

## Biochemical methane potential of organic substrates: Assessment and interpretation

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### ABSTRACT

Biochemical methane potential is one of the main indicators used to assess the suitability of organic substrates for anaerobic digestion. The aim of this paper was to review the role of this parameter in the evaluation of substrate biogas potential and to discuss methods for its determination, estimation and interpretation. Experimental approaches to biochemical methane potential testing, theoretical methods based on substrate composition, and kinetic models supporting data interpretation were examined. The variation in biochemical methane potential values among the main substrate groups was also discussed, with particular attention to lignocellulosic materials, food waste, agri-food by-products and sewage sludge. The importance of co-digestion as a means of improving methane yield and process stability was also highlighted. The scientific value of the paper lies in the integrated analysis of methodological, interpretative and application-related aspects of biochemical methane potential. The review showed that reliable biochemical methane potential assessment requires consideration of substrate properties, validation quality and the limited comparability of published results.

**Keywords:** biochemical methane potential, anaerobic digestion, organic substrates, methane yield, co-digestion, result validation, substrate assessment.

### INTRODUCTION

Anaerobic digestion (AD) is one of the main methods used for the management of organic waste and for energy recovery in the form of biogas. Interest in this process has increased in recent years (Kumar et al., 2024; Nayeri et al., 2024). This trend results from the need to reduce the amount of biodegradable waste and to increase the share of renewable energy sources in the energy mix. The efficiency of anaerobic digestion depends strongly on substrate properties, its susceptibility to biological degradation, and its capacity for methane production (Nayeri et al., 2024). For

this reason, it is important to use indicators that allow the suitability of different organic materials for biogas production to be assessed.

One of the most commonly used parameters in this field is biochemical methane potential (BMP) (Cabrita and Santos, 2023; Liu et al., 2024). This parameter defines the maximum amount of methane that can be obtained from a unit mass of the tested substrate under laboratory conditions (Hafner et al., 2026; Koch et al., 2020). BMP is widely used in both scientific research and engineering practice (Cabrita and Santos, 2023; Hafner et al., 2026). It enables the comparison of different substrate groups, the assessment of

their biodegradability, the selection of materials for mono-digestion or co-digestion, and the preliminary evaluation of the energy potential of wastes and by-products. The results of BMP tests are also used in the design and optimisation of anaerobic digestion systems (Koch et al., 2020).

Despite the widespread use of this parameter, the interpretation of BMP results is not straightforward (Hafner et al., 2026; Koch et al., 2020). Values obtained for the same type of substrate may differ across studies. This results from both variability in material composition and methodological differences. The outcome is affected by the test procedure, the type of apparatus, the method used to measure gas volume, the approach used to determine methane content, the calculation conditions, and the criteria adopted for test completion (Casallas-Ojeda et al., 2022). The way in which data are reported is also important (Liu et al., 2024). This includes the choice of reference units and the distinction between theoretical potential and experimentally determined values. As a result, the comparison of results reported in the literature is often difficult, and the assessment of the actual suitability of substrates requires careful analysis (Casavant et al., 2025).

The literature describes experimental methods for BMP determination, as well as theoretical and modelling approaches used for its estimation (Casallas-Ojeda et al., 2022; Koch et al., 2020). The most common approach is the batch test, in which the amount of biogas or methane produced is determined on the basis of gas volume, pressure, or gas composition (Hafner et al., 2026). Computational methods are also used. These are based on the elemental or chemical composition of the substrate and allow the theoretical methane potential to be estimated (Koch et al., 2020). Kinetic models are also becoming more important (da Silva et al., 2024; Llanos-Lizcano et al., 2024). They allow a more detailed interpretation of process performance and support the assessment of methane production rates. The diversity of research approaches means that it is necessary not only to present the available methods, but also to assess their usefulness, limitations, and mutual comparability.

The aim of this article is to review the importance of biochemical methane potential in the evaluation of organic substrates and to discuss the main methods used for its determination, estimation, and interpretation. The paper presents the role of BMP as an indicator of the biogas potential

of different substrate groups. It characterises the main experimental, theoretical, and modelling approaches. It also identifies the main problems related to the comparability of results. Particular attention is given to the importance of BMP in the assessment of methane yield and in the evaluation of substrate suitability for anaerobic digestion and co-digestion processes.

## BACKGROUND

Earlier research on biochemical methane potential has developed along several complementary lines. In the broader context of anaerobic digestion, review papers by Kumar et al. (2024) and Nayeri et al. (2024) showed that substrate characteristics remain one of the main factors determining methane production and overall process performance. In connection with this general perspective, subsequent studies increasingly treated BMP as a practical indicator supporting substrate evaluation rather than merely as an isolated laboratory parameter. Cabrita and Santos (2023) reviewed biochemical methane potential assays for a broad range of organic wastes and demonstrated their importance in feedstock screening and comparative substrate assessment, whereas Koch et al. (2020) emphasised that the interpretative value of BMP depends on a correct understanding of both the strengths and the limitations of the test itself. In this sense, the literature has gradually shifted from treating BMP only as a measure of methane yield towards viewing it as an analytical tool used in the broader assessment of substrate suitability.

