0.28-0.35	0.2-0.5
Magnesium (%)	0.12-0.18	0.1-0.2

The Microbial Functionality of CRC

The high diversity of bacterial communities in cattle rumen content (CRC) provides them with remarkable microbial performance that makes them more stable and efficient in the process of anaerobic digestion. These microorganisms offer strong buffering capacity, which is due to several pathways of volatile fatty acid (VFA) consumption, which are effective in stabilizing pH and averting the acidification crisis that is typical of feedstocks with high degradability (Ihoeghian *et al.,* 2022; Liu *et al.,* 2024). Also, rumen pre-adapted hydrolytic enzymes can be used to enhance the breakdown of persistent feed polymers in the CRC itself, simplifying the hydrolysis process and increasing the overall conversion rates of substrates (Wei *et al.,* 2022; Zhang *et al.,* 2024).

Other Feedstock: Sewage Sludge

Anaerobic digestion and sewage sludge Municipal wastewater treatment plants have one of the most established and commonly used feedstocks, which is sewage sludge, which offers a reasonably constant and predictable feedstock stream. It is a mixture of both primary and secondary sludge, which usually provides an average organic matter concentration and good moisture conditions to support wet digestion and can be integrated into centralized wastewater treatment facilities (Manea & Bumbac, 2023; Giwa *et al.,* 2023; Rasouli *et al.,* 2023). Sewage sludge addition stabilizes organic matter, decreases pathogen loads, and generates biogas, which can be utilized at the location to generate combined heat and power and reduce the energy footprint of wastewater treatment plants and facilitate energy-positive or energy-neutral plant activity (Mukawa *et al.,* 2021). Simultaneously, the digested sludge can be further processed into biosolids to be applied to the land to recycle nutrients, provided that there are appropriate regulatory and quality standards (Pratap *et al.,* 2024; Waseem *et al.,* 2025).

The co-digestion of the sewage sludge with the organic component of municipal solid waste or food waste has become a promising solution to enhance the level of biogas production, the stability of the process, and the economics of the already existing digester used in the treatment of wastewater (Azarmanesh *et al.,* 2023; Limonti *et al.,* 2024).

As demonstrated by experimental and full-scale research, the combination of sludge with easily degradable organics has been demonstrated to increase the rate of methane generation per unit reactor volume and enhance volatile solids reductions as long as loading rates, mixing, and risks of inhibition are well controlled (Sharmin *et al.,* 2025). This type of co-digestion system takes advantage of the existing infrastructure of digester systems, reducing the extra capital expenditure, and diversion of city biowaste off of landfills or incineration. As a result, sewage sludge AD, especially in co-digestion mode, is one of the primary opportunities that allow the municipalities to achieve the goals of wastewater treatment, waste diversion, as well as renewable energy generation (Jiang *et al.,* 2022; Prabhu and Mutnuri, 2016).

Other supplementary Feedstocks: Algae

Microalgae and macroalgae have gained considerable interest as universal feedstocks to anaerobic digestion because it grows at a high rate, has high areal productivity, and can utilize non-arable land and salty or wastewater resources (Babu *et al.,* 2021; Omokaro *et al.,* 2025; Sarker *et al.,* 2023). The nitrogen and phosphorus within the wastewater can be absorbed in microalgal biomass grown in wastewater treatment systems, and thus the cleaning of the nutrients can be associated with the generation of biogas by digging up the harvested biomass.

The combination of most algal species, which is high in proteins, carbohydrates, and in certain cases lipids, provides a positive substrate to produce methane (Geng *et al.,* 2025; Hosny et al., 2025; Nashath *et al.,* 2025). The problems of performance in mono-digestion systems can, however, be hampered by cell wall recalcitrance and high nitrogen content. In order to overcome these limitations, different modes of pretreatment (thermal, mechanical, chemical, and biological) have been established to improve the cell disruption and biodegradability, which frequently leads to significant improvements in the methane yield.

The concept of co-digesting algae with other wastes can also be used to enhance the performance of the process by balancing carbon-to-nitrogen ratios, buffering pH, and eliminating the risk of ammonia inhibition (Azarmanesh *et al.,* 2023; Bohutskyi *et al.,* 2019; de la Lama-Calvente *et al.,* 2022).

Investigations of co-digestion of wastewater-grown filamentous algae with sewage sludge have reported a larger biomethane production and more preferred net energy balances than sludge mono-digestion or sludge pretreatment only. The macroalgae, including the seaweeds, also serve as an additional resource base in the coastal areas and regions with high density of aquaculture, allowing region-specific AD systems to valorize the locally abundant biomass and not causing competition with food crops (Bohutskyi *et al.,* 2019; de la Lama-Calvente *et al.,* 2022). Even though commercialization of algae-based AD remains immature, these feedstocks increase the technical and geographic reach of AD, and is continuing to strengthen the idea that AD is a versatile platform of integrated waste and biomass-to-energy conversion.

1.4 Technologies and Types of Anaerobic Digestion Reactors

Anaerobic digestion (AD) technologies represent a wide-ranging engineering discipline that is designed to transform the organic wastes into biogas by means of controlled microbial metabolism, and the design of the reactor is optimized based on the characteristics of the feedstock, scale, climate, and economic factors. These systems are categorized in four main and systematic aspects of moisture content, operating temperature, organization of the reaction phase, and feeding regime which determine the process kinetics, stability and energy recovery efficiency (Ankathi *et al.,* 2024; Darmey *et al.,* 2025; Ostos *et al.,* 2024; Ibro *et al.,* 2024). This classification system helps in the selection of technology which is determined by the alignment between the characteristics of waste and the operational goals and also combats the challenges in the management of waste and production of renewable energy in the world. The digestion of anaerobic organisms can be divided into many different categories.

1.4.1 Classification on basis of Moisture Content

Anaerobic digestion systems differ by the basic content of total solids (TS) which determines the hydraulic behavior, mixing needs and effluent management (Carlos *et al.,* 2025; Zhao *et al.,* 2021).

Wet AD systems: Wet AD systems handle dilute slurries (5-20% TS), which are more common in practice since they are pumpable and do not need complex methods of operation as in livestock manure and municipal sludge (Leonzio, 2018). These designs require a lot of dilution water yet are the best in terms of uniformity in mass transfer (Table 2.3).

Dry AD systems: Dry AD systems, which deal with concentrated feedstocks (>20% TS), which include crop residues and food processing wastes, reduce the use of water and reactor footprints and make the management of digesta easier (Angelonidi & Smith, 2015). Comparative attributes: Table 2.3 outlines them:

Table 3. Wet versus Dry Anaerobic Digestion Systems (Angelonidi & Smith, (2015); Leonzio, (2018))

Parameter	Wet AD (5-20% TS)	Dry AD (>20% TS)
Water Requirements	High (dilution intensive)	Low (minimal addition)
Mixing Method	Hydraulic/pump circulation	Mechanical agitation
Reactor Footprint	Larger volume	Compact design
Primary Feedstocks	Manure, sewage sludge	Straw, food processing waste
Startup Dynamics	Rapid acclimation	Gradual microbial adaptation
Digestate Management	Liquid separation required	Solid stacking feasible

1.4.2 Classification in terms of Temperature

Temperature is a critical design consideration in anaerobic digestion (AD), which has a major impact on the dynamics of microbial communities, reaction kinetics, thermodynamic favorability, and pathogen reduction efficiency. There are three existing temperature regimes, including psychrophilic, mesophilic, and thermophilic, which address the requirements of different climatic conditions, energy provision, and sanitation, with each having a different biochemical profile and operational tradeoffs (Sarker *et al.,* 2018; Wu *et al.,* 2006; Zhang *et al.,* 2024). These performance metrics were summarised in Table 2.4 to be compared.

Psychrophilic AD

Psychrophilic AD can be fed at temperatures below 20degC and can use psychrophilic adaptive microbial consortia, which can grow on temperate and polar oceans. These systems need a low amount of external heating, and the balanced temperature of a passive maintenance provides very good energy ratios, making it economically appealing to decentralized, low-input applications, such as manure digestion in the area north (Akindolire *et al.,* 2022; Tiwari *et al.,* 2021).

Nevertheless, the low metabolic rates of psychrophilic microbes require long hydraulic retention periods (60-120 days) and, therefore, biogas productivity is limited to 150-250 L CH_4/kg VS and throughput in space-constricted systems (Parajuli et al., 2022; Rodriguez-Jimenez et al., 2022; Zafra *et al.,* 2020). Reduction in pathogen is moderate because of the unfavorable thermal stress, which places psychrophilic AD in an ideal state to be used as a non-portable digestate when energy savings are more important than restrictions in productivity (Alvarez-Fraga *et al.,* 2025; Seruga *et al.,* 2020).

Table 4. Temperature Classifications of Anaerobic Digestion Systems (Sailer *et al.* (2021))

AD Type	Temp. (°C)	HRT (days)	Methane Yield (L/kg VS)	Pathogen Reduction	Energy Balance
Psychrophilic	<20	60-120	150-250	Low	Highly favorable
Mesophilic	30-45	15-50	250-400	Moderate	Favorable
Thermophilic	45-65	14-16	350-500	High (>99%)	Energy neutral

Mesophilic AD

The Mesophilic AD, which is performed at 30-45 °C, prevails in the world deployment with a great majority of operational system systems exceeding 80 percent because of its unparalleled process stability and moderate power needs.

This regime favors strong and heterogeneous communities of microbes that are resilient to small changes in pH, loading, or temperature with hydraulic retention times of 15-50 days giving dependable methane generation of 250-400 L/kg VS (Humphrey *et al.,* 2024; Hmaissia *et al.,* 2024; Li *et al.,* 2016). Standard heating systems make operational control easy, whereas pathogen inactivation is moderate and adequate to be used in agriculture (Elving *et al.,* 2014). The moderate efficiency and low-sensitivity profile of inhibitors characterize the balanced performance, which makes mesophilic systems the ideal in the industry when working with various feedstocks, such as municipal sludge, food waste, and livestock manure (Kusi *et al.,* 2025; Bekrit and Ogwu, 2025; Pramanik *et al.,* 2019).

Thermophilic AD

The thermophilic AD (45–65°C) optimizes reaction rates and sanitation based on high temperatures that promote enzymatic hydrolysis, faster rate of methanogenesis attaining hydraulic retention times of 14-16 days and high biogas yields of 350-500 L/kg VS (Hu & Shen, 2024; Singh *et al.,* 2022). Different forms of valorization Enhanced lignocellulosic degradation can be applied to recalcitrant agricultural residues, whereas high thermal stress (>99% pathogen kill) can be used in sensitive applications such as soil amendment (Gomez, 2024; Charnnok *et al.,* 2025; Ebrahimi *et al.,* 2023).

Nevertheless, thermophilic systems require large amounts of energy to maintain the temperature at a specific level and are thus vulnerable to instability due to ammonia toxicity, VFA buildup or minor changes, which damage delicate archaeal populations (Hmaissia *et al.,* 2024; Haroun *et al.,* 2025). In the industrial environment, deployment is focused on throughput and biosecurity instead of energy efficiency with heat recovery plans cancelling the operational expenses (Nayeri *et al.,* 2024; Wu *et al.,* 2025).

