Dry anaerobic digestion of organic waste: operational determinants, reactor configurations, economics and process control

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Abstract

Dry anaerobic digestion (AD) enables the treatment of organic wastes at high total solids (TS) with reduced process-water demand and reactor volume, but high-solids operation also imposes limitations on mass transfer, substrate–inoculum contact, process kinetics and feed handling. This review critically synthesizes research and full-scale experience on the operational determinants, reactor configurations, process monitoring and economics of dry AD. The literature indicates that free-water availability, substrate degradability, inoculum activity and nutrient bioavailability are more informative for process performance than bulk parameters such as TS and total C/N ratio alone. Agricultural batch systems are operationally simple and require limited process control, but typically involve long batch cycles, multiple parallel reactors and substantial inoculum recycle, resulting in relatively low volumetric productivity. Continuous municipal systems can achieve higher throughput but are more susceptible to VFA and ammonia accumulation under high loading or proteinrich feedstocks. Pretreatment is most beneficial for recalcitrant substrates when it shortens retention time or increases reactor throughput, whereas intensive pretreatment of readily degradable wastes can reduce process stability. Full-scale comparisons show that lower investment and operating costs can offset the lower methane productivity of dry AD, while plant scale, gate fees, energy utilization and digestate management strongly influence profitability. Advanced sensors, modelling and AI-based control are promising, although their validation in heterogeneous high-solids matrices remains limited. Digestate management remains also as an important constraint because nutrient concentrations are low on a fresh-mass basis and

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agricultural use may be restricted for digestate derived from mechanically separated mixed municipal waste.

Keywords: Dry anaerobic digestion; high-solids digestion; organic waste; technoeconomics; process monitoring; biomethane

Abbreviations

AD, anaerobic digestion; AI, artificial intelligence; BMP, biochemical methane potential; C/N, carbon-to-nitrogen; CHP, combined heat and power; HRT, hydraulic retention time; IRR, internal rate of return; ML, machine learning; NPV, net present value; OFMSW, organic fraction of municipal solid waste; OLR, organic loading rate; TAN, total ammonia nitrogen; TS, total solids; UASB, upflow anaerobic sludge blanket; VFA, volatile fatty acid; VFA/TA, ratio of volatile fatty acids to total alkalinity; VS, volatile solids.

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1. Introduction

Anaerobic digestion (AD) is an established biological process for treating biodegradable organic wastes and converting part of their chemical energy into biogas. Diverting biowaste from landfill to AD avoids the uncontrolled methane emissions that result from anaerobic decay in landfills and yields a stabilized digestate that may be returned to soil when its quality meets regulatory requirements [Pramanik et al., 2019]. The technology has evolved from wet digestion of pumpable slurries to high-solids, or dry, configurations suited to substrates with limited free water, such as the organic fraction of municipal solid waste (OFMSW), food waste, solid manures, crop residues and selected industrial residues [Shohei et al., 2020].

Dry AD, also referred to as solid-state or high-solids AD, typically operates above 15% total solids (TS), and most full-scale and pilot systems operate at about 20-40% TS [Kothari et al., 2014]. Compared with wet AD, dry AD requires less process water, can operate at higher organic loading rates, and reduces reactor volume and digestate volume [Luning et al., 2003; Rocamora et al., 2020]. These advantages are accompanied by engineering constraints related to feedstock conveying, poor mass transfer, high viscosity, localized accumulation of inhibitors and difficult mixing [Momayez et al., 2019]. A concise comparison of wet and dry AD is provided in Table 1. Recent work on selectively collected biowaste also frames dry AD as particularly relevant for municipal organic-fraction treatment where water use, energy efficiency, contamination control and circular-economy integration are decisive design criteria [Bień et al., 2025].

Recent reviews emphasize that the limiting mechanisms in dry AD are physical as well as biochemical. Rheological properties, particle size, water distribution and substrateinoculum contact govern hydrolysis, the diffusion of soluble intermediates and the dilution of inhibitory compounds [Wang et al., 2023; Gao et al., 2023]. Thus, high methane yield cannot be achieved solely by increasing feed concentration; the solids content must be balanced against mass-transfer capacity, alkalinity, inoculum activity and reactor design.

Despite the maturity of several commercial dry AD technologies, wider implementation is still constrained by long start-up periods, limited process monitoring in high-solids matrices, feedstock heterogeneity and difficulty in maintaining homogeneous conditions [Fernández-

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Güelfo et al., 2012; Akinbomi et al., 2022]. Two recent lines of work address the root cause, namely slow conversion in the absence of a liquid phase. First, intracellular disintegration of biowaste by shockwaves accelerated methanogenesis even without a liquid phase [Stehel et al., 2018], and disintegration applied in the middle phase of a commercialscale dry fermentation, combined with pyrolysis of the digestate, shortened the payback period by more than 7% [Stehel et al., 2020]. Second, nutrient management based on the bioavailability of carbon and nitrogen, rather than on the total C/N ratio, has been proposed to accelerate biogas production from food waste while reducing the need for agricultural co-substrates [Maroušek et al., 2024]. Recent literature on organic solid waste AD further shows that reactor configuration, operating parameters, pretreatment choices and technoeconomic context must be considered together rather than as independent design variables [Prasanna Kumar et al., 2024].

For plant developers, operators and investors, the practical question is no longer whether dry AD works, since it has operated at full scale for three decades, but which constraint limits its profitability and, therefore, where investment in process improvement pays off. The question has become urgent for three reasons. Since 1 January 2024, European Union Member States have been required to collect biowaste separately or recycle it at source [Directive (EU) 2018/851], which increases the supply of stackable, contaminant-bearing feedstock for which dry AD is designed. The REPowerEU plan targets 35 billion m^3 of biomethane per year by 2030 [European Commission, 2022], whereas biomethane production in Europe reached 5.2 billion m^3 in 2024 [European Biogas Association, 2025]. Finally, only part of the global biomethane potential can be produced at or below prevailing wholesale natural-gas prices [IEA, 2025], so gains in capital productivity directly affect competitiveness.

Against this background, this review tests the following hypothesis: the principal barrier to wider deployment of dry AD is the slower conversion caused by limited free water, which prolongs the retention time and increases the reactor capacity, and thus the capital, required per tonne treated, rather than inhibition by VFAs, ammonia or hydrogen sulfide per se. A corollary is that interventions that accelerate conversion, such as disintegration, bioavailability-based nutrient management, digestate recirculation or improved inoculation,

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are economically justified only when the value of the reactor capacity they release and of the additional methane they yield exceeds their capital, energy and stability costs. If the hypothesis is confirmed, development effort should focus on kinetics and capital productivity; if it is rejected, process control and inhibitor management should take priority. The objective of this review is to evaluate this hypothesis by synthesizing evidence on the operational determinants, reactor configurations, monitoring and economics of dry AD, and to identify conflicting findings, knowledge gaps and research priorities that are relevant to industrial practice.

2. Materials and methods: review approach and scope

This manuscript is structured as a narrative review with a documented search strategy. Literature was identified in Scopus and Web of Science Core Collection, complemented by Google Scholar for books, book chapters and technical reports, and by backward and forward citation tracking of key reviews. The main search covered January 2000 to June 2026; earlier works were retained when they described seminal technologies or full-scale plants. Search strings combined process terms ("dry anaerobic digestion" OR "high-solids anaerobic digestion" OR "solid-state anaerobic digestion" OR "dry fermentation" OR "leach-bed") with topic terms (inoculum, total solids, co-digestion, C/N, pretreatment, reactor, plug-flow, batch, monitoring, sensor, machine learning, techno-economic, cost, digestate, full-scale). Records were included when they (i) concerned AD at or above about 15% TS, or wet-AD studies whose findings are directly transferable to high-solids operation (e.g., sensor development or pretreatment chemistry); (ii) reported original data, a critical review, a techno-economic or life-cycle assessment, or full-scale operating experience; and (iii) were published in English in peer-reviewed journals, edited books or by recognized agencies (e.g., IEA, IRENA and the European Biogas Association). Records were excluded when they addressed only wet AD of liquid substrates without relevance to high-solids operation, lacked methodological detail, or duplicated data published elsewhere. Regulatory documents were consulted to establish the legal context for digestate use. A literature synthesis was considered sufficient to test the hypothesis stated in Section 1 because its components, namely the effect of water availability

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on conversion rate, the incidence of inhibition at full scale, and the relationship between retention time, capital cost and revenue, have been quantified independently in many laboratory, pilot, full-scale and techno-economic studies. Consistency or inconsistency in the direction of these effects across feedstocks, scales and regions therefore provides a meaningful test, although a synthesis cannot replace a controlled experiment for quantifying effect sizes. Patents were not included as primary evidence. Patent documents disclose claims rather than independently verified performance, rarely report comparable operating data (TS, retention time, methane yield and costs), and would require a separate search methodology based on patent classification in databases such as Espacenet. The most important proprietary technologies are nevertheless covered through peer-reviewed full-scale performance data and supplier information (Table 4). Recent proprietary developments that are not yet documented in the scientific literature may therefore be under-represented, which we acknowledge as a limitation. Because dry AD performance depends strongly on feedstock, inoculum, reactor type and operating mode, numerical values are interpreted as indicative ranges or case-specific observations and, where studies disagree, the likely causes of the disagreement are discussed (Section 9).