In relation to this development, a substantial part of the literature has focused on the methodological basis of BMP assessment. Casallas-Ojeda et al. (2022) distinguished between experimental and theoretical approaches and discussed the principal techniques used to quantify methane production potential, including volumetric and manometric systems. This methodological perspective was developed further by Hafner et al. (2026), whose interlaboratory study demonstrated that substantial variation in BMP results may still occur even when experienced laboratories analyse comparable materials. In connection with these findings, Casavant et al. (2025) drew attention to the problem of test completion and showed that endpoint criteria may significantly influence the final result, particularly for slowly degradable substrates. Taken together, these studies indicate

that BMP values cannot be interpreted independently of the applied procedure, validation quality and reporting practice, and that methodological variation remains one of the main reasons for limited comparability between published results.

In parallel with experimental research, increasing attention has also been given to theoretical estimation and kinetic interpretation. Yasim and Buyong (2023) compared experimental and theoretical methane potential values for municipal solid waste and showed that the difference between them may provide useful information on substrate biodegradability and on the extent to which the theoretical potential is actually realised. In connection with this interpretative direction, da Silva et al. (2024) proposed an advanced modelling framework for BMP test evaluation, whereas Llanos-Lizcano et al. (2024) analysed both methane potential and degradation kinetics in selected organic waste streams. A related contribution was made by Liu et al. (2024), who developed a public biochemical methane potential database in order to facilitate broader comparison of published data. In view of these developments, the literature suggests that BMP research is already extensive, but that important challenges remain with respect to standardisation, data comparability and the integrated interpretation of methane yield, theoretical potential and degradation kinetics. For this reason, a focused review of BMP as a parameter used for substrate assessment and interpretation remains justified.

## **BIOCHEMICAL METHANE POTENTIAL AND SUBSTRATE SUITABILITY FOR BIOGAS PRODUCTION**

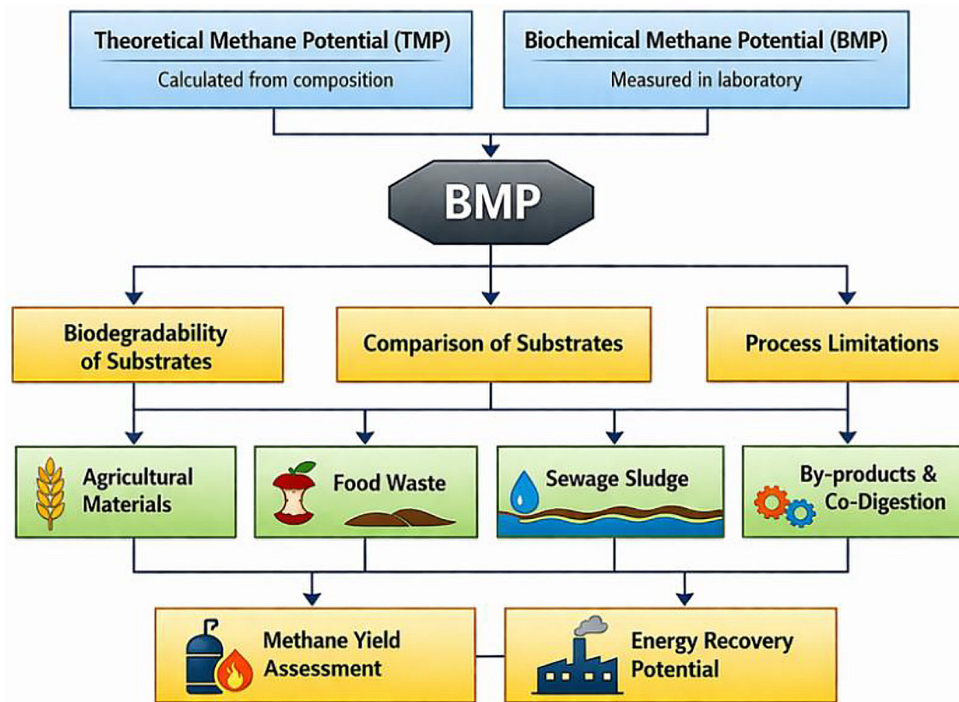
Biochemical Methane Potential is one of the most widely used indicators for assessing the suitability of organic substrates for biogas production (Cabrita and Santos, 2023; Liu et al., 2024). This parameter defines the maximum amount of methane that can be obtained from a unit mass of the tested organic material under controlled laboratory conditions (Hafner et al., 2026; Koch et al., 2020). In practice, BMP reflects the degree of biodegradability of organic matter and its capacity to be converted into the chemical energy contained in methane. For this reason, it is widely used in both scientific research and technical assessments related to substrate selection for anaerobic digestion (Koch et al., 2020). The importance of BMP

arises mainly from its comparative function. Its value makes it possible to compare different groups of substrates in terms of their methane potential. This applies to agricultural materials, food waste, sewage sludge, by-products from the agri-food industry, and multicomponent mixtures (Llanos-Lizcano et al., 2024). It therefore allows the identification of substrates with high suitability for energy recovery and those with more limited potential in anaerobic digestion. BMP supports the preliminary selection of materials for use in biogas plants and enables a more rational approach to their management.

When assessing biogas potential, it is important to distinguish between actual BMP and theoretical methane potential, often referred to as TMP or TBMP (Casallas-Ojeda et al., 2022; Koch et al., 2020). The theoretical methane potential is calculated from the elemental or chemical composition of the substrate and assumes complete degradation of organic matter into end products. This value is model-based and refers to ideal conversion conditions. By contrast, experimentally determined BMP reflects the actual amount of methane that can be obtained from the tested material under defined laboratory conditions. Differences between TMP and BMP result from the incomplete biodegradation of some organic compounds, limited accessibility of certain fractions, and the effect of test conditions (Yasim and Buyong, 2023). A comparison of these two parameters may help assess the extent to which the substrate potential is utilised and identify factors that limit the process.