1.4.3 Reaction Stage Hypothesis Organized Classification

One-stage AD

The one-stage anaerobic digestion (AD) process involves all four biochemical stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) in a single reactor vessel, which explains its utilization in about 90% of the world since it is simple in nature, requires less capital investment, and has few operational needs (Nayeri *et al.,* 2024; Hidalgo *et al.,* 2024). This setup is based on a balanced microbial community that adjusts to the common environmental factors (pH 6.8-7.2, equal temperature), with acidogenic bacteria present alongside methanogens even though their optima are different, with acid formers in the first group growing more effectively in slightly lower pH and higher temperature, and having methanogens in the second group requiring stability (Prasanna Kumar *et al.,* 2024; Carlos *et al.,* 2025). The design is very effective in the treatment of homogeneous feeds, such as manure or sewage sludge, with reliable production of biogas by natural syntrophy, but is susceptible to imbalances in the process: the rapid hydrolysis of highly degradable materials can overwhelm downstream methanogenesis with volatile fatty acids (VFAs), which will cause a pH collapse, VFA accumulation (>2000 mg/L), and digester failure (Uddin and Wright, 2022). Capital cost is reduced by 30-50% compared to multi-stage options, and footprints are reduced in case of decentralized use of one-stage systems, becoming the main workhorse of municipal and farm-scale AD in the world.

Multi-stage AD

Multi-stage AD uses phase-specific optimized reactors, which are normally two stage (separating acidogenesis/hydrolysis and methanogenesis) or three-stage (further separating acetogenesis), providing 15-30% higher conversion efficiencies by microenvironmental optimization (Carneiro *et al.,* 2022; Nayeri *et al.,* 2024; Simeonov *et al.,* 2025). The acidogenic stage uses high rates of organic loading (OLR >10 kg VS/m^3 d), lower pH (5.5-6.5), and increased temperatures to achieve the maximal production of VFA, whereas dedicated methanogenic reactors use conditions favorable to methanogen (pH 7.0-7.5, low H_2 partial pressure), where cross-inhibition can occur (Uddin and Wright, 2022; Osunde *et al.,* 2017).

Phase separation can improve resilience to substrate variability, shock loads are buffered in upstream reactors and reduces frequent failure modes such as ammonia toxicity or rapid acidification, and have been reported to improve stability by 25-40 percent when operating at variable feeds (Kumi *et al.,* 2020; Rajendran *et al.,* 2020). Multi-stage systems are not only capital-intensive (1.5-2x one-stage costs) and must be operated by skilled personnel, but they are also the most prevalent in the industrial sector where they process complex wastes (food processing effluents, high-strength wastewater), and thus can be considered as sophisticated systems to increase biogas recovery and digestate quality in challenging circumstances (Amorim *et al.,* 2005; Robin *et al.,* 2025).

1.4.4 Classification by Feeding Strategy

Batch Anaerobic Digestion (BAD)

The batch anaerobic digestion (BAD) process involves discrete and cyclic steps, full loading of the substrate, full biochemical transformation through all of the four stages until no further biogas is produced, emptying and loading of the reactor, and thus, it is specifically adapted to heterogeneous or seasonal wastes, particularly agricultural crop residues or periodic food processing by-products (Adekunle and Okolie, 2015; Akil and Jayanthi, 2012). It requires less complexity, less capital investment, no continuous feeding mechanisms, and small-scale operators can get biogas comparable to continuous systems in the active digestion phases (usually 30-90 days per cycle), provided that there are feedstock and temperatures (Issahaku *et al.,* 2024; Hayyat *et al.,* 2024). Nevertheless, endogenous intermittency is a problem: biogas generation is highly variable, and downstream storage or electric hybrid is needed to ensure consistent supply, and the significant changes in biogas production make the technology more laborious to start and stop, and there is a risk of insufficient digestion (residual VS >20) that prevents scalability (Mundra and Lockley, 2023; Pilarski *et al.,* 2025). The advantage of batch systems is seen in the decentralized, low-tech environments where the waste is available in discrete operational intervals, and offers cost-effective solutions in spite of lower throughput than continuous (Adeodu *et al.,* 2023; Korshunova and Boichenko, 2024).

Continuous Anaerobic Digestion (CAD)

By feeding fresh raw material and removing the same volume of digestate at constant time intervals, continuous AD ensures constant production of biogas and stability in the processes needed when scaled in the industrial level (Negahban *et al.,* 2025; Lima *et al.,* 2024; Nindhia *et al.,* 2025).

Continuously Stirred Tank Reactors (CSTRs).

The most common continuous design, Continuously Stirred Tank Reactors (CSTRs), includes the vigorous mechanical mixing of the contents to provide total homogenization, promoting greater contacts between the microbes and the substrate, diluting inhibitory compounds (VFAs, ammonia), and eliminating any dead zone, leading to 20-25 percent higher biogas yields compared to unmixed plug-flow reactors (Bekrit & Ogwu, 2025; Pramanik *et al.,* 2019). Hydraulic retention times of 1530 days stabilize in the case of organic loading rates of 210kg VS/m3d, and feed composition is strictly controlled to reduce shock loads and maximize the microbial acclimation (Carlos *et al.,* 2025; Zhao *et al.,* 2021). Continuous systems, with their predictable production, high volumetric efficiency, and flexibility to a wide range of feeds such as municipal sludge or food waste, are the future of well-known, utility-scale bioenergy production (de la Lama-Calvente *et al.,* 2022).

1.4.5 The Advanced Reactor Technologies (ART)

The state of the art is advanced anaerobic digestion (AD) reactors in which organic loading rate (OLR) is 5-10 times that of conventional CSTRs and effluent quality is also high (Ihoeghian *et al.,* 2022; Liu *et al.,* 2024). These designs respond to industrial requirements of small footprint, resilience to shock loads and stable operation with varying wastewater strengths, with most such uses being in food processing, breweries and petrochemical effluents (Detman *et al.,* 2021; Nagarajan *et al.,* 2022). This method of decoupling hydraulic retention time (HRT) and solids retention time (SRT >100 days) maintains dense microbial consortia (20-50 g VS/L) in advanced reactors, resulting in COD removal efficiencies >90% with an OLR greater than 20 kg COD/ m^3d, Table 2.5 technology profiles key technologies.

Table 5. Advanced Anaerobic Digestion Reactor Technologies (Nagarajan *et al.* (2022))

Reactor Type	Key Mechanism	OLR (kg COD/m³·d)	HRT (h)	COD Removal (%)	Primary Applications
UASBR	Granular sludge	10-35	4-24	85-95	High-strength WW
EGSB	Expanded granules	15-45	2-12	90-98	Dilute effluents
ABR	Baffled compartments	5-20	24-72	80-92	Shock-load tolerance
CSTR	Complete mixing	2-10	360-720	70-85	Solids-rich wastes
ASBR	Sequencing batch	3-15	12-48	82-94	Variable organics
AFBR	Fluidized biofilm	20-50	1-6	88-96	High-rate industrial

Upflow Anaerobic Sludge Blanket Reactors (UASBR)

UASBR grows self-organizing granular sludge (1-5 mm diameter, 50-70% VS) under the influence of selective pressure, which allows compact upflow operation, in which wastewater is passed through a compact layer of sludge (0.5-3 m/h) (Arowolo *et al.,* 2018; Carlos *et al.,* 2025).

Granules with methanogen-centralized layered consortia enable close spacing of substrate-microbe contacts and interspecies transfer of H_2 to produce biogas at a yield of 0.35-0.45 m^3/kg COD at OLRs of 10-35 kg/m^3d. UASBRs are also high-strength (COD 2000-20,000 mg/L) and require 2-6 months to stabilize operation, which is resistant to 50% fluctuations in OLR (Harirchi *et al.,* 2022).

Expanded Granular Sludge Bed (EGSB) reactors

Expanded Granular Sludge Bed (EGSB) units build upon UASBR concepts by increasing recycle ratios of 1020x to grow sludge bed by 2050% and enhance the mass transfer of dilute COD of 500-3000mg/L (Harirchi *et al.,* 2022; Geng *et al.,* 2025).

Recirculation of the effluent sustains the superficial velocities between 3-10 m/h and this does not cause biomass washout and encourages floc break up to achieve high substrate access with low HRTs of 2-12 hours and high COD removal of over 95%. At low-strength conditions, EGSB is superior to UASBR by 15-25% and most of brewery and pharmaceutical industries use EGSB, but high pumping energy (20-30% of biogas value) and cold climate limits its universal applicability (Hosny *et al.,* 2025; Nashath *et al.,* 2025).

Anaerobic Baffled Reactors (ABR) and sequencing batch reactors (ASBR)

The Anaerobic Baffled Reactors (ABR) and the Sequencing Batch Reactors (ASBR) focus on the operational robustness rather than the maximum rate. ABRs divide the reactor into 4-8 sequential chambers through downcomer/upcomer baffles, which impose plug-flow hydraulics, which approximate multi-stage phase separation, but recycle biomass on the sloping surfaces of SRT between 50-100 days (Piadeh *et al.,* 2024). Extraordinary shock resistance (OLR spikes 100 percent survivable) is suitable to variable municipal/industrial wastes, although reduced OLRs (5-20 kg/m^3d) reduce throughput. ASBRs operate on fill-react-settle-draw cycles in single vessels with the advantage of utilizing gravity settling (60-90 min) of 85-95% biomass retention to allow flexible loading of institutional organics with 20-40% enhanced yields when compared to batch systems (Parra-Orobio *et al.,* 2025; Tamasiga *et al.,* 2025).

Anaerobic Fluidized Bed Reactors (AFBR)

Anaerobic Fluidized Bed Reactors (AFBR) move inert media (sand, activated carbon; 0.52mm) in fluidized phases (15-30m/h upflow) to grow thick biofilms (10-30g VS/m^2) to achieve ultrahigh OLRs (20-50kg/m^3d) and HRTs less than 6 hours. The AFBRs are positioned to be used in petrochemical applications and this is because of exceptional recalcitrant substrate degradation (phenolics, long-chain fatty acids), however, media abrasion and clogging require regular backwashing (Jung *et al.,* 2019; Lyu *et al.,* 2018; Maric *et al.,* 2023).

2. METHANE POTENTIAL AND BIOGAS PRODUCTION

The anaerobic digestion of heterogeneous organic wastes to produce biogas can be considered the flagship product of the whole bioprocess and transform heterogeneous organic wastes into a multipurpose renewable fuel with a well-defined composition and energy properties (Amoo *et al.,* 2023a, 2023b).

In this part, biogas composition is outlined, the methane potential of various substrate classes is quantified and upgrading pathways that convert raw biogas into high quality biomethane that can be injected into grid, serve as transportation fuel and secondly, used in industry are explained. The knowledge of these parameters becomes critical in the optimization of the process, the evaluation of economic feasibility, and the selection of strategic feedstock in the business deployments.

Composition and Energy Content of Biogas

The biogas that comes out of anaerobic digester is a multicomponent gaseous mixture consisting of 65-70% of the gaseous mixture made up of methane (CH_4) as the primary energy carrier and 25-35% carbon dioxide (CO_2) as the primary non-combustible diluent (Abedin *et al.,* 2025). The Hydrogen sulfide (H_2S) concentrations are 0.01- 2% (100- 20,000 ppm) which presents extreme corrosion risks to downstream equipment by forming sulfuric acid during combustion, and fluctuations in water vapor content (5-10% saturation) require the removal of condensation to avoid condensation and microbial fouling in the pipelines (Un, 2022).