3. Theory of dry anaerobic digestion

Dry AD follows the same biochemical sequence as wet AD, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis, but proceeds more slowly because limited free water restricts enzyme access to particles, the diffusion of soluble intermediates and the dilution of inhibitors (Fig. 1) [Bollon et al., 2011; Gao et al., 2023].

4. Factors affecting dry anaerobic digestion

4.1. Microbial community and inoculum management

Successful dry AD depends on the coordinated activity of hydrolytic, acidogenic, acetogenic and methanogenic microorganisms. Hydrolytic microorganisms depolymerize carbohydrates, proteins and lipids to soluble monomers; acidogens convert these products to VFAs, alcohols, carbon dioxide and hydrogen; acetogens generate acetate, hydrogen and

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carbon dioxide; and methanogens convert acetate or hydrogen and carbon dioxide to methane. The slow growth rate and strict anaerobic requirements of methanogens make them particularly sensitive to sudden changes in pH, ammonia, VFAs, temperature and moisture [Harirchi et al., 2022; Wainaina et al., 2019].

The inoculum source strongly influences start-up performance because it determines the initial microbial diversity, buffering capacity and hydrolytic activity. Digestate from a stable AD plant is often preferable because the microbial community is already adapted to anaerobic conditions, whereas manure-based inocula may offer robust hydrolytic capacity and buffering but lower activity toward some waste streams. In dry thermophilic digestion of OFMSW, inocula from digested sludge, swine manure and their mixture produced higher methane yields and methane contents than cattle manure alone [Forster-Carneiro et al., 2007]. Targeted microbial capabilities can also be relevant; for example, rumen-derived communities may support degradation of fibrous substrates, while members of the phylum Chloroflexi have been associated with carbohydrate degradation in methanogenic bioreactors [Bovio-Winkler et al., 2021; Akuzawa et al., 2011].

The substrate-to-inoculum ratio must balance reactor utilization with biological safety. High substrate loading improves apparent volumetric productivity but increases the risk of acidification when methanogenic capacity is insufficient, whereas excessive inoculum reduces the fraction of fresh feed treated per batch. Reported safe ratios differ widely. For OFMSW, feedstock-to-inoculum ratios (VS basis) of 1, 2 and 3 recovered about 86%, 70% and 34% of the theoretical methane, and the reactor at a ratio of 3 failed through VFA accumulation [Dastyar et al., 2021], whereas wheat straw started successfully at substrateto-inoculum ratios of 1.2-3.6 [Rouches et al., 2019]. The difference reflects substrate degradability: rapidly hydrolysable, food-rich waste generates acids faster than a given inoculum can convert them, while lignocellulosic straw releases acids slowly. Responsesurface experiments further indicate that the inoculum ratio mainly affects start-up, whereas TS dominates later performance [Motte et al., 2013]. In high-solids poultry litter digestion, increasing inoculum and digestate recirculation improved methane production, illustrating the importance of maintaining active microbial contact in dry matrices [Marchioro

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et al., 2018]. Gradual acclimatization is also essential when changing temperature regimes or treating substrates with high ammonia, salinity, lipids or other inhibitory components. Temperature shifts should be implemented stepwise [Schnürer and Jarvis, 2010], and acclimatized inocula can substantially improve process stability under ammonia stress [Yan et al., 2019].

4.2. Substrate composition, pre-processing and pretreatment

Dry AD can treat diverse organic wastes, but substrate composition controls hydrolysis rate, buffering demand, inhibitory risk and digestate quality. OFMSW is highly heterogeneous and varies with collection system, season and local consumption patterns. Recent full-scale characterization of mechanically separated OFMSW confirms that feedstock properties depend strongly on waste source, composition and separation efficiency, reinforcing the need for plant-specific feedstock characterization before process design [Kabakci et al., 2024]. Food waste is usually rich in readily biodegradable soluble organics, which can increase methane potential but also accelerates VFA accumulation if hydrolysis and acidogenesis exceed methanogenic conversion [Franca and Bassin, 2020; Li et al., 2011]. Recent reviews of food-waste AD further identify foaming, acidification and ammonia inhibition as recurring barriers to stable biogas recovery, with pretreatment, codigestion and additives proposed as mitigation strategies [He et al., 2024].

Agricultural residues such as straw and corn stover contain cellulose, hemicellulose and lignin; these materials often require particle-size reduction or pretreatment to improve accessibility to hydrolytic enzymes [Amin et al., 2017]. Particle-size reduction should be optimized rather than maximized, because excessive size reduction can accelerate hydrolysis and intermediate accumulation, potentially inhibiting methanogenic activity [Vian et al., 2024]. For fruit and vegetable waste, particles smaller than 500 μm yielded only 162-187 mL CH4 g-1 VS, compared with 298-310 mL CH4 g-1 VS for larger particles, because intermediates accumulated and inhibited methanogenesis [ViguerasCarmona et al., 2025].

Pre-processing should remove inert and non-digestible contaminants, including plastics, metals, glass and stones. This step is important not only for biogas productivity but also for

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mechanical reliability and digestate acceptance. In mechanically separated OFMSW, nondigestible fractions and separation efficiency directly influence the quality of the feed entering the digester and the downstream acceptability of digestate [Kabakci et al., 2024]. Depending on the waste stream, mechanical sorting, magnetic separation, screening, shredding, pulping or dilution may be required before digestion [Bolzonella et al., 2006]. For lignocellulosic residues, physical, chemical and biological pretreatments can reduce particle size, lower crystallinity, disrupt lignin-carbohydrate complexes and increase biodegradability, and pretreatment combined with an appropriate inoculum has improved microbial community structure and reactor performance in pilot-scale digestion of municipal solid waste [Ventorino et al., 2018].

Whether pretreatment is worth its cost depends on how the additional conversion is monetized. At a full-scale German plant, ball milling of agricultural residues including horse manure consumed 5.2 kWh/ton fresh matter and increased the methane yield from 216 to 312 L CH_4/kgVS, giving a net energy gain of 166-332 kWh/tonVS [Heller et al., 2025]. For wheat straw, steam explosion increased total capital investment by 13% but reduced the methane production cost by 36% [Shafiei et al., 2013]. For food waste, thermal pretreatment at 80 °C increased the methane yield by 52% and the extra methane covered the heat demand, whereas the extra methane obtained after ozonation did not cover the energy demand of the ozonator [Ariunbaatar et al., 2014b]; low-temperature thermal pretreatment and two-stage configurations have been identified as the most cost-effective options for organic solid waste [Ariunbaatar et al., 2014a]. In dry fermentation, shockwaveinduced intracellular disintegration accelerated methanogenesis [Stehel et al., 2018], and at commercial scale it was more profitable to disintegrate the substrate in the middle phase of fermentation than before loading [Stehel et al., 2020]. Intensive disintegration by steam explosion, however, makes subsequent nutrient management more demanding, which must be included in the cost assessment [Maroušek et al., 2014]. Two economic rules emerge from these data. First, pretreatment is most likely to pay off for recalcitrant, lignin-rich or fibrous substrates, whereas readily degradable food waste gains little and may become less stable (Section 6.1). Second, in a dry AD plant whose capacity is limited by retention time, the main value of

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pretreatment lies in shortening the retention time, thereby increasing the throughput of an existing reactor or reducing the size of a new one, rather than in the increase in ultimate methane yield alone.

Feedstock characterization should include TS, volatile solids (VS), pH, alkalinity, C/N ratio, macro- and micro-nutrients, lipid and protein fractions, lignocellulosic content, and known inhibitors. When possible, biochemical methane potential (BMP) data should be used to estimate realistic methane yields and to compare actual full-scale performance with substrate-specific potential [Holliger et al., 2017]. At-line near-infrared spectroscopy can estimate the COD, carbohydrate and lipid contents of solid wastes rapidly and could support day-to-day feed-recipe decisions [Charnier et al., 2017].

4.3. Total solids, water availability and mass transfer

The defining feature of dry AD is high solids content. Increasing TS raises the amount of organic matter treated per reactor volume and can reduce heat demand and liquid effluent generation. However, the benefits decline when reduced free water and increased viscosity limit diffusion, decrease substrate-inoculum contact, impair pH buffering and create localized zones with high concentrations of VFAs, ammonia or salts. Several studies indicate that methane production can improve as TS rises to moderate high-solids levels, but further increases may reduce methane yield and slow kinetics [Bollon et al., 2011; Rocamora et al., 2020].

Mass transfer is therefore a primary design constraint. A recent review of high-solids AD emphasized that rheology, particle-scale transport, dead zones and insufficient mixing hinder methane production and remain major barriers to widespread application [Gao et al., 2023]. Particle-size effects also interact with mass transfer: although smaller particles can increase surface area, excessive reduction may create rapid intermediate release and methanogenic inhibition if buffering and biomass contact are insufficient [Vian et al., 2024]. Recent work on kitchen waste dry AD supports the existence of an optimum TS window: a TS of 20% produced higher cumulative methane yield than 15% or 25%, while 25% TS promoted VFA accumulation, ammonia stress and system destabilization [Liu et al., 2025].