Figure 1 presents the role of BMP in substrate assessment and its relation to theoretical methane potential. In Figure 1, “calculated from composition” refers to theoretical methane potential estimated from substrate composition, whereas “measured in laboratory” refers to experimentally determined BMP under laboratory conditions.

BMP is closely linked to the assessment of substrate biodegradability. Substrates containing large amounts of readily degradable compounds, such as sugars, lipids, or some proteins, usually reach higher BMP values than materials rich in lignin, poorly accessible cellulose, or other slowly degradable compounds (Donatelli and Chang, 2024; Anacleto et al., 2024). This means that BMP does not describe only the total amount of organic matter. It mainly reflects the fraction that can be effectively converted into methane. For this reason, BMP is more informative than the content of



**Figure 1.** The diagram illustrates BMP as an indicator of substrate biogas potential

organic dry matter or volatile solids when the aim is to estimate the actual methane yield.

This indicator is particularly useful in the assessment of substrates used in mono-digestion and co-digestion. For single materials, it enables the direct comparison of their energy-related suitability. For mixtures, it helps determine whether combining several substrates may improve methane yields. This has clear practical value, because many organic wastes do not show optimal properties when used alone, but may perform better in mixed systems (Manthos et al., 2023). BMP is therefore a useful tool in the formulation of feedstock mixtures and in the assessment of the potential benefits of co-digestion.

BMP also plays an important role in the assessment of substrate energy potential. Methane is the main energy-bearing component of biogas. The amount of methane that can be obtained from a given mass of material therefore provides an estimate of its practical value for energy recovery. BMP can support technological and economic analyses, especially at the initial stage of substrate selection for biogas installations. This applies to both conventional materials and new organic waste streams whose suitability for anaerobic digestion must first be verified.

It should be noted, however, that BMP should not be treated as the only indicator used in substrate

assessment. A high methane potential does not always mean high technological suitability under real operating conditions. Final process performance also depends on degradation rate, process stability, biogas composition, the presence of inhibitory compounds, and the physical properties of the material (Prasad et al., 2024; Anacleto et al., 2024). Despite these limitations, BMP remains a basic parameter for comparing and classifying substrates in terms of biogas potential. Its importance results from its clear interpretative value, broad comparative usefulness, and direct link with methane yield assessment. In this context, BMP is one of the key indicators used in the evaluation of substrates intended for anaerobic digestion.

## METHODS FOR THE ASSESSMENT AND VALIDATION OF BMP

BMP is assessed by means of experimental methods, theoretical estimation and kinetic interpretation (Cabrita and Santos, 2023; Koch et al., 2020). The scientific value of the result depends on the applied procedure, the quality of validation and the degree of methodological standardisation (Hafner et al., 2026; Holliger et al., 2016). The main approaches used in biochemical methane potential assessment are outlined below.

## Experimental determination of biochemical methane potential in batch tests

The general method used to determine biochemical methane potential is the batch biochemical methane potential test (Cabrita and Santos, 2023; Koch et al., 2020). This approach involves the incubation of the tested substrate with active inoculum under anaerobic conditions and the monitoring of gas production and methane content over time. It is widely used to assess substrate biodegradability and to compare the suitability of different materials for anaerobic digestion. In practice, the test is usually carried out in bottles or small reactors under controlled mesophilic or thermophilic conditions for a period ranging from several days to several weeks. The test is usually terminated when daily gas production declines to a low level.

Several groups of experimental methods are described in the literature (Casallas-Ojeda et al., 2022; Hafner et al., 2026). The simplest methods are volumetric systems, in which gas production is determined by liquid displacement or by direct volume reading (Casallas-Ojeda et al., 2022; Koch et al., 2020). In these systems, biogas volume is commonly measured by water displacement and subsequently corrected to standard conditions. Methane content was determined with a gas analyser. Volumetric methods are relatively simple, inexpensive and still widely applied. However, they require careful correction for temperature, pressure and water vapour.

Another important group includes manometric methods, in which the increase in pressure in the headspace is used to calculate the volume of gas produced (Casallas-Ojeda et al., 2022; Hafner et al., 2026). Their advantage lies in convenient serial measurements and a lower risk of reading errors related to gas volume. However, the result depends on the gas phase volume, the frequency of venting and the accuracy of the applied calculations. Comparative studies have shown that these factors may significantly affect the final result. For this reason, manometric methods require strict procedural standardisation (Hafner et al., 2020; Hafner et al., 2026).

Automated systems, such as the Automatic Methane Potential Test System (AMPTS), are becoming increasingly important (Hafner et al., 2026; Cabrita and Santos, 2023). These systems combine continuous volume measurement with carbon dioxide removal or with parallel gas

composition assessment. Their main advantages are high temporal resolution, lower labour requirements and better repeatability of measurements. They also support the analysis of methane production kinetics. Their main limitation is the cost of the equipment and their lower availability in routine laboratories. As a result, simpler manual systems are still commonly used, especially at the preliminary screening stage.

Regardless of the type of equipment, the biochemical methane potential result should be related to the organic fraction of the substrate, most often to volatile solids (VS). It is also necessary to subtract gas production originating from the inoculum itself. For this reason, a properly designed test includes a blank sample containing inoculum only and a control sample with a reference substrate, most often cellulose. Current guidelines indicate that the positive control should reach at least about 80 to 85 per cent of the theoretical yield. This confirms that the test has been conducted correctly (Holliger et al., 2016; VDI 4630, 2016).

