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Closing the Gap Between Laboratory BMP Tests and Full-Scale Anaerobic Digestion Performance

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Abstract - BMP tests measure the production of gas by different organic substances and are also used in full-scale design. On the other hand, methane output can take a significantly different turn. This can be attributed to differences in the experiments, the heterogeneity between substrates and inoculum used, and such unnoticeable details as reaction rates. In order to develop a relationship between laboratory BMP and full-scale methane production, the authors investigated 14 substrates, including food waste and agricultural residues. The authors explain in detail the following five aspects: total solids and volatile solids content of raw material, laboratory BMP observed values, a scientific explanation of the various issues, and finally, factor deviation for BMP at full-scale problems. The results shown here suggest that although laboratory BMPs are correlated with the methane output in scaled systems, they are also subject to strain. At the same time, the extent of these deviations, which amount to 13-26% across all substrates investigated, depends on the specifics of each substrate for biodegradation and construction type. The efficient nature of highly bio-reactive substrates means a reduced deviation, while lignocellulosic feedstocks of this kind are characterized by greater losses. Overall, BMP data tends to overestimate the capacities of industrial facilities, allowing these to produce methane from anaerobic digestion.

Keywords: Biochemical Methane Potential (BMP); Anaerobic Digestion; Scale-Up Effects; Methane Yield Prediction; Substrate Biodegradability; Lignocellulosic Biomass; Volatile Solids; Full Scale Digester Performance.

1. INTRODUCTION

Anaerobic digestion is one of the most important technologies for generating sustainable energy, preventing landfills, and controlling greenhouse gases, as organic waste treatment and power generation are combined to produce biogas. The Biochemical Methane Potential (BMP) test is the most widely used laboratory-scale technique to determine the maximum potential methane yield of organic substrates under controlled environmental conditions [1,12], among others. The methodology for BMP testing is convenient and standard, which makes it a commonly used method in substrate screening, co-digestion evaluation, and preliminary anaerobic digester design. However, despite a large body of evidence that methane yields based on BMP tests are not necessarily representative of the performance in full-scale anaerobic digestion plants [7–8], several studies have shown that simulating bench-scale BMP tests directly to industrial digesters generally results in an overestimation of methane production [3,11,13]. This discrepancy is attributed to the fact that BMP tests are conducted as idealized batch experiments and do not reflect the practical constraints and limitations of real full-scale continuous digesters, such as mixing efficiency, hydraulic limitations, substrate inhibition, biomass washout, and process fluctuations [12, 17]. Additionally, differences in inoculum source and activity, disparities in experimental methodology, and incongruences in test duration among laboratories further add to the uncertainty with respect to BMP interpretation [3,5].

The inconsistency between laboratory BMP and plant-scale methane yields depends strongly on the substrate characteristics, such as total solids content, volatile fraction of the solids content, degradability, and structural complexity [4,9,14]. As can be seen from the comparison data in Table 1, feedstocks that are easily degradable, like maize silage, vegetable waste, cattle manure, and rumen content, have low BMP-to-plant deviations (13–18%) and hence are ranked as optimal. In contrast, high lignocellulosic and inhibitory substrates, such as straw, bagasse, press mud, poultry litter, and certain agricultural wastes, have much larger deviations (21–26%), indicating significant scale-up losses. These results are in accordance with previous work that underlines the low accuracy of BMP assays for complex and industrial-agricultural feedstocks [4,9,10]. Recent progress in the field of anaerobic digestion research suggests that the simple application of standalone BMP values seems no longer suitable, and explicit model strategies accounting for scale-up effects, methane production kinetics, and actual operating conditions should rather be used [2,6,7,18]. The use of deviation-based performance classification, as developed in this study, can also provide a more pragmatic and application-specific means for associating laboratory BMP data with real full-scale methane production. As this approach enables the quantification of scale-up loss across numerous substrates, it further contributes to reducing the laboratory scale to full-scale gap and increasing confidence in using BMP for decision-making around anaerobic digester design, feedstock selection, and process operational conditions [8,12,15,18].