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The optimum TS reported in the literature is, however, not consistent. For kitchen waste, methane yields were 348, 406 and 293 mL/gVS at 15%, 20% and 25% TS, respectively [Liu et al., 2025], and 20% TS was also the best of the levels tested in mesophilic digestion of food waste [Yi et al., 2014]. In contrast, batch experiments over 10-35% TS showed only a slight decrease in methane production up to 25% TS and a threshold near 30% TS, above which liquid-gas mass-transfer limitation caused inhibition [Abbassi-Guendouz et al., 2012]; stable plug-flow digestion of food waste has been reported at 27-28% TS [Perman et al., 2024], and 30% TS was optimal for high-solids co-digestion of poultry litter [Karumanchi et al., 2026]. We attribute these apparent contradictions mainly to the fact that TS is a poor proxy for the water that is actually available to microorganisms. Fibrous substrates retain much of their water within particles and capillaries, whereas food waste releases free water, so that the same TS corresponds to very different free-water contents. The significant interaction between TS and particle size found in response-surface experiments supports this interpretation [Motte et al., 2013]. Reporting free-water or waterretention measurements alongside TS would make results comparable across studies and is identified here as a methodological gap.

Typical reported operating windows vary by feedstock and reactor technology. Dry AD systems can achieve VS removal of approximately 40-70%, organic loading rates around 12-15 kgVS/m^3/day in some configurations, and hydraulic or solids retention times of about 14-60 days, whereas wet AD commonly operates at lower organic loading rates and larger liquid volumes [Kothari et al., 2014; Li et al., 2011]. These values should be treated as design references rather than fixed targets; stable operation requires feedstock-specific validation.

4.4. Carbon-to-nitrogen ratio and co-digestion

Carbon and nitrogen are essential nutrients, but their imbalance can inhibit dry AD. Excess degradable carbon promotes acidification and VFA accumulation, while excess degradable nitrogen raises total ammonia nitrogen and free ammonia, both of which inhibit methanogenesis. A total C/N ratio of approximately 20-30 is often recommended [Rocamora et al., 2020]. However, C/N analyses must account for the bioavailability of carbon and

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nitrogen to the anaerobic microbial consortium, because lignin-bound carbon and some protein fractions are degraded slowly or not at all within the retention time. Chemically determined C/N ratios therefore overestimate the carbon that is actually available [Puyuelo et al., 2011]. An available C/N ratio that counts only the carbon in proteins, sugars, lipids and hemicellulose predicted process performance better than the total C/N ratio for nine feedstocks, with an optimum of 11-15 [Wang et al., 2017]. Nutrient management based on bioavailability allowed more intensive and more profitable digestion of food waste with less agricultural co-substrate than optimization of the total C/N ratio [Maroušek et al., 2024], and helped to manage the nutrient imbalances created by steamexplosion pretreatment of lignocellulose [Maroušek et al., 2014]. The difference between the recommended total C/N ratio (20-30) and the optimal available C/N ratio (11-15) is therefore not a contradiction but a consequence of the non-degradable carbon included in the total ratio.

Co-digestion is a practical strategy for adjusting the C/N ratio and improving process stability. Carbon-rich substrates such as straw, cardboard or paper-industry residues [Jansson et al., 2019] can dilute ammonia from protein-rich wastes or manures, while nitrogen-rich substrates can complement carbon-rich lignocellulosic materials. Co-digestion can also improve moisture, alkalinity and trace-element availability. Pairing high-C/N and low-C/N wastes improves process stability and biogas production when the mixture ratio is optimized [Ahmad et al., 2024], and biochemical-fraction ratios such as lipid:protein:carbohydrate explain methane yield, kinetics and synergism better than the C/N ratio alone [Rabii et al., 2024]. Reported examples are summarized in Table 2. Mixture design should be based on local feedstock availability, BMP testing, mass balance and digestate-quality requirements.

4.5. Practical implications for plant management

The results in Sections 4.1-4.4 translate into a limited number of managerial decisions, which are summarized in Table 3 and Fig. 3. The overarching implication is that operators should manage the free-water content and the rate of acid formation, rather than fixed setpoints for TS or total C/N ratio. In practice, this means (i) characterizing each new feedstock for degradability and water-holding capacity before changing the feed recipe; (ii) adjusting the

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inoculum or recirculated-digestate ratio to substrate degradability, with more inoculum for food-rich waste than for straw or manure; (iii) raising TS stepwise while tracking the VFA/TA ratio and gas production; and (iv) evaluating pretreatment by its effect on retention time and throughput rather than solely by the increase in BMP. For agricultural batch plants that operate with minimal instrumentation, these decisions can be implemented through feed recipes and batch-cycle scheduling rather than through continuous control.

5. Reactor configurations and operation

Dry AD reactors are commonly classified by operating mode (batch, semi-continuous or continuous), orientation (vertical or horizontal), mixing mechanism, and approach to inoculation or digestate recirculation. Reactor selection affects capital cost, feed handling, retention time, gas production profile, operator skill requirements and tolerance to feedstock heterogeneity. From a reactor-theory perspective, dry AD systems approximate heterogeneous plug-flow, packed-bed or mixed-solid bioreactors: batch garage systems rely on percolate distribution and staggered loading to approximate continuous gas production, whereas continuous plug-flow systems rely on axial movement, external mixing or digestate recirculation to keep fresh substrate in contact with active biomass [Patinvoh, 2019; Rocamora et al., 2022]. The major configurations are compared schematically in Fig. 2, and examples of commercial suppliers and process features are provided in Table 4.

5.1. Batch systems

Garage-type batch systems, including the BEKON and BIOFerm processes, are loaded with stackable substrate into sealed chambers, inoculated with digestate and/or percolate, and irrigated with recirculated percolate. Gas production declines after about three to four weeks, at least three chambers operated in staggered cycles are needed for a continuous gas supply, and solid inoculum can make up to 70% of the input for energy crops [Weiland, 2010]. The low mechanical complexity and tolerance to high TS are major advantages, but percolate recirculation must be controlled to avoid acidification and uneven wetting [Fu et al., 2018].

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Agricultural batch and continuous dry fermentation plants with electrical capacities of about 0.2-1 MW have operated in Central Europe since the early 2000s. In Germany, the Renewable Energy Sources Act of 2004 paid a technology bonus for dry fermentation, and about one in ten new agricultural biogas plants built at that time used dry digestion [Murphy et al., 2011]; by the end of 2006, around 20 plants used classic batch dry fermentation, with batch cycles of 14 days to six weeks at 17-35% dry matter [Hoffmann, 2007]. Similar plants were subsequently built in other countries. In Italy, a 910 kWe plant treating cow manure and agricultural products on a dairy farm reached 70-87% of its nominal output after start-up with an average retention time of 28 d [Chiumenti et al., 2018], and in England a nine-chamber garage plant of 1.2 MW processes about 30,000 tons/year in 28-d cycles [Rocamora et al., 2022]. Farmers value these systems because they require no pumping or stirring and little process control. Their principal drawbacks are the long batch cycle, which lowers volumetric productivity, the need for several parallel modules and large inoculum recycle, and the labour required for loading and unloading the chambers [Chiumenti et al., 2018]. Because automation is difficult in discontinuous box digesters, labour demand increases with throughput, and inactive zones and odour emissions have been observed at full scale [Kusch et al., 2011].

Textile-based dry AD bioreactors are an alternative for small-scale or portable applications. Their advantages include low capital intensity, ease of assembly and potential suitability for decentralized manure-straw digestion. Laboratory and pilot work has shown that textile bioreactors can produce biogas and digestate with potential fertilizer value, and an economic evaluation for straw-bedded manure at 22-30% TS indicated a maximum payback period of 5 years and internal rates of return of 19-57%, depending on reactor size [Patinvoh et al., 2017]. Long-term durability, gas tightness, material resistance and operational standardization must nevertheless be verified for each application [Jabbari et al., 2017].

5.2. Continuous systems

Continuous dry AD technologies include vertical plug-flow systems such as Valorga and Dranco and horizontal plug-flow systems such as Kompogas. Valorga uses a central baffle

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and intermittent pressurized biogas injection for mixing; Dranco relies on external mixing of incoming substrate with recycled digestate before feeding from the top; and Kompogas uses a horizontal reactor with slow axial mixing and digestate recirculation. Typical TS ranges reported for these systems are about 25-35% for Valorga, 30-40% for Dranco and 23-28% for Kompogas, although full-scale values depend on substrate and operator strategy [Maleki-Ghelichi and Sharifi, 2017].

Continuous systems can deliver more stable gas production than single batch reactors but require more robust feed preparation, mixing, conveying and process control. Full-scale experience with mechanically sorted OFMSW confirms the importance of controlling TS, viscosity, organic loading rate and nitrogen-rich co-substrates: at 10.5-12 kgVS/m^3/day and 16-18 days retention, a continuous dry AD plant produced 5.0-6.6 m^3biogas/m^3/day, but chicken manure above 20% of the feed caused process instability [Musluoğlu et al., 2025a]. Recent national-scale evidence from Türkiye further shows that continuous dry AD has become a dominant technology for OFMSW diversion from landfill, with dry, thermophilic and continuous systems representing most installed capacity in the reported plants [Musluoğlu et al., 2026].