## Theoretical methods for the estimation of biochemical methane potential

In addition to experimental methods, theoretical approaches are used to estimate the potential methane yield on the basis of substrate composition (Yasim and Buyong, 2023; Casallas-Ojeda et al., 2022). The most common are stoichiometric equations derived from the Buswell and Boyle approach (Yasim and Buyong, 2023; Koch et al., 2020). These equations make it possible to calculate theoretical methane potential from data on elemental composition or on the simplified chemical composition of biomass. In practice, estimates based on volatile solids, chemical oxygen demand (COD) or the share of the main organic fractions, such as proteins, lipids and carbohydrates, are also used.

These methods are particularly useful when a rapid assessment of many substrates is required or when experimental studies are limited by time, cost or laboratory capacity. They may serve as the first stage in the qualification of a material for further laboratory investigation. They also allow the comparison of different substrate groups on the basis of chemical composition and the preliminary estimation of the potential benefits of co-digestion.

The main advantages of theoretical methods are their speed and low cost. They are useful in the preliminary assessment of new substrates, in

comparative analyses and in design-related mass and energy balances. Their limitation is, however, fundamental. They assume complete conversion of organic matter into end products and do not account for hydrolysis constraints, incomplete accessibility of some organic fractions or the presence of inhibitory compounds. They also reflect only to a limited extent the different susceptibility of biomass components to biological degradation. For this reason, theoretical methane potential values are usually higher than experimentally determined biochemical methane potential values. The difference between theoretical methane potential and actual biochemical methane potential may itself provide useful information on the degree of substrate utilisation and on the presence of process limitations (Yasim and Buyong, 2023; Koch et al., 2020).

### Modelling methods and early prediction of biochemical methane potential

Kinetic models are increasingly used in biochemical methane potential studies. They do not replace measurement, but they support the interpretation of test performance. The most widely applied approach is the modified Gompertz model (da Silva et al., 2024; Llanos-Lizcano et al., 2024). This model allows estimation of three main parameters: maximum methane potential, maximum methane production rate, and lag phase duration. It is commonly used to analyse methane production kinetics and to assess the effects of different factors on process rate and lag phase.

In addition to the Gompertz model, first-order models, multi-component models and empirical approaches fitted to time-series data are also used (da Silva et al., 2024; Catenacci et al., 2022). Their usefulness is particularly high when the aim of the analysis is not limited to the final biochemical methane potential value, but also includes the comparison of degradation rates for different substrates. These models make it possible to describe cumulative methane production more accurately and to distinguish between substrates that are readily biodegradable and those that degrade more slowly. This allows a more detailed comparison of materials with similar final biochemical methane potential values but different degradation dynamics.

Recent studies also indicate that final biochemical methane potential may be predicted at an early stage on the basis of the initial part of the test curve (Catenacci et al., 2022; Casavant

et al., 2025). This has practical importance because the conventional batch test is often time-consuming. A reduction in the time needed to obtain a reliable prediction may be valuable in screening studies and in technological assessments. The effectiveness of such prediction depends on the quality of the input data, the type of substrate and the appropriateness of model selection. It also requires careful interpretation, because an excessively early prediction may lead to overestimation or underestimation of methane potential, especially in substrates with a high share of slowly degradable fractions.

### Validation, standardisation, and advantages and limitations of the methods

The main problem associated with biochemical methane potential methods remains the comparability of results between laboratories. Holliger and co-workers showed that biochemical methane potential values for the same substrate may differ substantially when studies are conducted according to different procedures (Holliger et al., 2016; Hafner et al., 2026). For this reason, the current approach to biochemical methane potential testing includes not only measurement itself, but also its validation. Key factors include inoculum quality and origin, the proper inoculum-to-substrate ratio, the use of blank tests and positive controls, correction of gas conditions and a consistent method of data reporting (Sicchieri et al., 2022; Ribeiro et al., 2020).

The most frequently cited reference documents are the guidelines proposed by Holliger and the German standard VDI 4630 (Holliger et al., 2016; VDI 4630, 2016). These documents organise the principles of sample collection, substrate preparation, test performance and result quality assessment. Their importance is considerable, because without a common standard even well-conducted studies may be difficult to compare with published data. Recent publications still indicate that the standardisation of biochemical methane potential testing has not yet been fully completed. This applies in particular to kinetic evaluation, methane production by inoculum itself and the propagation of measurement errors (Hafner et al., 2026; Baquerizo-Crespo et al., 2026).

From a practical perspective, experimental methods remain the most reliable because they reflect the actual susceptibility of a substrate to anaerobic digestion. Theoretical methods are

faster, but they provide only approximate values. Modelling methods increase the interpretative value of the test, but their validity depends on the quality of experimental data. The combined use of these approaches therefore appears to be the most rational solution. The batch test should remain the basis for biochemical methane potential assessment. Theoretical methods may support comparative analysis. Kinetic models should be used for deeper interpretation of results. This approach makes it possible to obtain an assessment that is more complete and methodologically sound (Koch et al., 2020; Hafner et al., 2026).

Table 1 summarises the principal approaches used for the determination, estimation, interpretation and validation of BMP-related results, including both direct experimental methods and complementary theoretical and modelling approaches.