2. OVERVIEW OF BIOCHEMICAL METHANE POTENTIAL (BMP) TESTING

The Biochemical Methane Potential (BMP) test is a laboratory tool that allows for the estimation of the maximum methane production attainable from organic substrates under anaerobic conditions. The assay is typically carried out as a batch test in which a known amount of substrate is combined with an active anaerobic inoculum and incubated until total methane production occurs (about 1-3 days) [1,12]. Methane production is usually reported based on volatile solids and thus permits relevant comparisons between dry matter contents, organic compositions, and structural features. Because of these characteristics, the BMP test has been established as a fundamental procedure in anaerobic digestion studies and initial process examinations. BMP tests, however, are conceptually simple and offer important information on substrate biodegradability, maximum methane potential (MMP), and relative energy recovery performance [4, 9]. As shown in Table 1, there is a wide range of BMP results for different substrates; low yields are obtained from materials such as cattle manure and straw, while much higher values are observed for food waste, vegetable residue, and distillery spent wash. This wide spectrum highlights the utility of BMP testing to discriminate between high-energy and inefficiently degradable substrates. However, BMP results need to be interpreted carefully, and reasonable care must be taken when laboratory findings are extrapolated for industrial-scale digestion systems where constraints due to the size of the process become prominent [7,12, 17].

2.1 Principles and Objectives of BMP Assays

The philosophy underpinning BMP testing is the measurement of ultimate methane yield from a given substrate under conditions where biological and operational constraints are minimized. This is achieved through the addition of an active inoculum "surplus," stabilization of environmental conditions (e.g., in terms of temperature and pH), and by reducing disturbing factors that might suppress microbial activity [1, 12]. With these optimum conditions, the amount of methane produced represents a theoretical maximum organic matter conversion. As a result, BMP tests are intended to serve as baselines rather than exact replicas of full-scale digester performance [3]. In addition to determining methane potential, BMP tests are finding applications in studying inhibition phenomena, nutrient sufficiency, and the impact of substrate structure, such as lignocellulosic content and structural complexity [4, 14, 16]. As shown in Table 1, substrates containing easily biodegradable organic substances (such as maize silage and vegetable waste) not only have higher BMP values but also exhibit less discrepancy between laboratory and plant-scale yields. More resistant materials, such as straw, bagasse, and press mud, are less efficient in conversion at the plant level. These findings indicate that although BMP tests can effectively compare substrates, their purpose must be clearly established to avoid misinterpreting laboratory results as indicators of actual use [11, 13].

2.2 Current Applications of BMP in Anaerobic Digestion Research

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3. LIMITATIONS OF LABORATORY-SCALE BMP TESTS

BMP assays at the laboratory level provide valuable information on the methane production potential of organic substrates, but a series of inherent limitations restrict their direct applicability to full-scale anaerobic digestion plants. These limitations are a consequence of experimental settings, biological diversity, and difficulties in interpreting the results; they ultimately lead to discrepancies often found between BMP results in the laboratory versus methane yields obtained at the plant scale [12,13]. As demonstrated in Table 1, experimental results from the comparative dataset reveal that substrates with similar BMP cannot necessarily be expected to behave similarly at full scale, emphasizing that BMP values alone do not provide a sound basis for industrial digestion prediction. The spread in BMP-to-plant deviations shown in Table 1 (13% to 26%) represents the cumulative effect of these constraints across a wide range of substrates. Other types of feedstock show lower deviations and stable behavior, such as maize silage and cattle manure, while lignocellulosic substrates and agro-industrial residues exhibit much higher discrepancies. These findings underscore the need for a critical evaluation of the limitations and challenges associated with laboratory BMP testing before any translation to full-scale AD plants is made [7,8].

3.1. Lack of Standardization and Experimental Variability

The lack of full harmonization across studies and testing labs also represents a significant limitation of the laboratory-based BMP tests. Although some general methodological recommendations exist, considerable variation is still observed in process conditions regarding the origin of the inoculum, inoculum-to-substrate ratios, fermentation times, mixing rates, nutrient supplementation, and gas measurement, which introduce high uncertainty in experimental work [1–3]. When using the same substrates, inter-laboratory benchmarking studies have shown that BMP values may differ greatly from one study to another, reducing reproducibility and cross-study comparison [3,12]. Such methodological disparities have a clear impact on the reliability of scale-up predictions using BMP values. As shown in Table 1, substrates including MSW-O, press mud, and poultry litter have moderate laboratory BMP levels with relatively high discrepancies in plant-scale methane production. These results indicate that discrete systems fail to capture important substrate-specific limitations of growth during continuous operation. Thus, unharmonized BMP data could result in false feedstock ranking and erroneous feasibility evaluation, especially when results from different studies are consolidated without adequate standardization [11, 15].