Trace elements, such as ammonia ($NH_3 < 100$ ppm), nitrogen ($N_2 < 1\%$), oxygen ($O_2 < 0.5\%$), and volatile siloxanes (cosmetics/textile), have little effects but affect the upgrading economics and end-use specifications (Arowolo and He, 2018). The calorific value of raw biogas is 20-25 MJ/m^3 (5500-7000 kcal/m^3) or 0.5-0.7 liters of diesel or 0.6-0.8 kg LPG per cubic meter with methane content having the main effect on energy density (Venkiteshwaran *et al.,* 2016). Table 3.1 illustrates heating value compositional effects.

Table 6. Biogas Composition and Calorific Value Relationships (Venkiteshwaran *et al.* (2016))

CH_4 (%)	CO_2 (%)	H_2S (ppm)	Lower Heating Value (MJ/m^3)	Diesel Equivalent (L/m^3)
50	45	500	18.0	0.45
60	35	1000	21.0	0.53
65	30	2000	22.8	0.57
70	25	5000	24.5	0.61
75	20	10000	26.3	0.66

The applications of this energy profile are flexible with direct combustion in modified gas engines result in the production of 2-3 kWh electricity and 2.5-3.5 kWh thermal with 1 m^3 of biogas (35-40% electrical efficiency); hot water boilers with 85-90 thermal efficiency; upgraded biomethane (>95% CH_4) can fully replace natural gas (100% interchangeability). The conventional preprocessing includes the use of H_2S mitigation through iron oxide scrubbers (below 250 ppm level) and water knockout drums, and biological desulfurization (microaerophilic Thiobacillus) is a recently introduced method to have a sustainable H_2S control (Harirchi *et al.,* 2022; Cao, 2025).

Comparative Methane Yield from Various Substrates

The most accurate way to measure the value of feedstock is methane potential expressed in liters of CH_4 per kilogram of volatile solids (L/kg VS), which is the best measure of inherent biodegradability, carbohydrate/protein/lipid ratios, and recalcitrance factors (Carlos *et al.,* 2025; Fanfoni *et al.,* 2024). Table 3.2 shows benchmark yields in major categories of substrates and these indicate glaring differences that guide the co-digestion strategies.

Table 7. Comparative Methane Production yields from the common substrates (Fanfoni *et al.* (2024))

Substrate Type	Methane Yield (L/kg VS)	Biodegradability (%)	Key Limitations
Food Waste	200-600	80-95	Process instability
Fruit/Vegetable Waste	300-450	85-92	Seasonal availability
Cafeteria Waste	594.6	90-95	High lipid content
Cow Manure	100-200	40-60	Lignocellulosic fibers
Poultry Waste	150-250	50-70	High N, NH_3 inhibition
Agricultural Residues	50-150	30-50	Lignin recalcitrance
Grass/Plant Material	100-200	45-65	Seasonal, fibrous
Paper/Cardboard	200-400	60-80	Cellulose crystallinity

Based on a high potential of methane (mean 400 L/kg VS) which is due to the presence of high amounts of readily hydrolyzable carbohydrates (starches, sugars) and lipids that produce 0.8-1.1 L CH4/g VS destroyed, food waste is categorically superior to lignocellulosic manures (0.2-0.4 L/g) (Negri *et al.,* 2020; Tomczak *et al.,* 2023).

Exceptional yields of cafeteria waste (594 L/kg VS) are attained by the optimal lipid: carbohydrate ratios but operational risks exist because of the rapid acidification, requiring stabilization (Nleya *et al.,* 2023). The indigestible fibers and slow hydrolysis rates also reduce potentials of manure substrates by 50-70% percent making them diluents, but not primary fuels, despite their abundance (Tomczak *et al.,* 2023).

Co-Digestion Optimization Strategies

The high yield yet volatile substrates (food waste) are synergistically married with nutrient-rich stabilizers (manure, rumen content), and balance of C/N ratios (20-30:1), added micronutrients supplementation, and effects of microbial inoculum are achieved by co-digestion (Mia and Zaman, 2025). Their optimum blending ratios are usually 60-80% food waste: 20-40% manure, alleviate ammonia toxicity (NH_4^+N <1500 mg/L), VFA concentration (>3000 mg/L threshold), and micronutrient deficiencies (Co, Ni, Fe), and rumen material provides pre-adapted lignocellulolytic consortia, which hastens hydrolysis by 30-40% (Matwani & Iddphonce, 2025). Optimized blends have reported 380-520 L/kg VS in reported field trials compared to 250-350 L/kg VS mono-digestion, and the quality of the digestates was improved to be used in agriculture.

Life-cycle assessments of AD Biogas and Fossil fuels

Life-cycle assessment (LCA) has emerged as an important instrument to positively assess the environmental performance of AD biogas systems versus conventional fossil fuel pathways that include consideration of the effect on the environment in feedstock collection to energy consumption. The majority of LCA analysis indicates that under the condition that AD is fuelled by a waste-derived feedstock, be it manure, sewage sludge, or the organic portion of municipal solid waste (OFMSW), the global warming potential of one unit of useful energy is significantly reduced compared to the one produced by coal, oil, or natural gas burning (Azarmanesh *et al.,* 2023; Limonti *et al.,* 2024). In addition to the effects of climate, AD biogas has less life-cycle burdens in fossil resources depletion, acidification, and the formation of particulate matters than coal- or oil-based energy chains (Jiang *et al.,* 2022).

Indicatively, LCA analysis of the biogas-powered cogeneration against coal-fired power plants indicates the drastic decrease of sulfur oxides and primary particle emissions, which is due to both the low level of sulfur content in biogas and lack of mining related emissions. The total environmental picture of AD may, however, be conditional on design options, such as control of methane leakages, containment of digestates, and end-use decision (heat, power, or transport fuel).

Environments Environmental benefits can be eroded by high levels of methane slip, insufficient storage of digestate, or extensive transport distances, but the opposite holds true, as systems optimized by tight gas collection, covered digestate stores, and local nutrient recycling are always more effective than fossil fuel baselines in various categories of impact (Prabhu & Mutnuri, 2016).

Biogas Upgrading and End-Use Applications

Raw biogas which is upgraded to biomethane (>95% CH_4, <10 ppm H_2S) through pressure swing adsorption (PSA), water scrubbing, or membrane separation open up high value markets producing pipeline-quality fuel (52-55 MJ/m^3) to replace fossil natural gas.

Current utilization is dominated by electrical generation (60% global capacity), which provides 2 kWh/m^3 of power at an efficiency of 38% with combined heat and power (CHP) systems having 85% total efficiency. Biomethane in compressed form (CNG vehicles), as well as in liquefied form (LBG), increase the range of transportation use, and the GHG reduction in their life cycle is 80-95% relative to fossil counterparts (Amoo *et al.,* 2023c).

3. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Current Challenges Limiting AD Deployment

Although anaerobic digestion (AD) has been proven technically mature and beneficial in terms of environmental performance, its global scale implementation has been faced with a complex set of barriers, including feedstock logistics, economic competitiveness, policy reliance and gaps in scientific understanding. The variability of feedstock becomes one of the major limitations here as the changes of agricultural wastes according to seasons generate the intermittency of supply to the reactors, and the geographic distribution of possible wastes, including the urban food waste and the industrial processing effluents generates the need to collect them and transport them across rural-urban boundaries (Abedin *et al.,* 2025).

These are compounded by market uncertainties where the biogas-derived products are priced unpredictably with the price subject to fluctuations in the energy markets of the region; biogas power cannot compete economically in jurisdictions where fossil electricity is subsidized, and biomethane purification requires expensive steps (pressure swing adsorption, membrane separation) and lack of access to pipelines (Adeshina *et al.,* 2023). Scalability is also impeded by the presence of policy landscapes, where AD economics depends on incentives that are dependent on jurisdiction such as feed-ins or renewable targets and waste disposal taxes, which are susceptible to political changes, making unsubsidized projects marginal in the competitive markets. The lack of knowledge on the synergy of substrates despite many years of biochemical potential assays highlights why empirical optimization of co-digestion matrices is required, since unforeseen inhibitory interactions (ammonia-VFA cross-toxicity, micronutrient synergies) keep leading to failures of the processes (Piadeh *et al.,* 2024).

Emerging Research Opportunities

New research directions hold the prospect of transformative improvements through the combination of AD with frontier biotechnologies, precision microbiology, digital process control and biorefinery paradigm. Coupling AD to volatile fatty acid (VFA) platforms has redirected acidogenic phases to chemical precursor production (acetate, butyrate to bioplastics, biochemicals) with pH-controlled reactors with 2-3x value creation compared to Methane-only systems, and electrochemical integrations of bio electrochemical, microbial fuel cells, and harvesting electrons on syntrophic intermediates allow electricity production and higher COD removal simultaneously (Piadeh *et al.,* 2024). The nutrient recovery innovations recover phosphorus as struvite and nitrogen as ammonium sulfate using side-stream precipitation and turn the digestate liabilities into high-value fertilizers offsetting the cost of operation by 20-30% (Alex-Oke *et al.,* 2025). A high-leverage frontier is advanced inoculum engineering, using metagenomic sequencing and synthetic biology to inoculate substrate-specific consortia that reduce startup times (60-90 days) and increase yields (15-25% higher) with specific lignocellulolytic or psychrophiles.

Predictive upset control is possible with real-time process intelligence through molecular diagnostics qPCR monitoring of methanogen populations, volatile metabolomics and machine learning models, trained on multi-sensor data (VFA/alkalinity ratios, biogas H_2S signatures), are able to predict upsets (Kaseem & Moscariello, 2025). These innovations are integrated in biorefinery to cascade AD in multi-pathway biomass valorization: biogas will power on-site, VFAs will nourish microbial electrosynthesis, digestate will be used to fertilize algal photobioreactors, and the solids remaining will be converted in pyrolysis into biochar/activated carbon (Bertrand, 2021). Such synergistic developments place AD not only in the contexts of waste treatment but as a foundational technology in large-scale circular bio economies requiring interdisciplinary convergence of microbial ecology, process engineering, data science, and policy innovation to achieve an extent of transformation of this scale, globally (Parra-Orobio *et al.,* 2025; Tamasiga *et al.,* 2025).

CONCLUSION

This review summarizes the important developments in anaerobic digestion (AD), such as food waste co-digestion by cattle rumen, sewage sludge, and algae; novel reactors such as UASBR and EGSB, and pretreatment, increase the yield of methane 20 -100 times, increase process stability, and transform large quantities of organic waste into predictable biogas, overcoming intermittency constraints of other renewable energy sources and reducing landfill emissions and fossil fuel dependency.

The impact of these innovations is profound, by abating tens of megatonnes of CO_2^-equivalent per year, meeting the goal of supporting net-zero targets with high-cost savings as the life-cycle analysis showed that the AD biogas is superior to the fossil fuels in terms of greenhouse gas, acidity, and resource indicators. As a pillar of fair clean energy transformation to a 9.7 billion world by 2050, conditional on breaking down impediments through specific R&D initiatives and policy support, scaled integration of AD with direct interspecies electron transfer, biogas upgrading, and hybrid grids by providing energy security, nutrient-rich digestate, and social-economic resilience under the influence of geopolitical and climatic stressors has been achieved.