### BMP IN SELECTED GROUPS OF ORGANIC SUBSTRATES

The value of BMP differs markedly across groups of organic substrates. This results from differences in chemical composition, the share of readily and poorly biodegradable fractions, lignin content, lipid and protein content, and susceptibility to hydrolysis. For this reason, biochemical methane potential and actual methane yield

should not be analysed without reference to the nature of the material. In comparative terms, the highest values are usually reported for food waste and some by-products of the agri-food industry. Lower values are typical of sewage sludge. The greatest variability is observed in lignocellulosic substrates. This pattern is confirmed by both thematic reviews and the biochemical methane potential databases currently being developed on the basis of batch test results (Cabrita and Santos, 2023; Liu et al., 2024).

### Plant-based and lignocellulosic substrates

Lignocellulosic substrates, such as straw, stalks, leaves, harvest residues and other plant wastes, represent an important group of materials considered for biogas production. Their main advantage is high availability and a high content of organic matter. Their main limitation is the complex lignocellulosic structure. Cellulose and hemicellulose can serve as methane precursors, but their accessibility to microorganisms is limited by lignin and by the compact structure of plant cell walls. As a result, raw lignocellulosic materials often show moderate or low biochemical methane potential, and their degradation proceeds more slowly than that of food waste. Recent reviews consistently indicate that, in this group of substrates, the result is determined not only by the content of organic

**Table 1.** Main approaches used for the determination, estimation, interpretation and validation of biochemical methane potential

Method group	Main principle	Advantages	Limitations/remarks	Ref.
Experimental batch methods	Incubation of substrate with inoculum under anaerobic conditions and direct measurement of biogas or methane production over time	Highest practical relevance. Reflects actual substrate biodegradability. Suitable for comparing substrates and mixtures	Time-consuming. Sensitive to inoculum quality, inoculum-to-substrate ratio, blank correction, gas normalisation and end-point criteria. Results may differ between laboratories	Koch et al., 2020; Hafner et al., 2026
Theoretical estimation methods	Calculation of methane potential from elemental composition, chemical composition, volatile solids, or chemical oxygen demand	Rapid and inexpensive. Useful for preliminary screening, design estimates and comparison of substrate groups	Assumes complete conversion. Does not reflect hydrolysis limits, bioavailability, inhibition, or actual process conditions. Usually overestimates experimental values	Yasim and Buyong, 2023; Casallas-Ojeda et al., 2022
Modelling methods and early prediction	Mathematical fitting of cumulative methane production curves and estimation of kinetic parameters	Improves interpretation of test dynamics. Supports comparison of degradation rates. May shorten screening time	Does not replace measurement. Strongly dependent on data quality and model selection. Early prediction may be unreliable for slowly degradable substrates	da Silva et al., 2024; Catenacci et al., 2022
Validation and standardisation framework	Quality assurance of the test through blanks, positive controls, replicates, gas correction and consistent reporting	Improves repeatability and comparability. Supports methodological consistency between studies	Still not fully harmonised internationally. Reproducibility remains a challenge, especially for kinetic parameters and inoculum-related variability	Holliger et al., 2016; VDI 4630, 2016

matter but above all by its biological accessibility (Prasad et al., 2024; Anacleto et al., 2024).

The considerable variation in biochemical methane potential within the same group of plant materials results from differences in structural composition. Lignin content remains one of the main factors reducing methane yield and slowing degradation. The literature reports a negative relationship between lignin content and experimental methane yield in fibrous substrates. This means that two plant materials with a similar content of organic dry matter may show clearly different biochemical methane potential values. For this reason, classification of a substrate as plant-based or lignocellulosic is not sufficient for predicting its energy value. Analysis of composition, particle size reduction and possible pretreatment is required (Prasad et al., 2024).

Recent studies also indicate that data sets and predictive models are increasingly used in the assessment of lignocellulosic substrates, because conventional biochemical methane potential tests are particularly time-consuming for this group. This results from slower hydrolysis and the longer time required to reach a methane production plateau. At the same time, experimental practice shows that appropriate substrate preparation, especially size reduction or physical, chemical or biological pretreatment, may significantly improve the bioavailability of carbohydrate fractions. This means that, for this group of substrates, the biochemical methane potential result should be interpreted not only as a property of the biomass itself, but also as a consequence of the method of preparation before digestion (Dębowski et al., 2024; Anacleto et al., 2024).

### **Food waste and by-products of the agri-food industry**

Food waste belongs to the group of substrates with the highest methane potential. This is due to the high proportion of readily biodegradable sugars, starch, proteins and lipids. Literature reviews and biochemical methane potential databases indicate that methane yields from food waste are usually much higher than those obtained from sewage sludge. In a database published in 2024, the median value for food waste was 429 mL CH<sub>4</sub>/g volatile solids, whereas the corresponding value for municipal sludge was 144.5 mL CH<sub>4</sub>/g volatile solids. This difference clearly illustrates the different degree of biodegradability and the

different energy value of the two substrate groups (Liu et al., 2024; Pilarska et al., 2023).

High BMP in food waste does not automatically mean the highest process stability. Recent reviews emphasise that digestion of food waste alone is often associated with a risk of acidification, foaming, and inhibition related to the accumulation of volatile fatty acids or ammoniacal nitrogen. For this reason, a high methane potential should always be considered together with the susceptibility of the system to overloading. In practice, this means that substrates with very favourable biochemical methane potential may require more careful process control than materials with lower potential but greater operational stability (Paranjpe et al., 2023).