3.2. Influence of Inoculum and Substrate Characteristics

Inoculum used is one of the most important and variable but least standardized factors in BMP testing and greatly affects derived methane yields [5,12]. The structure and metabolic activity of the microbial community, acclimation status, and nutrient availability, among other factors, can considerably affect methane production rates and final yields. Biological tests used to monitor BMP in the laboratory generally use highly active and well-adapted inocula to guarantee consistent performance, but this does not always represent the diversity of the microbial population that exists under operating anaerobic digestion conditions [5]. This limitation is exacerbated by the influence of the substrate itself, particularly when such material presents high lignocellulosic content, complex organic matrices, or inhibitory compounds [4,9]. Typically, substrates including straw, bagasse press mud, and poultry litter show significant differences between BMP and plant performance, even if they produce methane potential reasonably well under laboratory conditions (Table 1). This difference suggests that BMP tests may overestimate the actual biodegradability of complex substrates by ignoring limiting factors such as low hydrolysis rates, mass transfer resistance, and inhibition phenomena, which appear to be controlling under continuous full-scale digestion operations [10,14].

3.3. Kinetic Interpretation and Methane Production Curve Anomalies

BMP findings are frequently reported based on cumulative methane production curves, but the kinetic aspect is sometimes simplified or inadequately taken into account in regular BMP interpretations [13]. Discrepancies between liability and BMP can be introduced by features such as prolonged lag phases, multi-phasic methane generation, early plateaus, or delayed inhibitory effects, which in turn could have a crucial impact on process performance but may not always be apparent from theoretical BMP values exclusively [12,13]. These kinetic features are especially important for substrates with slow degradation kinetics and complicated biochemical routes. As shown in Table 1, some substrates classified as suboptimal have quite high laboratory BMP values but are characterized by poor methane recovery at the plant level, revealing kinetic constraints rather than the ultimate methane potential of the materials. For example, lignocellulosic wastes and agro-industrial by-products can be easily converted into a highly productive medium of methane through long-term laboratory incubation but cannot achieve the same conversion performance in hydraulic retention times usually adopted in industrial digesters [4,14]. Failure to consider kinetic limitations during BMP testing leads to an increasing risk of overestimating maximum achievable methane yields and illustrates the need for consideration of kinetics in BMP assessment methodology [3,12].

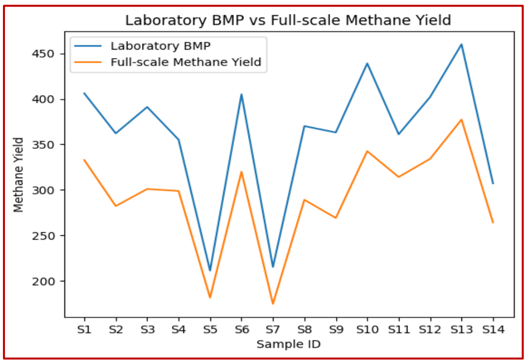
4. CHALLENGES IN TRANSLATING BMP RESULTS TO FULL-SCALE ANAEROBIC DIGESTION

A robust prediction of full-scale anaerobic digestion performance based on laboratory-derived Biochemical Methane Potential (BMP) data continues to be a key obstacle for the design and operation of biogas plants. While BMP experiments measure the maximum potential for methane production, industrial digesters operate under intricate and changeable acclimatization conditions that are not mirrored in laboratory settings [7, 12].