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CHAPTER 2
INTEGRATED PROCESS TECHNOLOGIES: FROM ADVANCED OXIDATION TO ENGINEERED BIOREMEDIATION

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INTRODUCTION

The pervasive and persistent contamination of global water resources by microplastics (MPs) and contaminants of emerging concern (CECs) constitutes a defining environmental challenge of the Anthropocene. These pollutants, originating from diverse domestic, industrial, and agricultural sources, evade conventional primary and secondary wastewater treatment processes, leading to their widespread dissemination in aquatic ecosystems and posing significant risks to ecological integrity and human health (Leong and Lebel, 2020; Kümmerer et al., 2019). This critical failure of existing infrastructure has catalyzed an urgent search for advanced, tertiary treatment solutions capable of effective abatement.

While traditional sorption and filtration can achieve phase transfer, they merely concentrate pollutants, creating secondary waste streams. Conversely, destructive technologies aim to mineralize or transform pollutants into benign substances, aligning more closely with circular economy principles. However, the vast physicochemical diversity of MPs—varying in polymer type, size, shape, and surface chemistry—coupled with the myriad of hydrophilic and persistent CECs, precludes a universal technological fix (Smith et al., 2025). The engineering community is therefore tasked with developing a versatile toolkit of advanced processes, each with distinct mechanisms, strengths, and limitations.

This chapter provides a critical and comparative review of four pivotal technological fronts that represent the current vanguard of research and development for aquatic MP and CEC remediation. The analysis moves beyond cataloging reported removal efficiencies to scrutinize the practical viability and sustainability of each approach. Specifically, it evaluates:

- Nano-enabled sorbents and catalysts, which offer high specificity and reactivity for targeted sequestration and degradation.
- Advanced oxidation processes (AOPs), which utilize potent reactive oxygen species for the destructive mineralization of recalcitrant molecules.
- Bioremediation and bioaugmentation strategies, which leverage microbial and enzymatic pathways for sustainable biodegradation.

- Hybrid membrane systems, which integrate separation with in-situ destructive processes to overcome the limitations of standalone units.

The evaluation framework explicitly focuses on scalability, energy and chemical demand, operational complexity, potential for secondary pollution, and integration potential within holistic, circular water management frameworks. By synthesizing the state-of-the-art and identifying persistent knowledge gaps, this chapter aims to guide researchers, engineers, and policymakers toward the design of intelligent, multi-barrier treatment trains that are not only effective but also economically and environmentally sustainable for implementation at scale.

1. NANO-ENABLED SORBENTS AND CATALYSTS

Engineered Biochars: Modification of biochars with iron oxides enhances affinity for specific CECs through both adsorption and Fenton-like reactions (Magagula, 2022). However, regeneration remains challenging (Li et al., 2022).

MXenes: While $Ti_3C_2T_5$ MXenes show >95% removal of Cr (VI) in lab studies (Peng et al., 2018), their scalable production costs and long-term stability in aquatic environments require further study (VahidMohammadi et al., 2021).

Molecularly Imprinted Polymers (MIPs): These offer exceptional selectivity (>98% for target molecules like bisphenol-A) but face economic barriers for large-scale application (Chen et al., 2016).

A comparative analysis of nano-sorbents is shown in Table.1.

2. ADVANCED OXIDATION PROCESSES (AOPS): CATALYTIC DEGRADATION PATHWAYS

Advanced Oxidation Processes represent a cornerstone technology for the destruction, rather than mere phase transfer, of recalcitrant organic pollutants like microplastics and CECs. They operate on the principle of generating highly reactive oxygen species (ROS), primarily hydroxyl radicals (•OH, E° = 2.8 V), which non-selectively oxidize complex molecules into simpler, less toxic end-products, ideally CO_2 and H_2O (Ma et al., 2025c).

Their efficacy against conventional bio-refractory compounds is well-established; however, their application to the heterogeneous and persistent challenge of microplastics requires nuanced optimization and often hybrid system design (Wang et al, 2024).

Table 1. Comparative Analysis of Nano-Sorbents

Material Class	**Target Pollutant (s)**	**Reported Removal Efficiency**	**Key Advantage**	**Primary Limitation**	**Technology Readiness Level (TRL)**	**References**
Fe_3O_4-coated Biochar	Cd^{2+}, Pb^{2+}, Tetracycline	>90% (batch studies)	Magnetic separation enables easy recovery; dual adsorption & catalytic function	Organic fouling in complex matrices; capacity loss after 3-4 cycles	3-4 (Lab/ Pilot)	Magagula (2021); Li et al. (2022)
$Ti_3C_2T_5$ MXene	Cr (VI), Dyes (Methylene Blue), Some Pharmaceuticals	~95% for ions; >85% for organics	Excellent chemical stability; high conductivity enables electrochemical	High scalable production cost; potential restacking in	2-3 (Lab)	Peng et al. (2018); VahidMohammadi et al. (2021)
Bisphenol-A MIP (Molecularly Imprinted Polymer)	Bisphenol-A, Structural Analogues	~98% (high selectivity in mixed solutions)	Exceptional molecular specificity reduces co-removal of benign substances	Complex synthesis; typically, single-use with difficult/expensive regeneration	3 (Lab)	Chen et al. (2023)
ZnO-g-C_3N_4 Photocatalyst	Polyethylene Microplastics, Diclofenac, Sulfamethoxazole	60-80% mineralization under visible light in 4-6 hours	Solar-driven; breaks down pollutants into simpler molecule	Slow kinetics; possible toxic nanomaterial leakage; efficiency	2-3 (Lab)	Musthafa & Mandal (2022); Javed et al. (2021)

			s (CO_2, H_2O)	drops in turbid water		
Aerobic Microbial Consortium (Bioaugmentation)	Polyethylene, Polypropylene, PET fragments	15-40% mass reduction in 30-60 days (highly variable)	Low energy input; environmentally benign; potential for full biodegradation	Extremely slow kinetics; sensitive to environmental conditions (T, pH, O_2)	3-4 (Lab/ Field Test)	Amobonye et al. (2021);

Advanced Oxidation Processes represent a cornerstone technology for the destruction, rather than mere phase transfer, of recalcitrant organic pollutants like microplastics and CECs. They operate on the principle of generating highly reactive oxygen species (ROS), primarily hydroxyl radicals (•OH, E° = 2.8 V), which non-selectively oxidize complex molecules into simpler, less toxic end-products, ideally CO_2 and H_2O (Dai et al., 2024). Their efficacy against conventional bio-refractory compounds is well-established; however, their application to the heterogeneous and persistent challenge of microplastics requires nuanced optimization and often hybrid system design (Wang et al, 2024).

2.1 Heterogeneous Photocatalysis: Harnessing Solar Energy

This sub-section employs semiconductor materials (photocatalysts) that, upon photoexcitation, generate electron-hole pairs capable of initiating redox reactions at their surface.

Mechanism & Common Catalysts: The process involves: (i) photon absorption with energy ≥ bandgap, (ii) charge carrier separation, (iii) migration to surface, and (iv) reaction with H_2O/O_2 to form $•OH/O_2•^-$. While TiO_2 (P25) remains a benchmark due to its stability and low cost, its wide bandgap (~3.2 eV) restricts activity to UV light (Liao, 2022). This has spurred research into visible-light-active catalysts like graphitic carbon nitride ($g\text{-}C_3N_4$) and bismuth oxyhalides (BiOX) (Ong et al., 2016).

Application to Microplastics: Studies demonstrate that photocatalysis can effectively fragment and mineralize common polymers. For instance, A 2025 study noted that PET microfibers could achieve a mass loss of 16.22% after 120 hours of treatment with C, N-TiO_2.

Other specialized composites, such as ilmenite-graphene oxide nanohybrids, have also been developed specifically to target the degradation of PET nano- and microplastics. Recent breakthroughs utilizing TiO_2/MPs ratios of 1:1 have demonstrated significant results, including a 34% mass loss of PE microspheres within just 8 hours of UV treatment. This process is evidenced by substantial chemical transformations, such as a 58.5% increase in the carbonyl index, which confirms chain scission (Aragon et al., 2025).

To move beyond UV dependence, researchers have developed visible-light-driven heterojunctions. For instance, a ZnO/g-C_3N_4 heterojunction (often in combination with other oxides like α-Fe_2O_3) has been shown to effectively induce surface pitting, cracks, and folds on PE microplastics under visible light, significantly increasing mass loss compared to photolysis alone. Implementing consecutive photocatalytic cycles with fresh catalyst has been shown to boost degradation yields, increasing the total mass loss of PE to 54% after five cycles (Baig et al., 2025).

Critical Challenges & Synergies

Mass Transfer Limitation: The solid-solid interaction between catalyst particles and microplastic surfaces is inefficient.

Secondary Pollution: Potential leaching of photocatalytic nanoparticles and the generation of toxic intermediate by-products require careful lifecycle assessment (Yeszhan et al., 2024).

Hybrid Approach: To address kinetics, photocatalysis is increasingly coupled with other AOPs (e.g., persulfate activation) or used as a pre-treatment to oxidize plasticizers, making the polymer matrix more amenable to biological attack (Ramirez-Escarcega et al., 2025).

2.2 Electrochemical Advance Oxidation Processes (EAOPs): Precision through Applied Potential

EAOPs use electricity to drive oxidation reactions directly at the anode surface or via electrogenerated oxidants.

Direct and Indirect Oxidation: Pollutants can be directly oxidized at a high-oxygen-overpotential anode (e.g., boron-doped diamond, BDD) or indirectly via electrogenerated chlorine, peroxydisulfate, or •OH from water oxidation (Ghernaout et al., 2020).

Emerging Electrodes for Plastic Degradation: Dimensionally stable anodes (DSA) and mixed metal oxide (MMO) coatings are being tailored for this purpose. A promising avenue is the use of Ti/SnO_2-Sb anodes, which have shown high efficiency for degrading polystyrene nanoplastics by generating abundant •OH (Zheng et al., 2024).

Scalability Consideration: While offering precise control, the main barriers for wastewater-scale application are energy consumption (kWh/g pollutant) and electrode fouling/long-term stability. Research focuses on 3D electrode architectures and catalytic coatings to enhance current efficiency (Satyam & Patra, 2025).

2.3 Ozone and Ozone-Based Processes

Ozone (O_3) is a potent oxidant (E° = 2.07 V) that reacts via direct ozonation or decomposes to form •OH.

Limitation with Microplastics: Ozone alone is often ineffective for rapid degradation of solid polymer matrices due to slow diffusion and reaction kinetics. Its primary role is in oxidizing the additives (phthalates, BPA) leached from plastics or in pre-oxidizing the polymer surface (Kye et al., 2024).

Enhanced Ozonation (O_3/H_2O_2, Catalytic O_3): The O_3/H_2O_2 (peroxone) process accelerates •OH generation. More effectively, heterogeneous catalytic ozonation using metal oxides (e.g., MnO_2, CeO_2) on supports like alumina provides active sites for O_3 decomposition and pollutant adsorption, significantly improving the degradation rate of coated microplastics (Topkaya et al., 2025).

2.4 Comparative Analysis and Integrated Design

This comparative analysis highlights that selecting an Advanced Oxidation Process (AOP) for the remediation of microplastics (MPs) and Contaminants of Emerging Concern (CECs) requires a strategic balance between efficiency, cost, and scalability.