Another important feature of food waste is the high variability of its composition. Material originating from households, catering, food processing or retail may differ in the proportion of lipids, starch, fibre and proteins. This directly affects the spread of biochemical methane potential values and the kinetics of methane production. In comparative studies, food waste often reaches very high methane yields, but at the same time shows high sensitivity to changes in feedstock composition. For this reason, in this group of substrates, biochemical methane potential should be treated as an indicator with high comparative value, but one that requires careful interpretation in relation to the specific source of waste (Donatelli and Chang, 2024; Pilarska et al., 2019a).

Numerous by-products of the agri-food industry also belong to the group of materials with high methane potential. Their advantage is often a more uniform composition than that of mixed municipal waste. At the same time, some of them may contain large amounts of lipids or readily fermentable carbohydrates, which increases biochemical methane potential but may also intensify process fluctuations. From the perspective of biogas practice, it is therefore particularly important to distinguish between high methane potential and the actual ease of process operation. In many cases, materials from this group show their highest technological usefulness in mixed systems (Lee et al., 2024).

### **Sewage sludge and substrates with lower BMP**

Sewage sludge is one of the most important substrates for anaerobic digestion in municipal

practice. Its importance results not from the highest biochemical methane potential, but from high availability and the need for stabilisation before further management. In comparison with food waste, its methane potential is usually lower. Data from a public biochemical methane potential database indicate a median value of 144.5 mL CH<sub>4</sub>/g volatile solids for municipal sludge. This limitation results from the presence of fractions that are less susceptible to biodegradation and from the character of biologically transformed organic matter, especially in waste activated sludge (Liu et al., 2024; Pilarska et al., 2019b).

Despite its moderate biochemical methane potential, sewage sludge has important process advantages. It provides an active microbial environment, favourable buffering capacity and a good ability to co-digest with materials richer in readily available organic carbon. For this reason, its importance as a sole substrate is now often lower than its role as a component of mixed systems. In practice, the combination of sludge with food waste, industrial by-products or plant substrates may improve nutrient balance, increase methane production and stabilise the process (Li et al., 2024; Pilarski et al., 2020).

### **Co-digestion as a means of improving BMP performance**

Co-digestion is now regarded as one of the most important tools for improving methane yield from problematic substrates or from materials that are not sufficiently valuable as a sole feedstock. The mechanism of the synergistic effect usually results from better balancing of the mixture composition, dilution of inhibitory compounds, improvement of the carbon-to-nitrogen ratio, and the creation of a more favourable environment for microorganisms. In the case of sewage sludge, co-digestion makes it possible to compensate for its moderate methane potential by adding more energy-rich co-substrates. In the case of food waste, it may reduce the risk of acidification and improve process stability (Li et al., 2024; Paranjpe et al., 2023).

In recent years, the literature has paid particular attention to systems based on the combination of sewage sludge and food waste. Experimental studies and reviews indicate that this direction is promising in terms of both methane yield and reactor stability. This confirms that high methane yield does not always correspond to optimal

process performance. In mixed systems, it is more common to achieve a compromise between high gas production and greater stability. Co-digestion is also of particular importance for lignocellulosic materials. When used alone, they show limited accessibility of biodegradable matter and slower degradation kinetics, but in mixtures with substrates rich in readily fermentable compounds they may achieve better performance. The extent of the synergistic effect depends on the proportion of individual components, their chemical properties and the conditions of the biochemical methane potential test. For this reason, the comparison of substrates solely on the basis of their individual biochemical methane potential values may be insufficient. For technological practice, the capacity to form stable and efficient mixed systems is equally important (Paranjpe et al., 2023; Lee et al., 2024).

From the perspective of assessing substrate groups, it may therefore be concluded that the highest biochemical methane potential values are usually observed for food waste and some homogeneous by-products of the agri-food industry. Lignocellulosic substrates show high variability and more often require pretreatment or co-digestion. Sewage sludge is characterised by moderate methane potential, but high usefulness as a component of mixtures. This pattern has important practical implications. It shows that substrate assessment should not rely solely on the highest biochemical methane potential value, but on the relationship between methane potential, process stability and the possibility of using a given material in mono-digestion or co-digestion (Pilarski et al., 2020; Li et al., 2024).

Overall, food waste and some homogeneous by-products of the agri-food industry usually show the highest biochemical methane potential. Lignocellulosic substrates show the greatest variability and more often require pretreatment or co-digestion. Sewage sludge is characterised by moderate methane potential, but high usefulness as a component of mixtures. The main features of these substrate groups are summarised in Table 2.