Table -1: Comparative Dataset Linking Laboratory BMP Results with Full-Scale Methane Yields for Diverse Organic Substrates

Sample ID	Substrate	TS (%)	VS (% of TS)	BMP (Lab) (L / Kg VS)	Scale-up factor	Full-scale yield (L CH4 / t VS)	BMP→ Plant deviation (%)	Target Class
S1	Food waste	18	90	406	0.82	332.6	18	Optimal
S2	OFMSW	16	82	362	0.78	282.0	22	Suboptimal
S3	Napier Grass	24	80	391	0.77	300.8	23	Suboptimal
S4	Sweet sorgum	18	91	355	0.84	298.6	16	Optimal
S5	Cattle manure	16	80	211	0.86	181.3	14	Optimal
S6	Poultry litter	28	75	405	0.79	319.8	21	Suboptimal
S7	Wheat straw	90	91	215	0.81	174.4	19	Optimal
S8	Press mud	24	77	370	0.78	288.9	22	Suboptimal
S9	Sugarcane bagasse	55	78	363	0.74	268.9	26	Suboptimal
S10	Paddy straw	85	84	439	0.78	342.4	22	Suboptimal
S11	Maize silage	25	95	361	0.87	314.0	13	Optimal
S12	Distillery spent wash	10	70	402	0.83	334.0	17	Optimal
S13	Vegetable waste	16	80	460	0.82	377.2	18	Optimal
S14	Rumen content	15	84	307	0.86	264.0	14	Optimal

As illustrated by the reference dataset in Table 1, plant-specific BMP values are commonly positively correlated with laboratory BMP; yet systematic BMP-to-plant differences ranging from 13% to 26% suggest substantial and consistent scale-up losses across a diverse array of substrates. These differences are due to the combined effects of operational constraints, natural inefficiencies in the process, and basic methodological disparities between batch BMP measurements and industrial digestion processes [8,11]. Optima from Table 1, such as maize silage, cattle manure, and vegetable waste, have relatively low deviations, while structurally complex or inhibition-sensitive substrates (i.e., bagasse, press mud, and poultry litter) show very poor scale translation. The current section discusses the main influencing factors of such deviations and highlights how BMP data will need to be interpreted in an overall operational context to facilitate meaningful full-scale performance assessment.

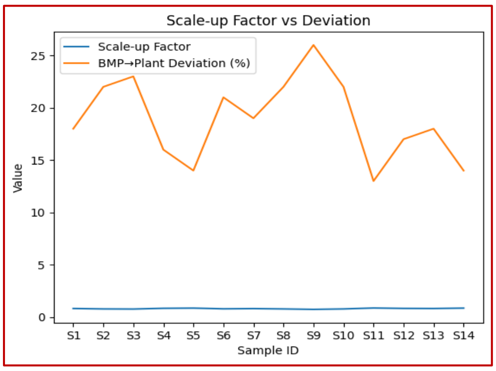


Graph -1: BMP (Lab) vs Full-Scale Methane Yield

Graph 1 reveals a robust positive linear relationship between laboratory BMP values and full-scale methane yields for all substrates. However, the yields achieved in full-scale plants are less than those in the laboratory due to process losses during scaling up. High BMP substrates, particularly vegetable waste and paddy straw, are more efficient in full-scale plants.

4.1. Scale-Dependent Operational Constraints

The direct use of BMP results on a full system scale is markedly limited by operational constraints that only become apparent at larger size scales. Methane production efficiency in the industrial AD process is inhibited by aspects such as poor mixing, fixed Hydraulic Retention Times (HRTs), Organic Loading Rate (OLR) limitations, temperature stratification, and washout of microorganisms [7,12]. In comparison, hydrolysis assays are performed under severely non-optimal conditions, which is reflected in the low degradation yields when compared to BMP tests, i.e., without any loading of inoculum for the same time period and in the absence of hydrodynamic resistance. The impact of these scale-related limitations is evident in Table 1, where substrates containing complex structures or slow rates of degradation result in more pronounced BMP-to-plant discrepancies. For example, sugarcane bagasse and paddy straw exhibit relatively high lab BMP values but with full-scale deviations of nearly 26%, suggesting that in practice, hydrolysis bottlenecks and/or insufficient residence time tend to constrain methane recovery [4,14]. These findings illustrate that scale-specific operating considerations significantly affect recalcitrant substrates and highlight the need to consider realistic operating conditions when scaling BMP results to design and performance expectations.