Selection depends on water matrix, target pollutant, and end-goal (full mineralization vs. partial oxidation for biodegradability). The comparative overview of key advanced oxidation process is shown in Table 2.

Table 2. Comparative Overview of Key AOPs for Microplastic/CEC Remediation

Process	**Primary Oxidant**	**Key Strength**	**Major Limitation**	**Estimated Operational Cost**	**TRL for MPs**	**Reference**
UV/H_2O_2	•OH	Well-understood, good for UV-transparent waters	H_2O_2 residual quenching needed; low UV penetration in turbid water	Medium	4-5	Sun et al., 2023
Heterogeneous Photocatalysis	•OH, h^+	Utilizes solar spectrum; catalyst reuse potential	Slow kinetics; catalyst recovery/separation issue	Low-Medium (if solar)	3-4	Silerio-Vazquez et al., 2022
Electro-oxidation (BDD anode)	•OH, direct e^- transfer	No chemical addition; high oxidation power	High energy cost; electrode durability	High	3-4	Brosler et al, 2023
Catalytic Ozonation	•OH, O_3	Faster than O_3 alone; reduces bromate formation	Catalyst leaching; complex water matrix effects	Medium-High	4	Gao et al., 2025

Technology Readiness Level (TRL), microplastics (MPs), Boron-Doped Diamond (BDD)

To overcome the limitations of individual processes, modern environmental engineering is shifting toward Integrated Design. No single AOP is universally optimal; instead, hybrid systems are recommended (Tsiarta et al., 2025):

Pre-Treatment (Physical): Utilizing Membrane Filtration or coagulation to reduce turbidity, which improves the efficacy of UV-based AOPs.

AOP Sequential Coupling: Using Catalytic Ozonation to break down large microplastic polymers into smaller fragments, followed by UV/H_2O_2 for the final oxidation of remaining CECs.

AOP-Biological Integration: Because AOPs are energy-intensive, the goal is often partial oxidation. AOPs can be used to transform non-biodegradable pollutants into smaller, biodegradable intermediates, which are then cost-effectively removed by a Biological Treatment stage (e.g., Activated Sludge) (Nguyen et al., 2024).

3. BIOREMEDIATION AND BIOAUGMENTATION: HARNESSING BIOLOGICAL PATHWAYS

While physicochemical methods like AOPs aim for rapid destruction, bioremediation offers a potentially sustainable, low-energy alternative by leveraging the catalytic power of microorganisms and enzymes to biodegrade or biotransform pollutants. For complex synthetic polymers like plastics, this process is inherently slow but holds the promise of complete mineralization to CO_2 and H_2O or valorization into useful products. The key challenge lies in enhancing the natural, often inefficient, metabolic pathways to achieve practically relevant degradation rates (Getino et al., 2025).

3.1 Microbial Consortia and Enzyme Systems

No single microbe possesses the full enzymatic arsenal to degrade complex polymers. Degradation typically requires synergistic consortia.

Mechanisms of Microbial Attack: The process is sequential: (1) Bio-deterioration: Microbes colonize the surface, creating a biofilm; (2) Bio-fragmentation: Extracellular enzymes (e.g., hydrolases, oxidoreductases) break polymer chains into oligomers and monomers; (3) Assimilation: Small molecules are taken up by cells and integrated into metabolic pathways (e.g., the TCA cycle) (Shokunbi et al., 2025).

Key Enzymes: Hydrolases (e.g., PETase, MHETase): Specifically target ester bonds in polyesters like polyethylene terephthalate (PET).

The discovery and engineering of Ideonella sakaiensis PETase marked a breakthrough (Silva et al., 2023).

Oxidoreductases (e.g., Laccases, Peroxidases): Attack C-C backbones of polyolefins (PE, PP) through oxidative reactions, often requiring mediator compounds. These enzymes are less specific and slower (Zhang et al., 2022).

Enhancement Strategies: Native enzyme activity is often insufficient. Protein engineering (directed evolution, rational design) is used to improve thermal stability, catalytic activity, and binding affinity. For instance, engineered FAST-PETase variants show significantly improved depolymerization rates under mild conditions (Joho et al., 2024).

3.2 Bioaugmentation Core Techniques

Bioaugmentation primarily utilizes two delivery methods to ensure the efficacy and longevity of introduced microbes (Muter, 2023):

Inoculation: The direct introduction of microbial biomass, which can include single potent strains or complex consortia. This process can be "cellular," relying on the survival of inoculated strains, or "genetic," where catabolic genes are spread to native populations via mobile genetic elements like plasmids.

Immobilization: Microorganisms are attached to solid carriers such as biochar, perlite, or synthetic beads. This protects microbes from environmental stressors (e.g., pH shifts, predatory protozoa) and enhances their stability, allowing for sustained activity over longer periods (Choi, 2025).

Strain Selection and Engineering

Recent research focuses on identifying and enhancing "plastic-eating" bacteria to address recalcitrant polymers (Jiang et al., 2025):

Isolation Sources: Potent degraders are frequently isolated from plastic-rich environments, including landfills, marine ecosystems, and the gut microbiomes of insects like waxworms and mealworms.

Genetic Engineering: Modern advances allow for splicing degradation pathways from various organisms into robust "industrial hosts."

Pseudomonas putida: This strain is often used as a chassis for genetic bioaugmentation because it can stably maintain engineered plasmids and efficiently degrade components like terephthalate (a PET breakdown product) in soil.

Pathways: Engineering efforts target enzymes like PETase and MHETase (from Ideonella sakaiensis) to be more robust, often increasing their catalytic efficiency and thermal stability for industrial applications.

Novel Sources: Beyond landfills, 2025 research has isolated a deep-sea Acinetobacter venetianus strain capable of degrading polyethylene (PE) by 12.2% within 56 days (Zhou et al., 2025).

Immobilization for Stability

Supports and Biofilms: Immobilizing enzymes like hydrolases on solid supports (biochar, silica gels) or within microbial biofilms significantly improves reusability and resistance to operational stress.

Activity Retention: In 2025, advanced enzyme-coated scaffolds are being developed for marine bioremediation to capture and degrade microplastics simultaneously (Ma et al., 2025a).

Metabolic Synergy: Synthetic microbial consortia are being designed so that one species initiates degradation while another converts the resulting monomers into value-added bioproducts like PHA bioplastics.

Limitations in Aquatic Systems

Competition and Establishment: Introduced strains often struggle to survive in open aquatic environments due to competition with native microflora.

Controlled Applications: Bioaugmentation is most effective in ex-situ systems such as (Naseem et al., 2023):

Bioreactors: For treating concentrated waste streams like plastic leachate.

Composting Facilities: Where bacterial consortia can degrade compostable plastics like PLA much faster than standard processes.

Pretreatments: To improve biological degradation in aquatic or soil systems, physical and chemical pretreatments (e.g., UV-irradiation, alkaline hydrolysis) are used to disrupt polymer bonds and increase susceptibility to microbial attack (Rezaei et al., 2024).

For organizations or researchers looking to implement these technologies, resources like the University of Minnesota Biocatalysis/Biodegradation Database (UM-BBD) or the enviPath tool provide essential metabolic pathway predictions.

3.3 Integrating Biological with Physicochemical Pre-Treatment

Given the kinetic barrier of biological action on intact polymers, a crucial strategy is pretreatment using mild AOPs or mechanical processes to create reactive sites on the plastic surface.

Concept of "Biological Readiness": A short oxidative pretreatment (e.g., UV/O_3, mild Fenton) can introduce carbonyl and carboxyl groups into polyolefin chains, making them more hydrophilic and susceptible to enzymatic cleavage (Bule Možar et al., 2024).

Synergistic Process Flow: A viable treatment train could be:
(Microplastic Waste) → (Mechanical Size Reduction) → (Mild Photocatalytic/Ozone Pre-oxidation) → (Bioaugmented Bioreactor).

This sequential approach leverages the speed of AOPs for initial activation and the sustainability of biology for final mineralization (Zhao et al., 2025).

3.4 Critical Analysis and Future Outlook

Bioremediation's primary appeal—its alignment with circular and green chemistry principles—is tempered by significant hurdles.

The Kinetics vs. Scale Dilemma: Even with engineered enzymes, degradation timescales (weeks to months) are often incompatible with the flow rates of municipal wastewater.

System Complexity and Control: Maintaining optimal conditions (pH, temperature, O_2, nutrient balance) for specific consortia in dynamic, real-world matrices are challenging and costly.

The End-Product Question: Complete mineralization to CO_2, while safe, is not a circular outcome. The future lies in bio-upcycling—designing pathways where plastic monomers are converted into higher-value bioproducts like bioplastics (PHA) or biosurfactants (Satti et al., 2024).

A comparison of biological degradation pathways for common polymers in shown in Table 3.

Table 3. Comparison of Biological Degradation Pathways for Common Polymers

Polymer Type	**Key Degrading Enzymes/Organisms**	**Optimal Environment**	**Degradation Timeframe (Lab)**	**Major Research Hurdle**	**Refrence**
PET (Polyester)	PETase, MHETase (*I. sakaiensis*)	Mesophilic, aqueous	Days-Weeks	Poor accessibility to highly crystallized PET; improving enzyme thermostability for industrial processing	Buhari et al., 2024
PE/PP (Polyolefins)	Laccase, Manganese Peroxidase (Fungal strains)	Solid-state, often with mediators	Months-Years	Extremely slow initial oxidation (C-C bond cleavage)	Cowan et al., 2022
PU (Polyurethane)	Urethanases, Esterases (*Pseudomonas* sp.)	Varied; typically, aqueous	Weeks-Months	Diversity of PU chemistries requires diverse enzyme cocktails	Soto-Hernández et al., 2025
PLA (Polylactic Acid)	Proteases, Lipases (e.g., Proteinase K)	Composting conditions	Weeks	Requires specific temperature (~60°C) and humidity	Shalem et al., 2024

4. HYBRID MEMBRANE SYSTEMS: COUPLING SEPARATION WITH DESTRUCTION

Membrane filtration alone (microfiltration, ultrafiltration, and nanofiltration) can effectively separate microplastics and some contaminants based on size exclusion, but it constitutes a concentration, not a destruction, process. This creates a concentrated waste stream (retentate) that requires further treatment.

Hybrid membrane systems strategically couple filtration with destructive processes (e.g., advanced oxidation, electrochemical, biological) either in an integrated single unit or as sequential stages to achieve simultaneous separation and degradation, minimizing waste and improving overall system resilience (Bodzek et al., 2023).

4.1 Membrane Bioreactors (MBRs) Enhanced with Advanced Oxidation

The conventional Membrane Bioreactor (MBR), which combines biological treatment with membrane filtration, can be augmented to target recalcitrant pollutants.

Integration of AOPs: Introducing low-dose oxidants (e.g., O_3, H_2O_2) or photocatalysts directly into the bioreactor or in a sidestream loop can pre-oxidize contaminants, enhancing their bioavailability to microbes and mitigating membrane fouling caused by microbial secretions (EPS/SMP) (Mohan & Nagalakshmi 2024).

Electro-Membrane Bioreactors (eMBRs): This innovative configuration integrates electrodes into the MBR. The applied electric field can: (1) reduce membrane fouling via electrocoagulation and electrophoretic motion of foulants, (2) generate in-situ oxidants (e.g., H_2O_2 at the cathode), and (3) stimulate microbial activity. This has shown promise in degrading complex pharmaceutical residues while maintaining flux (Moyo et al., 2022).