5.3. Purchase and running costs

Configuration-specific cost data are scarce because suppliers rarely disclose prices, but several recent assessments allow quantitative comparison (Table 6). For a 35,000 tons/year plant treating source-sorted OFMSW and producing biomethane in Italy, the investment was EUR 9.38 million for dry batch technology and EUR 11.40 million for wet technology (about EUR 268 and 326 per tonne of annual capacity), with annual costs of EUR 59 and 66 per tonne treated, respectively. The dry batch plant produced less biomethane (4,380 vs 5,526 Nm^3/day) and had about 21% lower energy performance, yet its payback period was about 10 years compared with 19 years for the wet plant, and Monte Carlo analysis gave a 90% probability that it would achieve the higher net present value [Francini et al., 2020]. This case illustrates the central trade-off of dry AD: lower methane output per tonne is outweighed by lower capital and operating costs when gate fees make up a large share of revenue. For a

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20,000 tons7year solid-state AD plant treating yard trimmings in Ohio, USA, the capital cost was USD 256 per ton of annual capacity, and the plant reached an internal rate of return of 8%, a net present value of USD 0.2 million and a payback of about 10 years, compared with 33%, USD 1.8 million and 4.9 years for composting, mainly because composting required less capital [Lin et al., 2019]. For Californian dry AD facilities of 25,000-300,000 tons/year, the break-even tipping fee fell from about USD 160 per ton to about USD 105 per ton as capacity increased, economies of scale appeared above about 75,000 tons/year, and materials handling was the largest cost category [Smith et al., 2021]. At the smallest scale, household dry-fermentation units of 2-6 m^3 in Egypt were profitable, with profitability increasing with unit size [Samer et al., 2020].

5.4. Emerging reactor innovations

Several reactor innovations target the kinetic limitation directly. Leach-bed reactors coupled with a high-rate methanogenic reactor separate hydrolysis in the solid bed from methanogenesis in the liquid phase. A leach-bed reactor coupled with an upflow anaerobic sludge blanket (UASB) reactor treated seasonal fruit and vegetable waste for about one year at 3.1 gVS/ L/day, raising the system methane yield to 360-375 L/kgVS (84-92% of the BMP) with 65% VS removal and without adding water [Kalogiannis et al., 2024]. Packing the downstream anaerobic filter with zeolite and volcanic rock increased methane production by 146% and removed 86% of the ammonium [Xiao et al., 2025]. Across stageseparated systems, biomethane production was 5.8-65.5% higher than in single-stage digestion [Tang et al., 2023]. At 27-28% TS, plug-flow reactors produced 317-328 NL_{CH4} /kgVS compared with 241-253 NL_{CH4}/kgVS in completely stirred reactors, with similar VS reduction [Perman et al., 2024], which supports the plug-flow principle used in commercial systems. A self-rotating drum reactor without an internal stirrer removed 69% of the TS of kitchen waste, 18% more than wet digestion [Pan et al., 2022]. Micro-aeration combined with sulfide-oxidizing bacteria removed 80-92% of H2S during high-solids co-digestion of poultry litter at 30% TS [Karumanchi et al., 2026], and in-situ biogas upgrading by hydrogen addition is being integrated with two-stage digestion [Yellezuome et al., 2023]. Most of these

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innovations have been demonstrated only at laboratory or pilot scale, and their capital and operating costs relative to conventional dry AD have not yet been reported; this is a key gap for industrial adoption.

6. Process monitoring and troubleshooting

6.1. Indicators, troubleshooting and pretreatment-related instability

Dry AD instability is usually expressed as declining methane concentration, reduced gas production, delayed start-up, odor, rapid pH shifts, high VFA concentration, ammonia inhibition, H_2S accumulation, uneven wetting, clogging or excessive digestate viscosity. Because dry systems are spatially heterogeneous, one bulk measurement may not capture localized inhibition. Monitoring should include gas flow, methane and carbon dioxide fractions, H_2S, pH, alkalinity, VFA/TA ratio, total ammonia nitrogen, free ammonia where possible, TS, VS, temperature and recirculation rate. For solid-state AD, stability thresholds of pH 7.5-8.3, a VFA/TA ratio below 1.5 and an initial C/N ratio of 10-29 have been proposed [Ajayi-Banji and Rahman, 2022]. The appropriate monitoring intensity differs between plant types: agricultural batch plants are commonly operated with gas quantity and quality measurements only, and corrections are made through the feed recipe of the next batch, whereas continuous municipal plants with shorter retention times and variable feedstock justify liquid-phase indicators. Table 5 summarizes common problems, likely causes and mitigation measures.

Start-up should be deliberately conservative. Practical measures include increasing inoculum activity, reducing initial organic loading, improving particle-size distribution, ensuring adequate moisture, mixing substrate with inoculum before loading, and gradually increasing recirculation or loading rate. Excessive percolate or digestate recirculation can mobilize VFAs and intensify acidification; therefore, recirculation should be adjusted using gas and liquid-phase indicators rather than fixed schedules [Kusch, 2013; Basinas et al., 2021].

When VFA accumulation occurs [Jiang et al., 2018], increasing alkalinity, reducing feed rate, increasing inoculum or digestate recycle in a controlled manner, and adjusting codigestion ratios may restore balance. Ammonia inhibition can be mitigated by lowering pH within a safe range, operating under mesophilic rather than thermophilic conditions, diluting nitrogen-

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rich substrates with carbon-rich co-substrates, acclimating the inoculum [Yan et al., 2019], or adding adsorbents such as biochar [Kizito et al., 2022] or granular activated carbon [Xiao et al., 2021]. Recent ammonia-inhibition reviews also emphasize that inhibition thresholds are condition-dependent and mediated by microbial adaptation, pH, temperature and free-ammonia concentration [Yang et al., 2025]. However, biochar performance is feedstock- and material-specific, and its effects on conductivity, VFAs, ammonia nitrogen, pH and microbial composition should be validated at bench scale before full-scale adoption [Devi and Eskicioglu, 2024]. H2S control requires attention to sulfurrich inputs, trace metals and gas-cleaning needs, especially when biogas is upgraded to biomethane or used in engines; at a full-scale garage plant, H2S concentrations of 179-488 ppm approached the 500 ppm limit at which the CHP unit shuts down [Rocamora et al., 2022].

Pretreated feedstock may lead to greater process instability. Pretreatment accelerates hydrolysis and can shift the rate-limiting step from hydrolysis to methanogenesis. In solidstate digestion of corn straw, freeze-vacuum-drying pretreatment raised peak VFA concentrations to about 20-22 g/L and lowered the minimum pH from 6.5 to 5.9, although the acidification was transient and the final methane yield was 24% higher [Liu et al., 2022]. Thermal pretreatment above about 120 °C forms refractory melanoidins through Maillard reactions; melanoidins formed at 160 °C and 180 °C reduced methane production by 49% and 90%, respectively, by inhibiting proteases, acidogens and acetoclastic methanogens [Wang et al., 2024]. Phenols and furans released during thermal pretreatment of olive mill solid waste also reduced the methane yield, which increased by 42% when these compounds were removed [Caroca et al., 2021]. Operators introducing pretreatment should therefore reduce the loading rate or increase the inoculum during the transition and monitor the VFA/TA ratio more frequently. Conversely, mild biological pretreatment can reduce start-up acidification, as shown for fungal pretreatment of wheat straw [Rouches et al., 2019].

6.2. Digital monitoring, advanced sensors and AI-based control

Online monitoring of dry AD is constrained by the difficulty of obtaining representative samples from a heterogeneous solid matrix, but several recent sensor developments are

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517 relevant. Dissolved hydrogen, an early indicator of imbalance between acidogenesis and
518 methanogenesis, was monitored with a membrane-free metal-oxide sensor for more than
519 three months with a detection limit below 50 ppbv, and changes were detected earlier than by
520 off-gas analysis [Janesch et al., 2024]. An automated capillary-electrophoresis analyser with
521 integrated solids separation measured acetate, propionate and butyrate every 12 min in
522 digestate containing up to 4.2% solids [Fernandez Feito et al., 2025], and a hand-held
523 nearinfrared spectrometer predicted total VFA with $R^2 = 0.87$ [Jiménez-Páez et al., 2024]. For
524 dry reactors specifically, electrical resistivity tomography mapped the liquid distribution non-
525 invasively in a 30 m^3 full-scale batch digester and identified zones with high residual methane
526 potential [André et al., 2016].
527 Data-driven tools are developing rapidly. A systematic review of machine-learning (ML)
528 applications in AD found that artificial neural networks were used in about two-thirds of the
529 studies and that most models predicted biogas or methane production; limited training data,
530 poor transferability between plants and the absence of explainable models were the main gaps
531 [Rutland et al., 2023]. Soft sensors based on deep learning outperformed regression models
532 and shallow networks for real-time estimation of VFA and biogas yield [Yan et al., 2021]. For
533 high-solids AD, a support vector machine predicted process performance with $R^2 = 0.91$, and
534 organic loading rate, hydraulic retention time and C/N ratio were the most influential inputs
535 [Ganeshan et al., 2024]. Recent reviews describe how sensors, models and optimization
536 strategies are being integrated into artificial intelligence (AI)-based AD control [Ling et al.,
537 2024; Marycz et al., 2025]. In a 15-year validation at an industrial plant, the reduced AM2
538 model tracked daily biogas production ($R^2 = 0.80$) with a computation time of 0.16 s, whereas
539 ADM1 reproduced the mean but not the dynamics, indicating that reduced models are better
540 suited to real-time digital twins [Chiguer et al., 2026]. Reinforcement-learning control has
541 outperformed proportional-integral and predictive controllers in simulations of two-stage AD
542 [Binid et al., 2026]. Nevertheless, nearly all ML models and online sensors have been
543 developed for wet digestion, and their calibration for spatially heterogeneous high-solids
544 matrices has not been validated. In our view, the most promising near-term route for dry AD
545 is to combine a small number of robust gas-phase and percolate signals (gas flow, CH_4, H_2S

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and H_2) with reduced mechanistic models, rather than to rely on solid-phase sampling, which is inherently unrepresentative in dry reactors.