### **FACTORS AFFECTING BMP VALUES AND RESULT INTERPRETATION**

The value of BMP is not an absolute property of a substrate. It reflects both the composition of the material and the accessibility of its

**Table 2.** Representative biochemical methane potential values and key features of selected groups of organic substrates

Substrate group	BMP range (mL CH <sub>4</sub> /g VS)	Key feature	Practical implication	Ref.
Lignocellulosic materials	120–320	High structural variability. Methane yield is limited mainly by lignin content and poor fibre accessibility	Often require pretreatment or co-digestion	Prasad et al., 2024; Dębowski et al., 2024
Food waste	350–550	Usually the highest BMP because of the high share of readily biodegradable compounds	High methane potential, but increased risk of overload and acidification	Liu et al., 2024; Pilarska et al., 2023
Agri-food by-products	250–500	Often high methane potential, but values depend strongly on composition and processing	Suitable co-substrates in mixed systems	Pilarska et al., 2019a; Lee et al., 2024
Sewage sludge	100–220	Moderate BMP and lower biodegradability than food waste	Valuable mainly as a stable component of co-digestion mixtures	Liu et al., 2024; Li et al., 2024
Sewage sludge with food waste or other co-substrates	200–520	Improved methane yield due to synergistic effects and better substrate balance	Often offers the best compromise between yield and stability	Li et al., 2024; Paranjpe et al., 2023

organic fractions to microorganisms. The most important factors are the share of readily biodegradable compounds, lignin content, the distribution of protein and lipid fractions, and the susceptibility of the biomass to hydrolysis. For this reason, a similar content of organic dry matter does not necessarily result in a similar methane yield. In practice, biochemical methane potential describes not only the quantity of organic matter, but above all the fraction that can be effectively converted into methane (Anacleto et al., 2024; Toufexis et al., 2024).

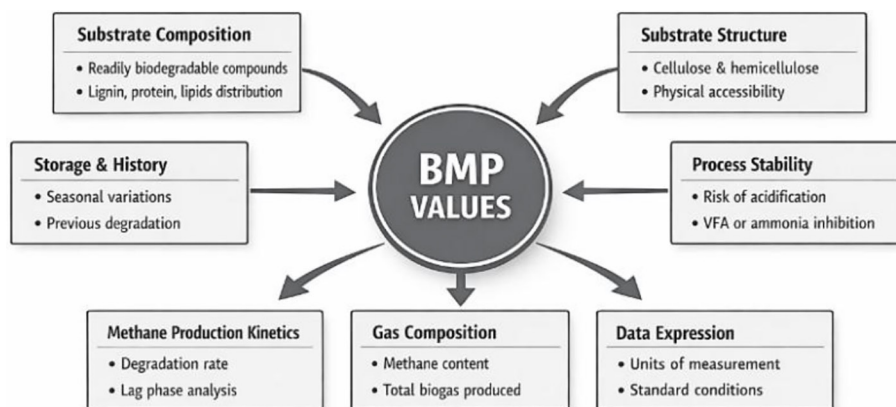
An overview of the main factors influencing BMP values and result interpretation is presented in Figure 2.

Substrate structure is an important interpretative factor. In lignocellulosic materials, the main barrier is the limited accessibility of cellulose and hemicellulose, which results from the presence of lignin and the compact structure of plant cell walls. Consequently, a low or moderate biochemical methane potential in these substrates does not always indicate a low content of chemical energy. It often reflects poor bioavailability of carbohydrate fractions. For this reason, the result obtained for straw, stalks or harvest residues should be interpreted together with information on size reduction or pretreatment. Recent reviews indicate that suitable biomass preparation may improve both final methane yield and process kinetics (Prasad et al., 2024; Anacleto et al., 2024).

In the case of food waste, a high biochemical methane potential usually results from a high proportion of sugars, starch, lipids and some proteins (Donatelli and Chang, 2024;

Pilarska et al., 2023). Such a composition favours rapid degradation and high methane yield, but it does not guarantee stable process performance. The literature shows that the same substrate may exhibit very favourable biochemical methane potential and at the same time increase the risk of acidification, foaming or inhibition associated with the accumulation of volatile fatty acids or ammoniacal nitrogen (He et al., 2024; Pilarska et al., 2023). This means that high methane potential should be interpreted together with the susceptibility of the system to overloading. BMP should therefore not be equated with full technological suitability. The history and origin of the material also affect BMP values. In food waste, manures and sewage sludge, important factors include seasonality, previous biological transformation, storage time and the degree of degradation before the test begins. Studies on agricultural materials and manures show that storage alone may reduce potential methane yield through partial degradation of readily available organic matter. Sewage sludge, in turn, contains a substantial share of biologically transformed matter, which is why its biochemical methane potential is usually markedly lower than that of food waste (Nayeri et al., 2024).

Evaluation of BMP should not be based solely on its final value. The dynamics of methane production are equally important. Two substrates may reach similar final biochemical methane potential values, yet differ in degradation rate, lag phase length and cumulative gas production profile. For this reason, kinetic models are increasingly used,



**Figure 2.** Factors influencing BMP values and assessment parameters

especially the modified Gompertz model and first-order models (da Silva et al., 2024; Llanos-Lizcano et al., 2024). These approaches allow a more precise assessment of whether the limitation is low overall biodegradability or rather slow hydrolysis and delayed microbial activity. This type of interpretation is particularly important for fibrous substrates and multicomponent mixtures.