4.2 Catalytic Membrane Reactors

Here, the membrane itself is functionalized to act as both a separator and a catalyst, or a catalyst is embedded within the membrane matrix.

Photocatalytic Membranes: Nanostructured photocatalysts (e.g., TiO_2, g-C_3N_4) are immobilized onto or within polymeric or ceramic membranes. As contaminated water passes through, pollutants are both retained and degraded on the active membrane surface under light irradiation, theoretically offering self-cleaning properties (Li et al., 2023).

Electrocatalytic Membranes: Conductive membranes (e.g., carbon nanotube-based, Ti-based) serve as electrodes.

Applying a potential across the membrane enables simultaneous filtration and electrochemical oxidation of organics that contact the surface. This is particularly effective for treating the concentrated retentate stream from a primary filtration stage (Kafle et al., 2024).

4.3 Sequential Hybrid Systems: Filtration followed by Targeted Destruction

A pragmatic design employs membranes as a high-efficiency concentrator, with dedicated downstream units for destruction of the concentrate.

Logic of Concentration-Followed-by-Destruction: This approach is energy-efficient, as destructive processes (like AOPs) are applied only to a small, concentrated stream (~5-10% of the original flow) rather than the entire volume. Nanofiltration (NF) or reverse osmosis (RO) can produce a clean permeate and a reject rich in MPs and CECs (Safulko et al., 2023).

Destructive Options for Concentrate: The brine/concentrate can be treated with:

- **High-intensity AOPs**: Examples include plasma oxidation or supercritical water oxidation, which are excessively energy-intensive for dilute streams but become feasible for small volumes (Weng & Pei 2016).
- **Evaporation/Crystallization:** For ultimate volume reduction and potential salt recovery, though this is energy-intensive (Sharana et al., 2022).
- **Specialized Bioreactors:** Operated at high biomass concentrations to handle the elevated pollutant and salinity levels (Kirthiga et al., 2025).

4.4 Critical Evaluation: Fouling, Complexity, and Energy Trade-offs

Fouling Paradox: While some hybrids aim to reduce fouling (e.g., eMBRs), others can exacerbate it (e.g., deposition of photocatalyst particles or oxidation by-products on membranes). Fouling management dictates operational cost and longevity (Chen et al., 2023).

System Complexity and Control: Integrating multiple unit operations increases capital cost and requires sophisticated process control to balance hydraulic retention time, oxidation dose, and biological activity. This complexity can be a barrier to widespread adoption in conventional treatment plants (Chen et al., 2025).

The Energy Balance: The total system energy must be evaluated. While concentrating pollutants saves energy in the destruction step, the high pressure required for NF/RO and the energy for oxidation/electrolysis can lead to a substantial cumulative footprint. Life Cycle Assessment (LCA) is crucial for true sustainability evaluation (Pirayesh et al., 2025).

A comparison of hybrid membrane system configuration is shown in Table 4.

Table 4. Comparison of Hybrid Membrane System Configurations

System Type	Core Integration	Primary Advantage	Key Challenge	Best Suited For	Reference
AOP-Enhanced MBR	Oxidant (O_3, catalyst) added to biological tank	Reduces fouling, enhances biodegradation of CECs	Risk of damaging microbial community with excess oxidant	Upgrading existing municipal WWTPs	Xue et al., 2016
Electro-MBR (eMBR)	Electrodes submerged in bioreactor	*In-situ* fouling control & oxidation;	Electrode scaling; long-term stability of materials	Industrial wastewater with high fouling	Zhang et al., 2023
Photocatalytic Membrane	Catalyst coated/embedded on membrane	Simultaneous separation & degradation; self-cleaning	Catalyst leaching; light penetration/distribution in modules	Decentralized, point-of-use treatment systems	Chi and Xu, 2022
NF/RO + Concentrate Destruction	Membrane concentrator → Dedicated destruction unit	Energy-efficient by treating small volume; high	Handling of complex, saline concentrate	Water reclamation and reuse applications	Hübner et al., 2024

*Nanofiltration (NF), Reverse Osmosis (RO), advanced oxidation processes (AOPs)

5. DISCUSSION: SYNTHESIS, TRADE-OFFS, AND PATHWAYS TO IMPLEMENTATION

The Treatment Technology Matrix: No Single Solution

The preceding analysis of nano-sorbents, AOPs, bioremediation, and hybrid systems reveals a fundamental truth: no single technology offers a universally optimal solution for the diverse spectrum of microplastics and CECs (contaminants of emerging concerns) in aquatic environments. Selection is dictated by a complex matrix of parameters, including contaminant type (polymer vs. soluble chemical), concentration, water matrix complexity (wastewater vs. freshwater), required effluent quality, and economic constraints (Krishnan et al., 2023).

The Removal-Destruction Spectrum: Technologies are positioned along a spectrum that ranges from separation methods, such as membranes and sorption, to processes that involve partial degradation, including biofragmentation and partial oxidation, ultimately leading to complete mineralization. Separation creates a secondary waste stream requiring disposal, while destruction aims to close the material loop but often at higher energy or chemical cost.

The Scale-Kinetics Dilemma: Biological and some photocatalytic processes offer "greener" pathways but operate on timescales (hours to days) often incompatible with the hydraulic retention times of large treatment plants. Conversely, high-energy AOPs like plasma oxidation are fast but prohibitively expensive for high-volume, low-concentration scenarios (Choi et al., 2024).

Overcoming Key Cross-Cutting Challenges

All advanced remediation strategies face common, formidable barriers that must be addressed for successful translation from lab to field.

Fouling and Stability: Whether membrane fouling, catalyst deactivation, or biofilm disruption, the loss of performance in complex real-world matrices is the primary operational hurdle. Research must shift from reporting ideal batch efficiencies to demonstrating long-term stability in continuous-flow systems with real wastewater (Nie et al., 2024).

Secondary Pollution and Lifecycle Impacts: The potential for nanomaterial leakage, toxic by-product formation (e.g., bromate from ozonation, chlorinated organics from electrochemical processes), and the environmental burden of energy/chemical use necessitate comprehensive Life Cycle Assessment (LCA). A technology that removes microplastics but has a high carbon footprint or creates more toxic intermediates is not sustainable (Ramadan et al., 2024).

Detection and Monitoring: The effectiveness of any treatment is contingent on reliable analytical methods to measure removal of both particulates and associated chemicals. Standardized protocols for sampling and analyzing complex, degraded mixtures of MPs and CECs are urgently needed to enable fair comparison between studies (Sharma et al., 2024).

The Imperative of Integrated, Smart Treatment

The future lies not in a singular "magic bullet" but in intelligently sequenced hybrid systems. The goal is to leverage the strength of each technology where it is most effective, creating a synergistic process train.

Proposed Framework for a Next-Generation Treatment Plant: A conceptual advanced treatment train could involve:

- **Primary Concentration:** Use of low-energy physical separation (e.g., dynamic membrane filtration, dissolved air flotation) to remove the bulk of particulate MPs.
- **Pre-Treatment/Breakdown:** The concentrate and the soluble fraction undergo mild catalytic pre-oxidation (e.g., heterogeneous Fenton, catalytic ozonation) to functionalize polymers and break down complex CECs.
- **Biological Polishing:** The effluent, now containing more biodegradable intermediates, enters a high-rate, bioaugmented bioreactor (e.g., moving bed biofilm reactor - MBBR) for final organic carbon removal.
- **Polishing & Resource Recovery:** A final polishing step (e.g., activated carbon, advanced oxidation) ensures stringent effluent standards. Crucially, waste streams (sludge, spent sorbents) are routed to resource recovery (e.g., anaerobic digestion, thermal conversion to syngas) (Venkatachalam et al., 2024).

- **The Role of Digitalization:** Smart sensors, machine learning for process control, and digital twins can optimize such complex systems in real-time, adjusting chemical doses, hydraulic flow, and energy input based on incoming pollutant loads (Ma et al., 2025b).

Concluding Remarks and Future Horizons

Addressing the crisis of microplastics and CECs requires a paradigm shift in environmental engineering—from linear "remove and dispose" to circular "capture, destroy, and valorize." The technologies reviewed are rapidly evolving, with the most promising advances occurring at their interfaces (e.g., bio-electrochemical systems, photocatalytic membranes).

The path forward demands:

Interdisciplinary Research: Close collaboration between material scientists, microbiologists, process engineers, and data scientists.

Pilot-Scale Validation: Rigorous, long-term testing of integrated systems under real conditions, with transparent reporting of costs and failures.

Supportive Policy and Regulation: Standards that incentivize advanced treatment and internalize the environmental cost of pollution, driving innovation and implementation.

The engineering community has the toolkit to confront this challenge; the task now is to assemble it wisely, efficiently, and with unwavering commitment to systemic sustainability.

CONCLUSION

This chapter has provided a critical review of the frontier technologies poised to address the persistent challenge of microplastics and contaminants of emerging concern in aquatic systems. From the precision of nano-sorbents and the destructive power of advanced oxidation processes to the sustainable promise of bioremediation and the integrated efficiency of hybrid membrane systems, each approach presents a unique set of capabilities and limitations. The analysis underscores that technological silos are insufficient; the complexity of the pollution matrix demands smart, multi-barrier treatment trains that leverage sequential strengths.

The paramount challenges remain scalability, energy efficiency, and the avoidance of secondary impacts, all of which must be evaluated through holistic life-cycle assessment. The subsequent chapter will build upon this technological foundation by examining the economic, policy, and circular economy frameworks necessary to translate these engineering solutions from pilot-scale innovation to widespread implementation, ultimately guiding the design of resilient and sustainable water infrastructure for the future.

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CHAPTER 3
CIRCULAR ECONOMY STRATEGIES FOR THE VALORIZATION OF DAIRY SLUDGE

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INTRODUCTION

The dairy industry is one of the most resource-intensive sectors within the global agro-food system, particularly in terms of water, energy, and raw material consumption. Rapid growth in global dairy demand, driven by population increase and changing dietary patterns, has resulted in a significant expansion of milk processing activities worldwide. As a consequence, large volumes of wastewater and sludge are generated during dairy processing operations, including milk reception, pasteurization, cheese and yogurt production, and cleaning-in-place (CIP) procedures (Mohapatra et al., 2025).

Recent studies report that dairy processing plants typically generate between 2 and 6 L of wastewater per liter of milk processed, depending on plant size, processing technology, and water management practices. The treatment of this wastewater inevitably leads to the production of considerable quantities of sludge, commonly referred to as dairy processing sludge (DPS), which represents a major environmental and operational challenge for the dairy sector (Mohapatra et al., 2025).

DPS is characterized by a high content of biodegradable organic matter, including fats, proteins, lactose-derived carbohydrates, and suspended solids, as well as significant concentrations of nutrients such as nitrogen and phosphorus. These characteristics make DPS both an environmental liability and a potentially valuable secondary resource. When improperly managed or disposed of, DPS can cause severe environmental impacts, including eutrophication of surface waters, groundwater contamination, soil degradation, odor nuisance, and the emission of greenhouse gases such as methane and nitrous oxide (Basri et al., 2025). In addition, uncontrolled sludge disposal may pose public health risks due to the presence of pathogenic microorganisms and residual chemicals from cleaning agents.