7. Process economics and scale-up considerations

Revenues of dry AD plants come from gate (tipping) fees, sales of energy and associated certificates, and, where permitted, digestate sales, whereas costs are dominated by capital charges, materials handling and digestate management. The relative weight of these items determines which design is most profitable. In the Italian comparison discussed in Section 5.3, a gate fee of EUR 62 per ton and certificates for biomethane used as transport fuel made the lower-cost dry batch plant more profitable than the higher-yield wet plant [Francini et al., 2020]. In California, vehicle fuel generated 4-12 times more revenue than electricity or pipeline injection because of low-carbon fuel and renewable identification number credits [Smith et al., 2021]. In China, food-waste treatment projects in 29 pilot cities had a mean profit-to-cost ratio of 0.08 without subsidies and 0.95 with subsidies [Chen et al., 2021]. In Türkiye, 23 OFMSW AD plants, most of whose capacity uses dry technology, represent a total investment of USD 850 million for 4.0 million tons/year of capacity (about USD 210 per tonne of annual capacity) and operated at 65% utilization in 2024 [Musluoğlu et al., 2026]. These quantitative data are summarized in Table 6.

Techno-economic analysis should therefore be integrated early in process development. Increasing TS reduces reactor volume, but it can increase mechanical complexity and reduce methane yield if mass transfer becomes limiting. Shorter retention time reduces the number or size of reactors only if process stability and methane recovery are maintained. The biogas pathway is also important: for solid-state AD of agricultural wastes at 8,000 tons/year, the combined heat and power pathway gave a net present value of USD 0.60 million and an internal rate of return of 23%, compared with USD 0.40 million and 20% for biomethane [Li et al., 2020], whereas upgrading to biomethane requires higher capital cost but gives access to transport-fuel and grid-injection markets. Recent OFMSW modelling confirms that OLR and pretreatment interact strongly in determining technical feasibility, profitability and carbon footprint; pretreatments can offset inhibition at higher OLRs, but only within specific operating windows [Demichelis et al., 2024].

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Biomethane economics depend strongly on scale. The average cost of biomethane from upgraded biogas has been estimated at about USD 19 per MBtu, of which upgrading contributes USD 2-4 per MBtu [IEA, 2020], and 90% of the global biomethane potential lies at USD 10-30 per GJ, with large digesters up to 40% cheaper than small ones [IEA, 2025]. Upgrading costs fall from USD 0.25-1.07 per m^3 CH_4 at raw-biogas capacities of 20-200 m^3/h to USD 0.14-0.18 per m^3 CH_4 at 1,000 m^3/h [IRENA, 2017]. A 35,000 tons/year dry batch plant produces about 180 Nm^3/h of biomethane [Francini et al., 2020], well below the average capacity of European biomethane plants of 483 m^3/h [European Biogas Association, 2025], i.e., in the size range where specific upgrading costs rise steeply. Where no certificate, credit or feed-in scheme compensates for the difference between the production cost of biomethane and the wholesale price of natural gas, biomethane cannot compete on price alone [IEA, 2025]. Connecting several dry AD plants to a shared upgrading unit, or selecting combined heat and power where the heat can be used locally, can therefore be decisive for small and medium-sized plants.

Digestate management should be treated as a core economic variable. For a 400 tons/day digestate stream at a full-scale continuous dry AD plant treating mechanically sorted OFMSW, capital costs ranged from USD 4.2 million for three-stage dewatering to USD 9.8 million for direct thermal drying, and net income from USD 22.6 to USD 16.6 per tonne of OFMSW [Musluoğlu et al., 2025b]. The market value of digestate is limited by its composition. Digestate consists mostly of water: Danish full-scale digestates contained 4771 g/kg dry matter and about 4.5-5.0 g/kg total Kjeldahl nitrogen, of which 60-63% was ammonium, and less than 1 g/kg phosphorus [Romio et al., 2024]. Its nutrient concentrations on a fresh-mass basis are therefore one to two orders of magnitude lower than those of mineral fertilizers, and a substantial part of its nitrogen and phosphorus is in organic forms that are not immediately available to plants [Möller and Müller, 2012;

Czekała, 2022]. Dry AD digestate has a higher dry-matter content, which reduces transport cost per unit of nutrient, but its value derives mainly from organic matter and slowly released nutrients rather than from immediate fertilizer replacement [Al Seadi et al., 2013]. Contaminants further constrain digestate outlets. All fertilizer samples from biowaste

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digestion and composting plants in a German study contained microplastic particles, whereas digestates from energy-crop plants contained few or none [Weithmann et al., 2018], and reported digestate concentrations range from about 70 to 1,670 particles per kg dry matter [Porterfield et al., 2023]. Under the EU Fertilising Products Regulation, digestate from the organic fraction of mixed municipal household waste separated by mechanical, physicochemical, biological or manual treatment is excluded from CE-marked fertilising products, and impurities larger than 2 mm are limited to 5 g/kg dry matter [Regulation (EU) 2019/1009]; Germany has additionally introduced input controls on plastic impurities in biowaste delivered to treatment plants [BioAbfV, 2022]. For plants treating mechanically separated mixed waste, digestate may therefore have to be composted for non-agricultural use, incinerated or landfilled, which turns it from a revenue item into a cost. In Shenzhen, China, dry AD combined with digestate incineration had the lowest lifecycle cost of the scenarios compared [Xiao et al., 2022]. Advanced valorization routes, including nutrient recovery, membrane separation and biochar production [Zielińska and Bułkowska, 2024], or pyrolysis of dry-fermentation residues [Stehel et al., 2020], can create additional revenue, but their capital costs must be weighed against the low nutrient concentration of raw digestate.

8. Representative full-scale case studies

Dry AD has been implemented at laboratory, pilot, demonstration and full scales. Full-scale plants typically include upstream sorting, size reduction or mixing, the main digester, biogas handling or upgrading, and digestate dewatering, composting, curing or other management steps. In Europe, dry systems provide about 60% of the installed capacity for OFMSW digestion [De Baere and Mattheeuws, 2010], and agricultural dry fermentation plants of about 0.2-1 MW have operated in Central Europe since the early 2000s (Section 5.1). Table 7 summarizes selected plants and operating features reported in the literature. The case studies highlight four practical lessons. First, temperature selection must balance kinetics against stability: under thermophilic conditions, ammonia (about 2 g NH_3-N/L) and acid accumulation (6-14 g/L) caused severe process disturbance in Swedish food-waste plants, and the Mörrum plant was converted to a lower temperature [Westerholm et al., 2020],

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although thermophilic dry AD of OFMSW can be about twice as fast as mesophilic operation [Fernández-Rodríguez et al., 2013]. Second, retention times for heterogeneous food waste at full scale (27-49 d) are longer than those for easily degradable slurries [Persson et al., 2019]. Third, digestate handling and contaminant control are integral to project feasibility rather than secondary issues [Musluoğlu et al., 2025b]. Fourth, agricultural batch plants show that dry AD can be operated with minimal process control when the feedstock is consistent, at the cost of long batch cycles and manual handling [Chiumenti et al., 2018].

9. Critical synthesis: conflicting findings, knowledge gaps and perspectives

9.1. Why reported results differ

Table 8 summarizes the principal conflicts in the dry AD literature and our interpretation of their causes. Four conflicts are particularly relevant for design. (i) The optimum TS ranges from 20% to 30% (Section 4.3), mainly because TS does not measure the free water available to microorganisms. (ii) Thermophilic dry AD of OFMSW was about twice as fast and had a 107% higher methane yield coefficient than mesophilic operation [FernándezRodríguez et al., 2013], and thermophilic digestion of corn stover degraded cellulose faster with 10-50 times more cellulolytic microorganisms but five-fold higher VFA concentrations [Shi et al., 2013]. At full scale, however, thermophilic food-waste plants suffered ammonia inhibition [Westerholm et al., 2020], whereas for high-solids oily food waste both regimes reached similar yields and the thermophilic regime recovered better from acidification when Fe, Co and Ni were supplemented [Wu et al., 2024]. The outcome therefore depends on protein content and trace-element supply rather than on temperature alone. (iii) Safe inoculum ratios differ by a factor of three or more between food-rich OFMSW and straw (Section 4.1), in line with differences in the rate of acid formation. (iv)
Digestate recirculation of 60% outperformed 50% in a continuous dry reactor [Chen et al., 2020], and frequent percolate recirculation kept free ammonia low in poultry-litter digestion [Marchioro et al., 2018], whereas 30% recirculation had no significant effect in plug-flow reactors [Perman et al., 2024], percolate recirculation time had only a marginal effect for OFMSW [Dastyar et al., 2021], and early recirculation can spread acids through the bed

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[Kusch, 2013]. Recirculation is beneficial when it distributes inoculum and alkalinity into acidifying zones and harmful when it transports acids into zones with low methanogenic activity, so its effect depends on timing and on the acid status of the recirculated liquid. A common cause underlies these conflicts: most studies report bulk parameters (TS, total C/N ratio and recirculation ratio) that are proxies for the local variables that actually control conversion, namely free water, bioavailable substrate and the local balance between acid production and consumption.