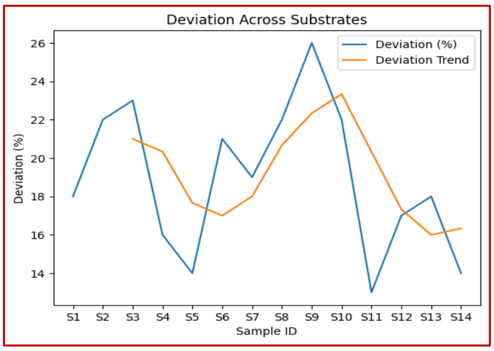


Graph -2: Scale-up Factor vs Deviation

Graph 2 depicts the correlation between BMP→plant deviation and scale-up factor for all substrates. Lower scale-up factors indicate more deviations, which show a drop in conversion efficiency during plant scale-up. This illustrates the difficulties of scaling up anaerobic digestion from laboratory to full scale.

4.2. Process Losses and System Inefficiencies

In addition to scale limitations, intrinsic process losses and system inefficiencies contribute to the disparity between laboratory BMP estimates and realized full-scale methane yields. At the plant scale, losses of methane may occur through dissolved gas in digestate, fugitive emissions, incomplete conversion of OM, and internal energy requirements for mixing, pumping, and heating [8,12]. These losses are normally disregarded in BMP tests, but they become quite significant in the case of industrial AD systems. Indeed, the influence of such inefficiencies is clear from Table 1, where substrates (including OFMSW, press mud, and poultry litter) are presented, demonstrating average AD bio-methane potential but classified as suboptimal due to BMP-to-plant deviation in excess of 20%. These trends indicate that not only does slow degradation and nutrient imbalance cause inhibitory effects, but they also limit recoverable CH4 despite good laboratory potential [9,10]. If these losses are not considered, then plant-scale performance can be systematically overestimated, making the need for correcting efficiencies as part of a robust techno-economic assessment of anaerobic digestion projects apparent [11,15].



Graph -3: Deviation Across Substrates

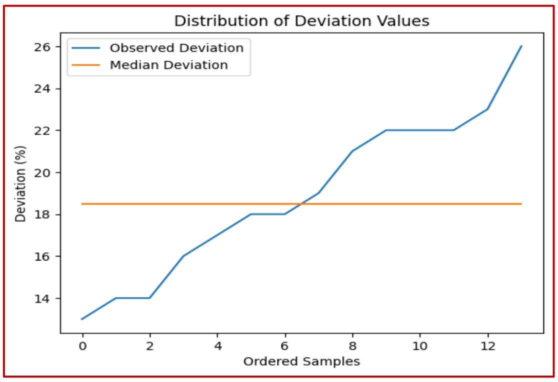
Graph 3 demonstrates the variation of BMP→ plant deviation among organic substrates. More deviations are obviously seen for fibrous and lignocellulosic materials than for the easily biodegradable wastes. The general shift pattern implies that these deviations are systematic, impacting the substrates rather than being random noise.

4.3. Differences Between Batch and Continuous Digestion Systems

One of the main shortcomings of BMP-based performance prediction is that batch laboratory tests and continuous full-scale digestion operations are fundamentally different. BMP assays are operated as closed-batch systems without material inflow or outflow, which enables slow or multi-phase decomposition reactions to be carried out after long-term incubation [1,12]. On the other hand, full-scale digesters work at fixed HRTs and under continuous or semi-continuous operating conditions, which may not provide complete degradation of slowly biodegradable organic matter. This difference is of particular importance when working with lignocellulosic and agro-industrial substrates, as shown in Table 1. Materials such as wheat straw, bagasse, and press mud deliver high methane yields under extended laboratory conditions, while performance is limited at the plant scale due to kinetic limitations and short residence times [4,14]. In contrast, substrates that are easily biodegradable, such as maize silage, vegetable waste, and rumen content, show more uniform behavior in both laboratory and industrial plants, leading to lower deviations as well as a better grade of classification. These findings corroborate that BMP tests are predominantly indicative of ultimate methane potential rather than of operation-related changes in methane yield, thus supporting the use of kinetic-informed and scale-corrected interpretation strategies [3,12].