Traditionally, dairy sludge management has relied on disposal-oriented practices such as landfilling, incineration, and direct land application. However, these approaches are increasingly considered unsustainable. Landfilling contributes to long-term environmental pollution and methane emissions, incineration requires high energy inputs and generates air pollutants, while uncontrolled land application may lead to nutrient leaching and regulatory non-compliance (Basri et al., 2025).

Moreover, rising disposal costs and increasingly stringent environmental regulations are placing additional pressure on dairy industries to seek alternative sludge management solutions.

In this context, environmental engineering research has progressively shifted from waste disposal toward waste valorization, in line with the principles of the circular economy. Circular economy-based strategies aim to transform DPS from a waste stream into a source of renewable energy, nutrients, and value-added materials, while simultaneously reducing environmental impacts and improving resource efficiency (Elgarahy et al., 2025). Technologies such as anaerobic digestion, composting, thermochemical conversion (pyrolysis and hydrothermal carbonization), and integrated hybrid systems have gained increasing attention as sustainable pathways for DPS management.

Among these approaches, anaerobic digestion is widely recognized for its ability to recover energy in the form of biogas, while thermochemical processes enable the production of stable carbon-rich materials such as biochar and hydrochar, which can be reused in agriculture and environmental remediation. Integrated systems combining biological and thermochemical treatments are particularly promising, as they maximize energy recovery, nutrient recycling, and greenhouse gas mitigation (Saleh et al., 2025).

Against this background, the present chapter provides a comprehensive review of recent scientific advances (2024–2025) in the sustainable valorization of dairy processing sludge from an environmental engineering perspective. The chapter critically analyzes conventional and emerging valorization technologies, assesses their environmental and economic performance based on life cycle assessment studies, and discusses key challenges and future research directions for the implementation of circular economy strategies in the dairy sector.

1. CHARACTERISTICS OF DAIRY PROCESSING SLUDGE

Dairy processing sludge originates primarily from physicochemical and biological wastewater treatment units, including primary sedimentation, dissolved air flotation, and activated sludge systems.

Its composition varies depending on milk type, processing operations, cleaning-in-place practices, and treatment configuration. Typical DPS characteristics reported in recent literature include high chemical oxygen demand (COD), high volatile solids (VS) content, and significant nutrient concentrations (Mohapatra et al., 2025). These properties make DPS particularly suitable for biological and thermochemical conversion processes.

To provide a clearer understanding of the typical composition of dairy processing sludge and its suitability for valorization pathways, Table 1 summarizes the representative physicochemical characteristics of DPS as reported in recent studies

Table 1. Typical Physicochemical Characteristics of Dairy Processing Sludge ((Mohapatra et al., 2025))

Total solids	3–8%
Volatile solids	65–80% of TS
COD	20–80 g/L
Total nitrogen	30–60 g/kg TS
Total phosphorus	5–15 g/kg TS

The high biodegradability of DPS represents both a risk and an opportunity. While uncontrolled degradation leads to emissions and pollution, controlled valorization enables resource recovery.

2. CONVENTIONAL MANAGEMENT PRACTICES AND LIMITATIONS

Conventional management practices for dairy processing sludge (DPS) have historically focused on disposal-oriented solutions, including landfilling, incineration, and direct land application. While these approaches are widely implemented due to their relative simplicity and established regulatory frameworks, they are increasingly recognized as environmentally and economically unsustainable in the context of modern waste management and circular economy objectives (Basri et al., 2025).

Landfilling remains a common practice in regions with limited wastewater treatment and valorization infrastructure, particularly in developing countries.

However, DPS disposal in landfills leads to significant environmental concerns, including the generation of methane through anaerobic degradation, leachate production, and long-term soil and groundwater contamination. Methane emissions from landfilled organic sludge contribute substantially to climate change, while leachate management imposes additional operational and financial burdens (Basri et al., 2025). Furthermore, increasing landfill taxes and space limitations are progressively restricting the viability of this option.

Incineration is another widely applied management route, particularly in industrialized regions where volume reduction and pathogen destruction are prioritized. Incineration can reduce sludge volume by up to 80–90%, thereby minimizing disposal requirements. Nevertheless, this process is highly energy-intensive, especially for sludge with high moisture content such as DPS, which often necessitates extensive pre-drying. In addition, incineration generates air pollutants, including nitrogen oxides (NO_x), particulate matter, and potentially toxic residues in the form of ash, which require further treatment or disposal (Saleh et al., 2025). These factors significantly increase operational costs and limit the environmental sustainability of incineration-based approaches.

Direct land application of DPS is often promoted as a low-cost solution that enables nutrient recycling, particularly nitrogen and phosphorus, which are beneficial for agricultural soils. However, this practice is associated with several risks if not properly controlled. These include the potential spread of pathogens, odor nuisance, accumulation of heavy metals, and nutrient leaching into surface and groundwater systems, leading to eutrophication (Hamdi et al., 2019). Regulatory constraints regarding sludge quality, application rates, and seasonal restrictions further limit the widespread applicability of land application, particularly in regions with intensive agriculture.

Collectively, these limitations highlight the inadequacy of conventional DPS management practices in addressing current environmental, economic, and regulatory challenges. Disposal-based approaches not only fail to exploit the significant energy and material potential of DPS but also contribute to greenhouse gas emissions and resource inefficiencies. Consequently, there is growing interest in alternative management strategies that prioritize resource recovery and value generation rather than waste disposal (Mohapatra et al., 2025).

These challenges have driven the development and implementation of sustainable valorization pathways that integrate energy recovery, nutrient recycling, and material reuse. Such approaches represent a paradigm shift from linear waste management models toward circular economy-based systems, which are increasingly regarded as essential for the long-term sustainability of the dairy industry.

3. SUSTAINABLE VALORIZATION PATHWAYS

3.1 Anaerobic Digestion and Biogas Production

Anaerobic digestion (AD) is the most mature and widely implemented technology for the sustainable valorization of dairy processing sludge (DPS), owing to its ability to simultaneously reduce organic pollution and recover renewable energy. AD involves the biological conversion of organic matter into biogas under anaerobic conditions through a sequence of biochemical stages, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The produced biogas typically consists of 55–70% methane (CH_4) and 30–45% carbon dioxide (CO_2), and can be utilized for heat and electricity generation or upgraded to biomethane for grid injection and transport applications (Jacob et al., 2025).

DPS is particularly well suited for anaerobic digestion due to its high volatile solids content and readily biodegradable organic fractions, including fats, proteins, and carbohydrates derived from milk processing operations. However, the presence of complex organic structures, long-chain fatty acids, and residual cleaning agents can limit biodegradability and process stability, leading to suboptimal methane yields if AD is applied without prior treatment (Jacob et al., 2025). Consequently, recent research has increasingly focused on enhancing AD performance through the application of physical, chemical, and biological pretreatment techniques.

Pretreatment methods aim to improve sludge solubilization, disrupt microbial cell walls, and increase the availability of organic substrates for anaerobic microorganisms. Among these approaches, oxidative pretreatment using hydrogen peroxide (H_2O_2) has gained significant attention due to its effectiveness and relatively low environmental impact.

Kheiredine et al. (2025) demonstrated that H_2O_2-based oxidative pretreatment significantly enhanced the biodegradability of dairy sludge, resulting in methane yield increases of up to 35% compared to untreated sludge. Similar improvements have been reported for other pretreatment techniques, including thermal, ultrasonic, and alkaline treatments, which promote organic matter solubilization and accelerate hydrolysis, the rate, limiting step of anaerobic digestion.

In addition to improving methane production, pretreatment strategies can enhance process stability and reduce hydraulic retention time, thereby improving the overall efficiency and economic viability of AD systems. Co-digestion of DPS with other agro-industrial residues has also been shown to balance nutrient composition, mitigate inhibitory effects, and further increase biogas yields (Mohapatra et al., 2025).

From an environmental engineering perspective, AD-based valorization of DPS offers significant benefits, including substantial reductions in chemical oxygen demand (COD), lower greenhouse gas emissions compared to conventional disposal methods, and the production of digestate that can be further valorized as a biofertilizer or subjected to downstream thermochemical processing. Life cycle assessment studies consistently indicate that AD-based systems outperform landfilling and incineration in terms of climate change mitigation and resource efficiency.

Overall, anaerobic digestion represents a cornerstone technology in the transition toward sustainable and circular management of dairy processing sludge. When combined with appropriate pretreatment and integrated valorization pathways, AD can significantly enhance energy recovery, reduce environmental impacts, and contribute to the implementation of circular economy strategies within the dairy industry.

To illustrate the impact of pretreatment intensity on anaerobic digestion performance, Figure 1 presents the effect of oxidative pretreatment on methane yield during the anaerobic digestion of dairy processing sludge.

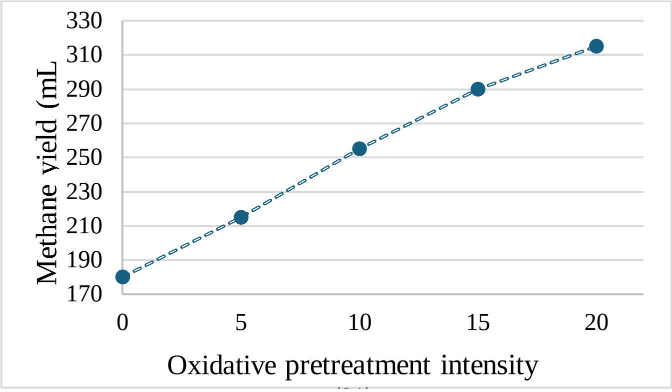

Figure 1. Effect of oxidative pretreatment intensity on methane yield during anaerobic digestion of dairy sludge (Source: (Jacob et al., 2025)).

3.2 Composting and Agricultural Valorization

Composting is a biological stabilization process that converts dairy processing sludge (DPS) into a stable, nutrient-rich soil amendment through controlled aerobic biodegradation of organic matter. This process contributes to volume reduction, organic matter stabilization, and transformation of nutrients into forms that are more suitable for agricultural reuse. Due to its relatively low technological complexity and moderate investment costs, composting remains a widely adopted management option for agro-industrial sludge, particularly in regions where advanced energy recovery technologies are not fully implemented (Basri et al., 2025).

The effectiveness of DPS composting strongly depends on appropriate process control to ensure pathogen inactivation, odor mitigation, and nutrient conservation. Critical operational parameters include temperature, aeration rate, moisture content, and the carbon-to-nitrogen (C/N) ratio. Maintaining thermophilic conditions above 55 °C for sufficient residence time is essential to achieve hygienization and eliminate pathogenic microorganisms, while suboptimal aeration can promote anaerobic zones and lead to nitrogen losses through ammonia volatilization (Basri et al., 2025).

Recent studies emphasize the importance of co-composting DPS with suitable bulking agents, such as straw, sawdust, or agricultural residues, to improve porosity, oxygen diffusion, and structural stability of the composting matrix.

Co-composting has been shown to significantly enhance compost maturity, reduce odor emissions, and improve nitrogen retention compared to mono-composting of sludge. In addition, the incorporation of biochar during composting has received increasing attention due to its ability to retain nutrients, reduce greenhouse gas emissions, and improve the physicochemical properties of the final compost product (Basri et al., 2025).