9.2. Evaluation of the hypothesis

The evidence reviewed supports the hypothesis for agricultural batch systems. In these systems, inhibition is rarely limiting when the feedstock is consistent; instead, batch cycles of three to six weeks, at least three parallel modules and inoculum recycle of up to 70% of the input set the reactor capacity and capital cost per tonne [Hoffmann, 2007; Weiland, 2010], and solid-state AD has been reported to require retention times up to three times longer than liquid AD [Li et al., 2011]. The Italian techno-economic comparison shows that dry batch technology can nevertheless be the more profitable choice because its capital and operating costs are lower [Francini et al., 2020], which is consistent with the corollary that capital productivity rather than methane yield drives the economics. For continuous municipal plants, the hypothesis is only partly supported. Ammonia and VFA accumulation have been documented at full scale in Sweden and England [Westerholm et al., 2020; Rocamora et al., 2022], and instability occurred in Türkiye when chicken manure exceeded
20% of the feed [Musluoğlu et al., 2025a]. In these plants, kinetics and inhibition are colimiting, and measures that accelerate hydrolysis, such as pretreatment, can aggravate inhibition (Section 6.1). The hypothesis is therefore confirmed for low-intensity agricultural systems and must be qualified for high-rate continuous systems, in which acceleration is worthwhile only when it is accompanied by adequate buffering and nitrogen management.

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9.3. Knowledge gaps and perspectives

On the basis of this synthesis, we identify six knowledge gaps: (1) Standardized reporting: full-scale studies seldom report free-water content, particle-size distribution, bioavailable carbon and nitrogen fractions, retention-time distribution, energy use and costs together, which prevents meta-analysis. (2) Cost of innovation: for leach-bed-UASB systems, rotating drums, micro-aeration, conductive additives and in-situ upgrading, technoeconomic data at relevant scale are almost absent (Section 5.4). (3) Sensors for solid matrices: online sensors and ML models have been developed almost exclusively for wet AD, and their validity in heterogeneous dry reactors is unknown (Section 6.2). (4) Pretreatment timing: the observation that disintegration during, rather than before, fermentation can be more profitable [Stehel et al., 2020] deserves systematic investigation across feedstocks. (5) Digestate quality: the fate of microplastics and persistent pollutants during dry AD and their implications for the legal status and value of digestate require quantitative study, particularly for OFMSW. (6) Full-scale microbiology: long-term microbial dynamics under thermophilic, high-ammonia conditions remain poorly characterized in industrial high-solids digesters [Westerholm et al., 2020].

In our view, the most rewarding direction for industry is to treat retention time as the primary design variable and to evaluate every intervention, whether pretreatment, nutrient management, recirculation or monitoring, by its effect on throughput per unit of reactor volume at acceptable risk. For agricultural operators, this points to low-cost measures such as optimized inoculum ratios, bioavailability-based feed recipes and, for fibrous substrates, mechanical disintegration. For municipal operators, it points to moderate acceleration combined with nitrogen management, source-separated feedstock to protect digestate outlets, and monitoring based on gas-phase signals. For researchers, it means reporting results in terms that can be transferred between studies and plants.

10. Conclusions

This review examined the hypothesis that the main barrier to wider deployment of dry AD is the slower conversion caused by limited free water rather than inhibition per se. The

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hypothesis is supported for agricultural batch systems, which operate with minimal process control but require batch cycles of three to six weeks, several parallel modules and large inoculum recycle; their main drawback is the longer processing time and the associated lower volumetric productivity and labour demand. For continuous municipal plants with protein-rich or variable feedstock, ammonia and VFA accumulation have been documented at full scale, so kinetics and inhibition are co-limiting. Economically, dry AD trades lower methane output for lower capital and operating costs: reported capital costs were about 256268 USD or EUR per tonne of annual capacity for plants of 20,000-35,000 tons/year, and a dry batch plant had a payback period of about 10 years compared with 19 years for a wet plant of equal capacity. Pretreatment pays off mainly for recalcitrant feedstocks and when it shortens the retention time; with readily degradable waste, it can reduce stability. Digestate has low nutrient concentrations, and its agricultural use is restricted when it originates from mechanically separated mixed municipal waste, so source separation is a precondition for digestate revenue. Conflicting findings on optimum TS, temperature, inoculum ratio and recirculation are largely explained by the use of bulk proxies instead of free water, bioavailable substrate and local acid balance. Priorities for future work are standardized full-scale reporting that includes cost data, techno-economic evaluation of emerging reactor concepts, sensors and models validated for solid matrices, and quantitative assessment of contaminants in dry AD digestate.

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1180 **Tables** 1181

1182 Table 1. Comparison of wet and dry anaerobic digestion systems [Luning et al., 2003; 1183 Rocamora et al., 2020].

Factor	Wet anaerobic digestion	Dry anaerobic digestion
Typical total solids	Usually <15% TS	Usually >15% TS; commonly 20-40% TS
Water demand	High because feedstock is diluted and pumped as slurry	Low because stackable or paste-like feedstocks are treated
Reactor volume per unit of feed	Higher	Lower
Organic loading rate	Generally lower	Generally higher, subject to mass-transfer limits
Mass transfer and mixing	Usually easier	Often limited by low free water and high viscosity
Feed handling	Pumping is easier, but grit and floating plastics can cause problems	Conveying and loading are more difficult; tolerant of some inert material but presorting remains important
Digestate handling	Large liquid fraction; dewatering or liquid treatment often required	Lower liquid volume; digestate is easier to stack, compost or transport
Common operational risks	Foaming, scum, sedimentation, washout, dilution-related heat demand	Localized acidification, clogging, uneven wetting, ammonia/VFA accumulation, difficult sampling

1184

1185 Table 2. Examples of co-digestion effects in dry anaerobic digestion processes.

Co-substrates	Reported effect of co-digestion	Reference

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Distillers grains and swine manure	Adjusting the mixture to a C/N ratio near 30 improved methane content, pH control and process stability compared with mono- digestion of distillers grains at higher C/N; stable operation was reported up to an OLR of 8 kg VS m-3 d-1.	Sensai et al. (2014)
Food waste and cattle manure	Raising the C/N ratio from about 22 to 29 increased VS reduction by approximately 20% and methane yield by approximately 16.7%; a methane yield of 0.43 m3 CH4 kg-1 VS reduced was reported at 30% TS.	Arelli et al. (2018)
Food waste and cardboard	Addition of cardboard with high C/N ratio reduced the intensity of VFA accumulation during dry AD of food waste with low C/N ratio.	Capson-Tojo et al. (2017)
Cow manure and corn straw	Improved methane production was reported when manure was mixed with straw; the study also showed the importance of TS and digestate recirculation ratio for pilot-scale operation.	Shen et al. (2021)
Cow manure and swine manure	Co-digestion at a cow dung:swine manure ratio of 3:2 increased specific methane yield to approximately 0.40 L g-1 VS,	Li et al. (2014)
	compared with lower yields from mono-digestion.	

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Corn straw and swine manure	Combining high-C/N straw with low-C/N manure produced a mixture C/N ratio near 21, improving stability and mitigating ammonia inhibition observed during manure mono-digestion.	Gong et al. (2020)
MSW/food waste mixtures	Optimizing co-digestion ratios can improve biogas production and digestive stability by balancing degradable carbon, nitrogen and buffering capacity.	Ahmad et al. (2024)
Source-separated organic waste and thickened waste activated sludge	Mixture design based on biochemical fractions such as lipid:protein:carbohydrate can complement C/N ratio in explaining methane yield, kinetics and synergistic effects.	Rabii et al. (2024)

1186 1187 Table 3. Translation of key findings into managerial decisions for dry anaerobic digestion 1188 plants.

Finding	**Managerial decision**	**Indicator to monitor**
Inoculum demand depends on substrate degradability [Dastyar et al., 2021; Rouches et al., 2019].	Increase the inoculum or recirculated-digestate share for food-rich OFMSW; a lower share is acceptable for straw and manure.	VFA, VFA/TA and pH during the first 1-2 weeks; gas production rate.
The optimum TS depends on substrate water-holding capacity [Abbassi-Guendouz et al., 2012; Liu et al., 2025].	Raise TS stepwise and set TS limits per feedstock rather than plant-wide.	Gas production rate, VFA/TA, percolate flow and wetting uniformity.
Total C/N overestimates available carbon [Wang et al., 2017; Maroušek et al., 2024].	Formulate co-digestion recipes on degradable fractions (BMP, fibre, protein and lipid contents).	TAN, free ammonia and VFA.