5. BRIDGING THE LABORATORY-TO-PLANT GAP

To mitigate the gap between lab-scale BMP tests and full-scale applications, an approach is needed that shifts from simple BMP estimates based on specific samples to holistic, application-relevant calculations. Although BMP tests are useful for screening the biodegradability of substrates, the comparison dataset in Table 1 shows that the underestimation factor of laboratory BMP values is flawed for predicting methane yields on an industrial scale. This factor is not a dependent parameter, ranging from 13% to 26%, depending on feedstock composition. These results reveal that BMP data should be interpreted with standardized procedures, kinetic knowledge, and scale-responsible adjustment strategies for better application in plant-scale planning and decision support [7,8,12]. Modern research increasingly indicates that BMP testing should not serve as the sole predictor of digester performance but rather form part of an integrated evaluation along with operational limitations, degradation kinetics, and in situ plant data [2,6,15]. Within this context, the classification of substrates as optimal or suboptimal, based on the deviations shown in Table 1, provides a useful and intuitive tool for translating laboratory results to full-scale applications. The following sub-sections enumerate the significant methodological approaches that will help bridge the gap between laboratory and plant.



Graph -4: Distribution of Deviation Values

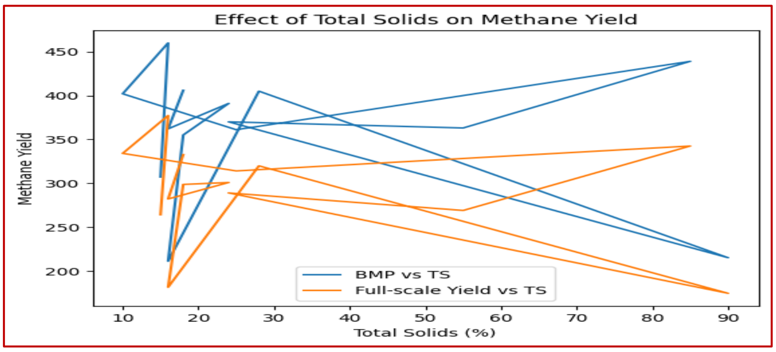
Graph 4 represents the distribution of BMP to plant % deviation, which is in a range of about 14% to 26%. The majority of substrates lie close to the mean deviation, indicating that scale-up shows similar behaviour. The number of substrates that have high variations is low, implying consistent plant scale process operation.

5.1. Standardization and Harmonization of BMP Protocols

The first step in increasing the predictability of BMP testing is the general adoption of common methods among laboratories. It is well-known that differences in inoculum sources, substrate pretreatment, inoculum-to-substrate ratios, fermentation times, mixing conditions, and measurement of biogas are major causes of variability between reported BMP values [1,3,12]. Since methods of analysis are not standardized, BMP datasets derived under different experimental conditions are hard to compare and therefore not very useful for large-scale feedstock selection and digester design. The use of standardized BMP methodologies has facilitated easier interpretation of substrate-dependent performance trends, such as those shown in Table 1, wherein easily degradable substrates like maize silage, cattle manure, and vegetable waste generally show lower deviation between BMP and CH4 yield than structurally complex ones like press mud, poultry litter, and bagasse. Standardization is used to provide greater comparability, reduce ambiguity, and increase the data credibility of BMP results when used for industrial feasibility studies [11,15].

5.2. Kinetic-Based Evaluation and Quality Control

The incorporation of kinetic insights into BMP interpretation is a key step towards enhancing scale-up predictability. Traditional BMP testing tends to focus largely on the ultimate methane yield and often disregards degradative kinetics, lag times, and multi-phase gas production behavior, all of which are pivotal in low-rate performance [3,12]. Kinetic parameters, such as methane production rate constants and time-to-maximum generation, provide an important perspective on whether a given substrate can be expected to actually utilize its potential methane output within operational hydraulic retention times. The value of kinetic-informed evaluation is evident in Table 1; several substrates have high laboratory BMP values (e.g., paddy straw, sugarcane bagasse, and press mud) but are rated as suboptimal due to limited scalability. These materials generally have slow hydrolysis and long degradation phases, limiting their suitability to a batch BMP test and the industrial digester space [4,14]. Hence, the incorporation of kinetic quality control parameters in BMP testing allows for the avoidance of overestimation of plant-scale methane production and better substrate selection.