Although composting does not enable direct energy recovery, unlike anaerobic digestion, it plays a crucial role in nutrient recycling and soil organic matter replenishment within circular agricultural systems. DPS-derived compost can partially substitute synthetic fertilizers, thereby reducing dependence on non-renewable nutrient resources and contributing to improved soil fertility and structure. Nevertheless, concerns remain regarding the potential accumulation of heavy metals and emerging contaminants, highlighting the need for stringent quality control measures and compliance with regulatory standards prior to land application.

From a circular economy perspective, composting represents a complementary valorization pathway that supports the closure of nutrient loops between dairy processing facilities and agricultural systems. When integrated with upstream energy recovery technologies, such as anaerobic digestion, composting of digestate or residual solids can significantly enhance overall resource efficiency and environmental performance of DPS management systems (Basri et al., 2025).

3.3 Thermochemical Valorization: Pyrolysis and Hydrothermal Carbonization

Thermochemical processes such as pyrolysis and hydrothermal carbonization (HTC) are increasingly investigated as promising pathways for the valorization of dairy processing sludge (DPS), particularly when biological treatment alone is insufficient to fully recover material value. These processes enable the conversion of organic sludge into stable, carbon-rich products while significantly reducing volume and improving material stability. Pyrolysis involves the thermal decomposition of dried sludge under oxygen-free conditions, typically at temperatures ranging from 400 to 700 °C, producing three main fractions: solid biochar, liquid bio-oil, and gaseous syngas.

In contrast, HTC treats wet sludge under subcritical water conditions at moderate temperatures (180–250 °C) and elevated pressures, eliminating the need for energy-intensive drying steps and yielding hydrochar as the primary solid product. Both pyrolysis and HTC offer advantages in terms of pathogen destruction, reduction of organic pollutants, and stabilization of potentially hazardous components. In particular, the solid char products obtained from these processes exhibit enhanced physicochemical properties, including high carbon content, increased surface area, and improved structural stability. Biochar derived from DPS has demonstrated considerable potential for various environmental applications, including its use as a soil conditioner to improve soil structure and nutrient retention, as an adsorbent for organic and inorganic pollutants in soil and water systems, and as a carbon sequestration material contributing to long-term climate change mitigation (Gautam et al., 2025).

Despite these benefits, thermochemical valorization processes generally require higher capital investment and operational control compared to biological treatments. Consequently, they are often considered most effective when integrated with upstream processes such as anaerobic digestion, where digestate can be further stabilized and converted into value-added carbon materials. From an environmental engineering perspective, pyrolysis and HTC represent complementary technologies that enhance the overall efficiency of DPS management and support the transition toward circular and low-carbon waste management systems. To clarify the main thermochemical conversion routes available for dairy processing sludge, Figure 2 illustrates the valorization pathways through pyrolysis and hydrothermal carbonization.

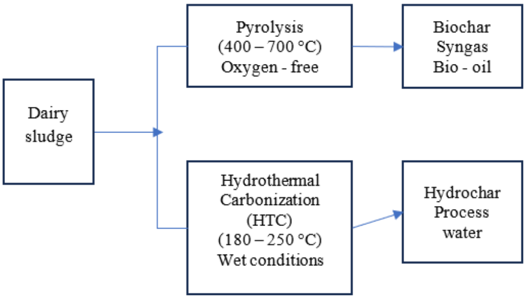

Figure 2. Thermochemical Valorization Pathways Of Dairy Sludge Through Pyrolysis And Hydrothermal Carbonization (Source: (Gupta Et Al., 2025)).

3.4 Integrated and Hybrid Valorization Approaches

Integrated systems combining anaerobic digestion (AD) with thermochemical processes offer a promising strategy for maximizing resource recovery from dairy processing sludge (DPS). In such hybrid configurations, AD is typically employed as a primary treatment step to stabilize organic matter and recover energy in the form of biogas. The resulting digestates, which still contains a substantial fraction of organic carbon and nutrients, can subsequently be subjected to thermochemical treatments such as pyrolysis or hydrothermal carbonization to further enhance material valorization.

The conversion of digestate through pyrolysis enables the production of biochar, a stable carbon-rich material that can be reused in agricultural and environmental applications. This sequential approach not only maximizes overall energy recovery by combining biogas production with downstream material conversion, but also significantly reduces the volume and environmental footprint of residual solids. Moreover, the integration of biological and thermochemical pathways allows for improved nutrient management, as nutrients retained in the digestate can be partially stabilized within the char matrix, reducing losses and improving long-term soil availability.

Such hybrid valorization approaches align strongly with circular economy objectives by closing energy and material loops, minimizing waste generation, and enhancing resource efficiency across the treatment chain. From an environmental engineering perspective, integrated AD–thermochemical systems represent an effective pathway toward sustainable sludge management, offering both environmental benefits and opportunities for value creation within the dairy industry ((Gupta et al., 2025)).

As a synthesis of hybrid valorization strategies, Figure 3 illustrates an integrated circular framework highlighting energy recovery, material reuse, and environmental benefits associated with dairy processing sludge management.

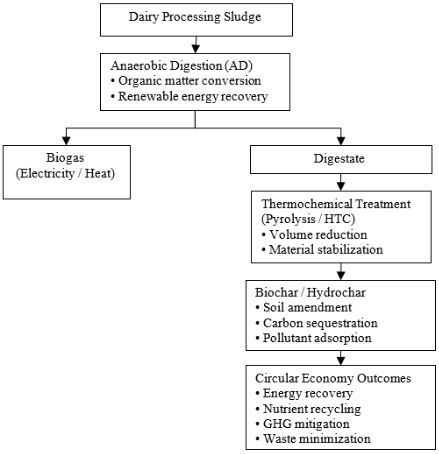

Figure 3. Integrated Circular Valorization Framework For Dairy Processing Sludge (Source:(Gupta et al., 2025)).

4. ENVIRONMENTAL AND ECONOMIC ASSESSMENT

Life cycle assessment (LCA) is widely used to evaluate the environmental performance of DPS management scenarios. Recent LCAs consistently show that AD-based valorization pathways significantly reduce GHG emissions compared to landfilling and incineration (Ahmad et al., 2025).

Based on life cycle assessment results, Figure 4 illustrates the differences in greenhouse gas emissions among landfilling, incineration, and anaerobic digestion-based valorization pathways for dairy processing sludge.

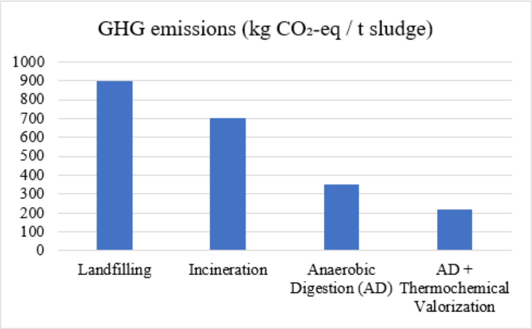

Figure 4. Comparison of greenhouse gas emissions for different dairy sludge management options (Ahmad et al., 2025))

From an economic perspective, AD is generally the most cost-effective option at medium to large scales, particularly when energy recovery incentives are available. Thermochemical processes show promise but often require higher capital investment.

5. CHALLENGES AND FUTURE PERSPECTIVES

Despite significant technological advances in the valorization of dairy processing sludge, several technical, economic, and institutional challenges remain. One of the major constraints is the inherent variability in sludge composition, which depends on milk type, processing operations, seasonal production patterns, and wastewater treatment configurations. This variability can affect process stability, treatment efficiency, and the quality of valorized products, making standardization and large-scale implementation more complex.

Scale-up limitations also represent a critical barrier to the widespread adoption of advanced valorization technologies. Many processes that demonstrate promising performance at laboratory or pilot scale encounter operational, economic, and logistical challenges when transferred to industrial-scale applications. High capital investment costs, energy requirements, and the need for skilled operation can limit the feasibility of these technologies, particularly for small and medium-sized dairy processing facilities.

Regulatory and institutional barriers further influence the deployment of sustainable sludge valorization pathways. In many regions, unclear or restrictive regulations regarding waste classification, product quality standards, and land application of sludge-derived products hinder market development and industrial uptake. In addition, market uncertainty for valorized products such as biochar, hydrochar, and recovered nutrients can discourage investment and slow technology adoption.

Future research efforts should therefore focus on process optimization and the development of integrated and hybrid systems that enhance overall efficiency, robustness, and economic viability. Advances in digital monitoring, automation, and data-driven process control offer significant potential to improve system performance, reduce operational risks, and enable adaptive management of variable feedstocks.

In parallel, supportive policy frameworks and economic incentives are essential to facilitate the transition from linear waste management practices toward circular and resource-efficient systems. Emerging technologies, including bioelectrochemical systems and advanced nutrient recovery methods, represent promising future directions for dairy processing sludge valorization. These approaches have the potential to enable targeted recovery of energy and nutrients while minimizing environmental impacts, further reinforcing the role of environmental engineering in advancing sustainable and circular solutions for the dairy industry.

CONCLUSION

Sustainable valorization of dairy processing sludge represents both a critical challenge and a significant opportunity for environmental engineering in the context of increasing resource scarcity, climate change mitigation, and stricter environmental regulations. Dairy processing sludge, traditionally regarded as a problematic waste stream, contains substantial amounts of organic matter and nutrients that can be strategically recovered and reused through appropriate treatment and valorization pathways. Addressing this challenge requires a shift from conventional disposal-oriented practices toward integrated, resource-efficient management strategies.

The integration of biological and thermochemical pathways within a circular economy framework offers a robust solution for transforming dairy processing sludge from an environmental burden into a valuable source of renewable energy, nutrients, and bio-based materials. Biological processes such as anaerobic digestion enable effective organic matter stabilization and energy recovery in the form of biogas, while thermochemical treatments such as pyrolysis and hydrothermal carbonization further enhance material recovery by converting residual solids into stable carbon-rich products. These integrated approaches maximize overall resource efficiency, reduce greenhouse gas emissions, and support long-term environmental sustainability.

Despite the demonstrated technical potential of these valorization pathways, their large-scale implementation remains constrained by several challenges, including process optimization, economic feasibility, regulatory compliance, and market acceptance of valorized products.

Continued research is therefore essential to improve process efficiency, develop cost-effective hybrid systems, and better understand the environmental impacts of emerging technologies through comprehensive life cycle assessment. In parallel, supportive policy frameworks and economic incentives are required to encourage the adoption of sustainable sludge management practices within the dairy industry.

Furthermore, effective collaboration between academia, industry, and policymakers is crucial to bridge the gap between research and practical application. Ultimately, the sustainable valorization of dairy processing sludge represents a key pathway toward more resilient, low-carbon, and resource-efficient dairy production systems, reinforcing the central role of environmental engineering in advancing sustainable industrial development.

Abbreviations

AD	Anaerobic Digestion
BOD	Biological Oxygen Demand
CE	Circular Economy
CH_4	Methane
CIP	Cleaning-In-Place
COD	Chemical Oxygen Demand
CO_2	Carbon Dioxide
DPS	Dairy Processing Sludge
GHG	Greenhouse Gas
HTC	Hydrothermal Carbonization
LCA	Life Cycle Assessment
NO_x	Nitrogen Oxides
TS	Total Solids
VS	Volatile Solids

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