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Pretreatment pays mainly for recalcitrant feedstocks [Shafiei et al., 2013; Heller et al., 2025].	Invest where retention time can be shortened or throughput raised; avoid intensive pretreatment of readily degradable food waste.	Specific energy use (kWh t1), methane yield and retention time.
Excessive particle-size reduction can inhibit methanogenesis [Vian et al., 2024; Vigueras-Carmona et al., 2025].	Specify a target particle-size window rather than maximal shredding.	Particle-size distribution and early VFA peak.
Ammonia inhibition occurs at full scale in thermophilic plants treating protein-rich waste [Westerholm et al., 2020].	Prefer mesophilic operation or carbon-rich co-substrates for protein-rich feed; change temperature stepwise.	TAN, free ammonia and temperature.

1189 1190 Table 4. Examples of commercial dry anaerobic digestion suppliers or technologies.

1191 Websites accessed 8 June 2026.

Supplier/technology	**Main feature**	**Website**
FOV Biogas	Textile-based reactor construction for decentralized dry AD applications.	https://www.fovbiogas.com/
Kanadevia Inova (formerly Hitachi Zosen Inova)	Kompogas dry AD technology; robust modular systems and automation options.	https://kanadeviainova.com/renewablegas/technologies/dry-anaerobicdigestion
DRANCO nv	Vertical high-solids fermenters with external mixing of	https://dranco.be/

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	fresh substrate and digestate.	
Valorga International	Vertical dry AD process using biogas injection for mixing and no internal mechanical mixer.	https://www.urbaserenvironnement.fr/
STRABAG Umwelttechnik GmbH	Horizontal plug-flow reactor concept for high-solids digestion.	https://www.strabagumwelttechnik.com/
BEKON	Garage-type single-step batch dry fermentation system.	https://www.bekon.eu/

1192

1193 Table 5. Troubleshooting common dry anaerobic digestion problems and mitigation 1194 options.

Problem	**Likely cause**	**Mitigation measure**	**Reference**

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Delayed start-up	Insufficient methanogenic activity; high initial organic loading; poor substrate-inoculum contact.	Use active inoculum or digestate from a stable reactor; reduce initial loading; mix substrate and inoculum before feeding; maintain adequate moisture; increase loading stepwise.	Kusch (2013); Fernández-Güelfo et al. (2012)
Unstable gas production	Uneven wetting, particle accumulation, localized acidification, ammonia inhibition or excessive digestate/percolate recirculation.	Improve feed preparation; adjust moisture; monitor VFA/alkalinity and TAN; operate at mesophilic temperature when ammonia risk is high; optimize co-digestion and recirculation.	Basinas et al. (2021); Jiang et al. (2018)
Low methane yield	Mass-transfer nt limitation, nutrieor imbalance, excessi TS, trace-elem deficiency incomplete hydrolysis.	Optimize particle size and TS; improve inoculation; balance C/N ratio; consider trace elements such as Ni, Co, Fe, Mo, W and Se where deficient; test biochar or conductive additives only after bench validation.	Gao et al. (2023); Devi and Eskicioglu (2024)
Instability after	Accelerated	Reduce loading and	Liu et al. (2022);

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introducing pretreatment	hydrolysis shifts the rate limitation to methanogenesis; melanoidins, phenols or furans formed at high pretreatment temperature.	increase inoculum during the transition; monitor VFA/TA more frequently; avoid severe thermal pretreatment (above about 120 °C) of readily degradable waste.	Wang et al. (2
Sulfur-related odor or high H2S	Sulfur-rich feedstock; sulfate reduction; inadequate gas cleaning.	Avoid excessive sulfate-rich inputs where possible; control feedstock composition; use iron salts, activated carbon, biological desulfurization or other gas-cleaning methods as appropriate.	Rocamora et al. (2022)
Ammonia-related odor or inhibition	High protein or manure loading; high pH and temperature increasing free ammonia.	Co-digest with carbon-rich substrate; lower organic nitrogen loading; acclimatize inoculum; consider mesophilic operation; evaluate adsorbents such as granular activated carbon or biochar after validation.	Yan et al. (2019); Yang et al. (2025)

1195 1196 Table 6. Quantitative economic data for dry anaerobic digestion and related biomethane 1197 production.

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Case (region, feedstock, scale)	Key economic data	Reference
Italy; source-sorted OFMSW; 35,000 t yr-1; dry batch vs wet AD with biomethane upgrading	Investment EUR 9.38 vs 11.40 million; annual cost EUR 59 vs 66 t-1; revenue EUR 101 vs 111 t-1; payback about 10 vs 19 years (6% discount rate, 20 years).	Francini et al. (2020)
USA (Ohio); yard trimmings; 20,000 t yr-1; solid-state AD vs composting	Capital cost USD 256 vs 84 per tonne of annual capacity; IRR 8% vs 33%; NPV USD 0.2 vs 1.8 million; payback about 10 vs 4.9 years.	Lin et al. (2019)
USA (California); municipal organics; 25,000-300,000 t yr-1 dry AD	Break-even tipping fee about USD 160 t-1 at 25,000 t yr1, falling to about USD 105 t-1 at 300,000 t yr-1; median landfill fee USD 66 t-1; vehicle-fuel revenue 4-12 times that of electricity or pipeline gas.	Smith et al. (2021)
Türkiye; OFMSW; 23 plants, 4.0 million t yr-1	Total investment USD 850 million (about USD 210 per tonne of annual capacity, calculated); most capacity dry, thermophilic and continuous; 65% utilization in 2024.	Musluoğlu et al. (2026)
Türkiye; mechanically sorted OFMSW; digestate 400 t d-1	Digestate-management capital cost USD 4.2 million (dewatering) to 9.8 million (thermal drying); net income USD 22.6 to 16.6 per tonne of OFMSW.	Musluoğlu et al. (2025b)

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China; agricultural wastes; 8,000 t yr-1 solid-state AD	CHP pathway: NPV USD 0.60 million, IRR 23%; biomethane pathway: NPV USD 0.40 million, IRR 20% (20 years).	Li et al. (2020)
China; food waste; 29 pilot cities	Mean profit-to-cost ratio 0.08 without and 0.95 with subsidies.	Chen et al. (2021)
Sweden; textile bioreactors; straw-bedded manure at 2230% TS	Maximum payback 5 years; IRR 19-57% depending on reactor size.	Patinvoh et al. (2017)
Global; biomethane from upgraded biogas	Average cost about USD 19 MBtu-1, of which upgrading USD 2-4 MBtu-1; 90% of potential at USD 10-30 GJ-1.	IEA (2020); IEA (2025)
Upgrading scale effect	USD 0.25-1.07 m-3 CH4 at 20-200 m3 h-1 raw biogas vs USD 0.14-0.18 m-3 CH4 at 1,000 m3 h-1.	IRENA (2017)
Pretreatment (Germany, full scale; wheat straw, model)	Ball milling: 5.2 kWh t-1 fresh matter, +44% methane, net gain 166-332 kWh t-1 VS; steam explosion: +13% capital, -36% methane production cost.	Heller et al. (2025); Shafiei et al. (2013)

1198 1199 Table 7. Examples of full-scale dry anaerobic digestion facilities and reported operating 1200features.

Location	**Process summary and reported performance**	**Reference**

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Mörrum, Sweden	Capacity: 20,000 t yr-1 (15,000 t food waste and 5,000 t green waste). Temperature: 55°C until 2017, then changed to 42°C due to instability under thermophilic operation. Retention time: 27-49 d. Gas production: 14-15 GWh yr-1.	Persson et al. (2019); Westerholm et al. (2020)
Lahti, Finland	Capacity: 26,000 t yr-1 food waste. Temperature: 42°C. Retention time: 37 d. Gas production: 50 GWh yr-1.	Westerholm et al. (2020)
Härnösand, Sweden	Capacity: 6,000 t yr-1 food waste. Temperature: 39°C. Retention time: 48 d. Gas production: 5.2 GWh yr-1.	Westerholm et al. (2020)
Bassum, Germany	Capacity: 13,500 t yr-1 municipal residual waste. Thermophilic operation. Retention time: 21 d. Reported gas production: 250 m3 t-1 dry matter.	Kothari et al. (2014); Weiland (2000)
San Jose, USA	Capacity: 90,000 t yr-1 municipal organic waste. Reported power production: 1.6 MW.	Linville et al. (2015)
Türkiye national deployment	Twenty-three full-scale OFMSW AD plants were reported for 2011-2024, with an aggregate wet capacity of approximately 4.0 million t	Musluoğlu et al. (2026)

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	yr-1 and 120 MW installed capacity; dry, thermophilic and continuous systems represented the dominant share of capacity.	
Gorizia area, Italy (agricultural)	Dairy farm with about 1,000 cows; cow manure and agricultural products; 11 batch cells; three CHP units totalling 910 kWe; 641-788 kWe achieved after start-up; average retention time 28 d; significant labour for loading and unloading.	Chiumenti et al. (2018)
England, United Kingdom (garage type)	Nine garage-type batch reactors; about 30,000 t yr-1; 1.2 MW; 28-d cycles at 3540 °C; TAN up to 5.2 g L-1 and H2S of 179-488 ppm; percolate recirculation at the operator's discretion.	Rocamora et al. (2022)

1201 1202 Table 8. Conflicting findings in the dry anaerobic digestion literature and their likely
1203 explanations.