Graph -5: Effect of TS on Laboratory BMP

Graph 5 indicates that TS content is not linearly correlated with methane yield. At elevated TS content, the MP of methane declines despite high BMPs, indicating mass transfer blockage and low biodegradability in solid substrates.

5.3. Correction Factors and Scale-Up Considerations

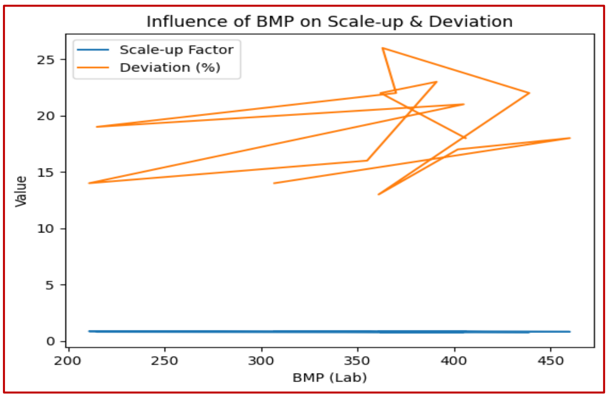
The use of empirically derived correction factors is vital for converting laboratory BMP results to realistic full-scale estimates of methane potential. Scaling factors, such as those presented in Table 1, have been designed to account for these conversion losses caused by operational limitations, kinetic restraints, and system inefficiencies not captured under laboratory conditions [7–8]. For the current dataset, the scale-up factors vary between 0.74 and 0.87, indicating significant variation in substrate potential for full-scale methane generation capacity. With the use of correction factors, one can establish a more direct and quantitative relationship between laboratory methane potential and industrial performance. For substrates like maize silage and cow manure, the high scale-up factor and low standard deviation are favorable for their direct utilization in full-scale reactors. On the other hand, bagasse and poultry litter-based substrates need to be adjusted cautiously to avoid unrealistic yield estimates [9,10]. Consequently, including the scale-up adjustments enhances the precision of methane yield prediction and robustness in techno-economic assessments for AD projects [11,15].

5.4. Integration of BMP Results with Full-Scale Operational Data

The most effective means to close this gap lies in denominator and company BMP data expressed against full-retention operational anaerobic digestion plant performance. Knowledge of plant-specific methane production, organic loading rates, hydraulic retention times, and operational stability is highly valuable for validating laboratory estimates and refining scale-up parameters [8, 12]. In combination with the BMP data sets, such operational data sets support the iterative calibration of correction factors and performance categories. The benefit of this consolidated approach is shown in Fig. 1 and Tab. 1, where laboratory BMP values are transparently related to measured full-scale methane yields and corresponding deviation indicators. This model allows the assessment of substrates in terms of both theoretical methane potential and industrial performance. In this sense, the integration of BMP assessment into a data-driven decision-support system would constitute an important part of narrowing the gap between laboratory testing and implementation at a large-scale level [2,6,7,15].

6. IMPLICATIONS FOR INDUSTRIAL ANAEROBIC DIGESTION DESIGN AND OPERATION

The side-by-side analysis in Table 1 provides valuable implications for the engineering and operations of industrial anaerobic digesters to improve their performance. The consistently high BMP-to-plant differences (13% to 26%) in the present study suggest that BMP estimates obtained from laboratory tests alone cannot be used to accurately size a digester or predict methane yields and economic returns. Feedstocks identified as being of the best quality, along with maize silage, vegetable waste, and rumen content, show higher scale-up factors (0.82–0.87) and low deviation levels, indicating better reproducible behavior under continuous digestion conditions. These features render them strong candidates for core feedstock identification, overload strategies in organic loading boosts, and increased energy recovery aimed at full-scale application sites [7,8,12]. Conversely, structurally challenging agro-industrial residues (sugarcane bagasse, paddy straw, press mud, poultry litter, and Napier grass) have exhibited lower than expected scale-up efficiencies and deviations, highlighting the reactive need for conservative design assumptions, longer retention times, or preemptive pretreatment measures when these substrates are significant in the mixed feed [4,9,14]. From an operational point of view, they underline the importance of substrate-specific management strategies and regular monitoring. Feedstocks with higher deviation values in Table 1 tend to suffer from hydrolysis bottlenecks, inhibitory effects, and incomplete conversion under practical operating conditions, which might result in process instability if not properly handled [10,12]. Digesters being fed these substances could potentially benefit from their co-digestion with substances that are more easily bio accessible, improved mixing arrangements, and/or flexible load schedules to maintain stable methane production. In addition, the inclusion of empirical scale-up factors into standard design and planning processes allows for more accurate estimation of plant-scale methane production, thereby reducing risks associated with excessively large gas handling infrastructure as well as overly optimistic revenue predictions [11,15]. Overall, the deviation-based substrate performance framework presented in this study facilitates a shift to data-informed design and operation of digesters, where lab BMP is methodically adjusted for scale effects and corroborated with full-scale experience. This methodology enhances operational stability, increases techno-economic reliability, and facilitates decision-making for industrial AD projects [2,6,7].