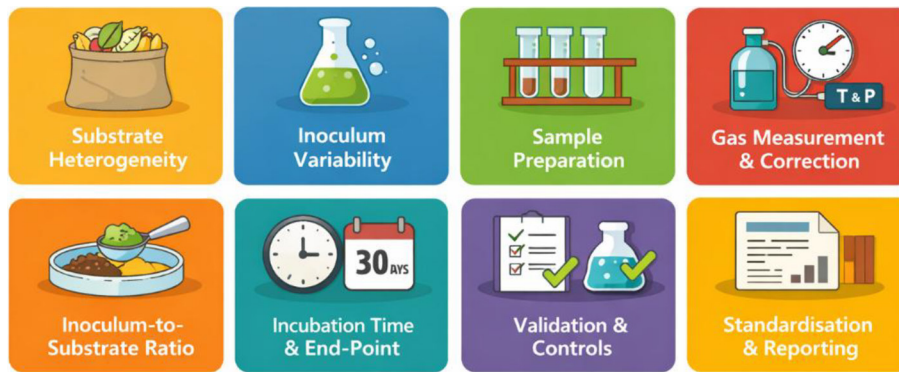
A further important distinction concerns BMP and total biogas yield. High gas production does not automatically mean high methane production, because methane content depends on substrate composition and process performance. Biochemical methane potential values should therefore be related to the actual CH<sub>4</sub> content and not only to total biogas volume. From an energy perspective, the key issue is not the total amount of gas, but the amount of methane as the main energy carrier. This distinction is especially important when comparing substrates with different fermentation kinetics and different carbon dioxide shares in biogas (Cabrita and Santos, 2023; Koch et al., 2020).

The interpretation of results is also affected by the way data are reported. In the literature, biochemical methane potential is most often expressed per volatile solids, but values are also reported per dry matter, fresh mass, chemical oxygen demand or feed mass. Without a common basis of expression, comparison of results may lead to incorrect conclusions. In practice, interpretation should therefore include not only the numerical value itself, but also the unit used, the gas normalisation conditions and the substrate characteristics. Only then can biochemical methane potential serve as a reliable indicator of biogas potential (Casallas-Ojeda et al., 2022; Hafner et al., 2020).

## LIMITATIONS OF BMP METHODS AND RESULTS COMPARABILITY

The main limitation of BMP testing remains the comparability of results obtained in different laboratories. Even for the same substrate, published values may differ substantially. These discrepancies result not only from natural variation in substrate composition, but also from differences in test design, sample preparation, inoculum type and activity, inoculum-to-substrate ratio, incubation time and the procedure used to correct gas volume to standard conditions. For this reason, a biochemical methane potential value alone has limited comparative value if methodological information is not provided (Hafner et al., 2026; Koch et al., 2020). Figure 3 illustrates the principal methodological factors contributing to differences in BMP results between studies and laboratories.

A particularly important source of uncertainty is the inoculum. Its origin, previous exposure to specific substrates, methanogenic activity and level of endogenous gas production strongly affect the final result. Recent studies show that failure to account for methane production from the inoculum itself may lead to incorrect estimation of both final biochemical methane potential and kinetic parameters. This problem is especially important for substrates with low methane potential, where the relative contribution of inoculum-derived gas may be considerable. Another limitation is the lack of full harmonisation in test end-point criteria and result reporting. In some studies, the test is terminated after a fixed number of days. In others, it is stopped when daily gas production falls below an adopted threshold.



**Figure 3.** Limitations affecting the comparability of BMP results between studies and laboratories

Differences are also observed in the number of replicates, the use of blank tests, the application of positive controls and the reporting of measurement uncertainty. As a result, data from apparently similar experiments are not always truly equivalent. This problem was one of the main reasons for the development of standardisation guidelines, including the recommendations of Holliger and the VDI 4630 standard (Holliger et al., 2016; VDI 4630, 2016).

A separate issue concerns theoretical and modelling approaches. Stoichiometric methods are useful at the preliminary assessment stage, but they assume complete conversion of organic matter and do not account for limitations in bioavailability or inhibition. Kinetic models increase the interpretative value of the test, but their quality depends directly on the quality of the experimental data and the appropriateness of model selection. They cannot replace a properly conducted batch assay. For this reason, the most reliable strategy remains a combined approach in which the experimental test provides the basis, while theoretical methods and models play a complementary role (Yasim and Buyong, 2023; da Silva et al., 2024).

In practice, improving the comparability of BMP results requires rigorous validation, complete reporting of input data and greater procedural consistency between laboratories. The development of public biochemical methane potential databases and new inter-laboratory studies shows that this is now one of the most important directions in methodological development. Despite this progress, standardisation is still incomplete. For this reason, the interpretation of biochemical methane potential values still requires caution and must always take account of the conditions under which the result was obtained (Liu et al., 2024; Ribeiro et al., 2020).

## CONCLUSIONS

Biochemical methane potential remains one of the most important indicators used in the assessment of the suitability of organic substrates for anaerobic digestion. Its importance lies in its ability to support the comparison of different material groups, the preliminary assessment of biodegradability, and the interpretation of potential methane yield in technological and energy-related terms. At the same time, the literature confirms that BMP cannot be considered separately from substrate properties, sample preparation, the applied method, and the quality of result validation.

1. Biochemical methane potential is a reliable and useful indicator of substrate biogas potential, but its value reflects primarily the fraction of organic matter that is actually susceptible to conversion into methane.
2. Experimental methods, especially batch tests, remain the basis for biochemical methane potential determination, whereas theoretical methods and kinetic models play complementary and interpretative roles.
3. The highest BMP values are usually reported for food waste and some homogeneous by-products of the agri-food industry, whereas lignocellulosic substrates show high variability and sewage sludge shows moderate methane potential.
4. The interpretation of BMP should not rely solely on the final value, because process kinetics, methane share in biogas, and process stability are also important.
5. The main practical limitation remains the incomplete comparability of results between studies, which results from procedural differences, inoculum quality, and the method of data reporting.

Future research should focus on greater standardisation of biochemical methane potential procedures and on combining experimental measurements with kinetic analysis and more complete substrate characterisation, in order to improve the reliability of assessment and the practical usefulness of the results.

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