Parameter	**Conflicting findings**	**Likely explanation**	**Reference**
Optimum TS	20% TS optimal for kitchen and food waste vs a threshold near 30% TS and stable operation at 27-30% TS for OFMSW, plug-flow food waste and poultry litter.	TS does not reflect free water; waterholding capacity and particle size differ between substrates.	Liu et al. (2025); Abbassi-Guendouz et al. (2012); Perman et al. (2024)

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Temperature	Thermophilic operation about twice as fast with higher methane yield coefficient vs ammonia and acid inhibition in thermophilic fullscale plants.	Protein content (ammonia release), trace-element supply and acclimation.	Fernández-Rodríguez et al. (2013); Westerholm et al. (2020); Wu et al. (2024)
Inoculum ratio	Feedstock-toinoculum ratio of 3 failed for OFMSW vs ratios up to 3.6 successful for wheat straw.	Rate of acid formation depends on substrate degradability.	Dastyar et al. (2021); Rouches et al. (2019)
Recirculation	Higher recirculation improved performance and limited free ammonia vs no significant or marginal effect, or acid spreading.	Timing and acid status of the recirculated liquid; distribution of inoculum and alkalinity.	Chen et al. (2020); Perman et al. (2024); Kusch (2013)
Particle size	Smaller particles increase surface area vs particles below	Hydrolysis faster than methanogenic capacity; interaction	Vigueras-Carmona et al. (2025); Motte et al. (2013)
	500 µm inhibited methanogenesis.	with TS.	
C/N ratio	Recommended total C/N of 20-30 vs optimal available C/N of 11-15.	Total C/N includes non-degradable carbon.	Wang et al. (2017); Puyuelo et al. (2011)

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Pretreatment	Methane yield increased by 24-52% vs transient acidification and melanoidin inhibition.	Pretreatment severity and substrate degradability.	Liu et al. (2022); Wang et al. (2024); Ariunbaatar et al. (2014b)

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Figures

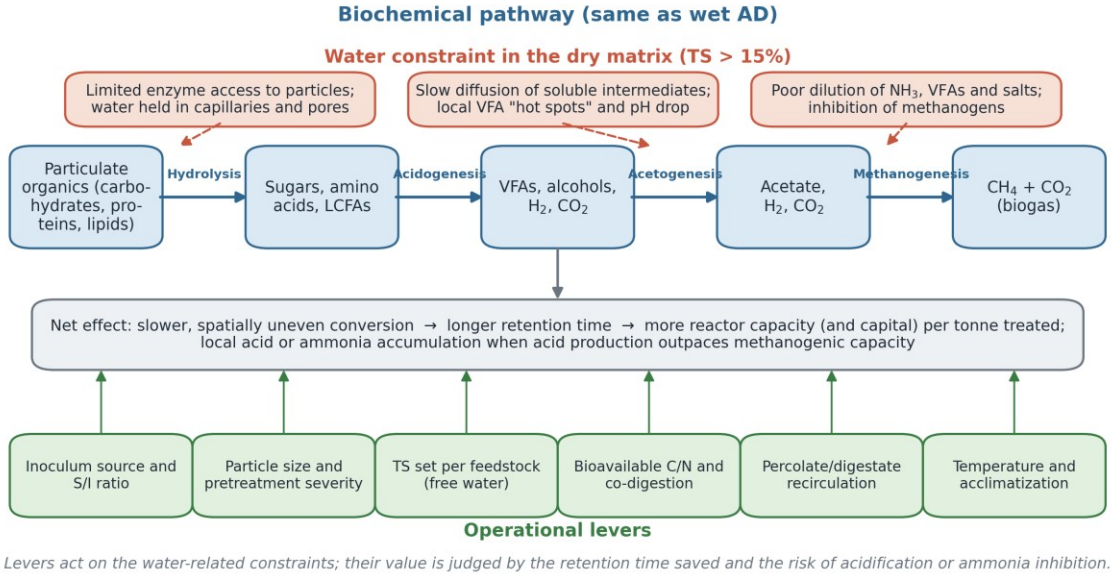
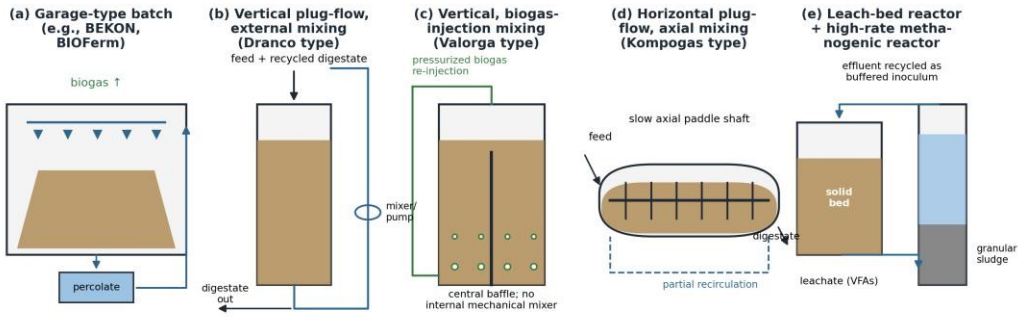


Figure 1. Conceptual pathway of dry anaerobic digestion. The biochemical sequence is the same as in wet AD, but limited free water restricts enzyme access to particles, the diffusion of intermediates and the dilution of inhibitors; operational levers act on these constraints.

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Operation	Batch; staggered chambers (≥3)	Continuous	Continuous	Continuous	Batch bed + continuous liquid
Typical TS	17-35% (up to 40%)	30-40%	25-35%	23-28%	>20% in bed
Mixing/ contact	Percolate irrigation	External mixing with recycled digestate	Biogas injection	Slow axial paddles; partial recirculation	Leachate circulation
Main strength	Low mechanical complexity; little process control	High OLR; robust to high TS	No moving parts inside digester	Plug flow; hygienization	Separates hydrolysis and methanogenesis
Main limitation	Long cycle (3-6 wk); loading/unloading labour	Feed preparation and pumping of paste	Gas-injection energy; settling of inerts	Mechanical wear; limited TS range	Mostly pilot scale; costs not reported

Figure 2. Schematic comparison of major dry anaerobic digestion reactor configurations: garage-type batch with percolate recirculation, vertical plug-flow with external mixing (Dranco type), vertical reactor with biogas-injection mixing (Valorga type), horizontal plug-flow with slow axial mixing (Kompogas type), and an emerging leach-bed reactor coupled with a high-rate methanogenic reactor. TS ranges and retention times are from the literature cited in Section 5.

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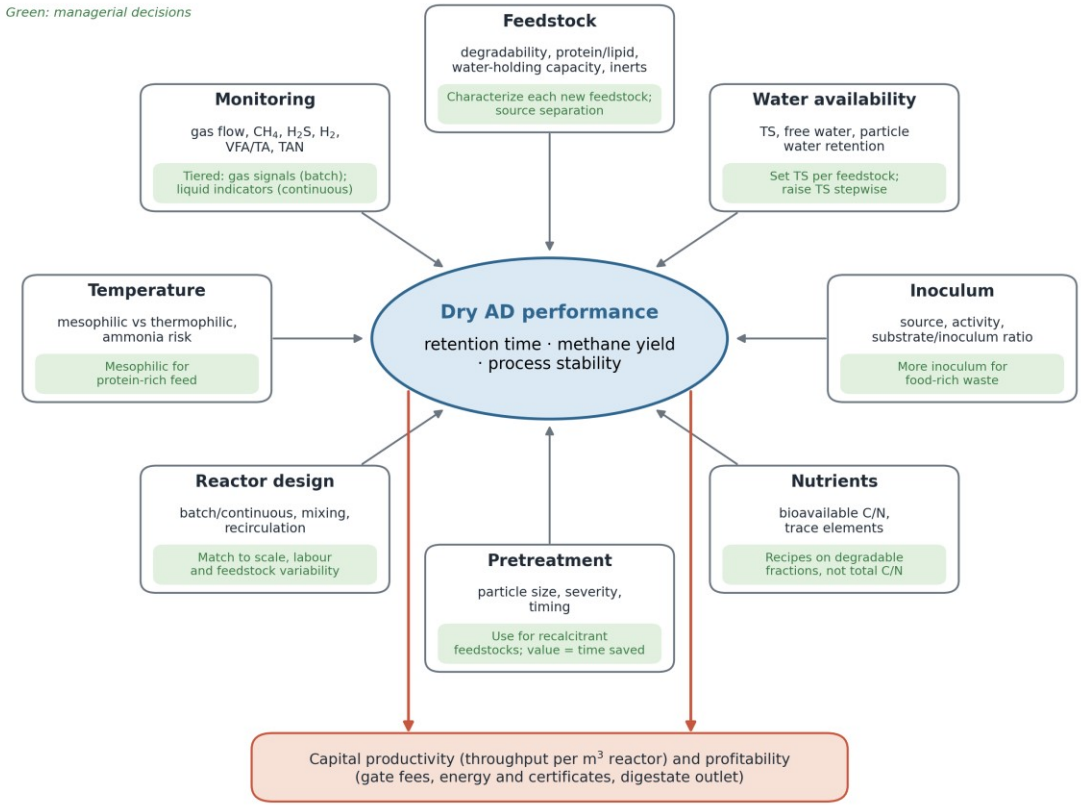


Figure 3. Factors affecting dry anaerobic digestion performance and their translation into managerial decisions. Feedstock, water availability, inoculum, nutrient bioavailability, pretreatment, reactor design and monitoring determine retention time, methane yield and stability, which together determine capital productivity and profitability.

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