Graph -6: Substrate Wise Deviation

Graph 6 indicates a situation in which a high laboratory BMP may not always lead to better scale-up efficiency. The magnitude of the scale-up factor changes with BMP content, which is a sign of possible process variation. Even at high BMP, discrepancies imply that BMP is insufficient to anticipate plant-scale performance.

7. FUTURE PERSPECTIVES AND RESEARCH NEEDS

Table 1 shows that the further development of anaerobic digestion research therefore requires an extension from static laboratory BMP values to include a consideration of scale. The 13–26% deviations observed in BMP compared to plant performance for different substrates also support the development of better BMP methods that incorporate degradation kinetics, operational restrictions, and substrate-specific corrections. Lignocellulosic and agro industrial feedstocks such as sugarcane bagasse, paddy straw, press mud, and poultry litter have poor scale-up efficiencies (0.74–0.79) and higher deviations, indicating some hydrolysis limitations under industrial processes, with risks of inhibition. This calls for standardized kinetic performance parameters and applicable thresholds to distinguish theoretical methane potential from practical yield. Interconnected databases of laboratory, pilot, and full-scale systems are essential to validate BMP interpretation. Although the clustering in Table 1 provides some utility, there is a need for it to be tested at different digester designs, temperatures, and co-digestion scenarios. The utility of long-term operational indicators such as loading endurance, methane stability, and inhibition resilience, in combination with BMP and kinetic parameters, could improve the systems for feedstock screening and digester design. Specific investigations of pretreatment, microbial acclimation, and adaptable loading control can minimize scale-up discrepancies and consequently improve BMP testing to become a more precise indicator for industrial AD performance.

8. CONCLUSIONS

This article compares laboratory BMP (Biochemical Methane Potential) results against full-scale AD (Anaerobic Digestion) plant performance based on 14 organic substrates. The results are indicative that both the BMP assays lead to only rough estimates of the SMA, and its determination is typically overestimated with respect to plant performance, for which we have noted differences in the range of 13-26%. High degradability feedstocks, such as maize silage and vegetable waste, displayed better scale-up efficiencies (0.82–0.87), whereas lignocellulosic materials like sugarcane bagasse presented lower efficiencies (0.74–0.79) and higher deviations, which implied some losses attributed to upscaling. The present work provides a model-based approach to translate BMP results into realistic predictions for full-scale AD performance, highlighting the relevance of substrate biodegradability, kinetics, and operational constraints. The ranking of substrate performance assists in the selection of feedstocks with predictable industrial behavior and raises questions about more conservative designs for others. In general, BMP testing should become a scale-sensitive decision support system remodeling for better predictions of CH4 production and anaerobic digestion process design/control.

9. DECLARATIONS

The authors affirm that this manuscript represents original research and has not been published previously or submitted concurrently to any other journal. All analyses are based on secondary data derived from laboratory-scale BMP studies and reported full-scale anaerobic digestion performance. The research does not involve experiments on human subjects or animals.

10. FUNDING

No external funding was received from public, commercial, or non-profit funding bodies to support this study.

11. CONFLICT OF INTEREST

The author declares that there are no competing financial or non-financial interests that could have influenced the outcomes or interpretation of this research.

12. DATA AVAILABILITY

All data generated or analyzed during this study are presented within the article, including the consolidated comparative dataset (Table 1) and related graphical outputs. Supplementary data can be made available by the corresponding author upon reasonable request.

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