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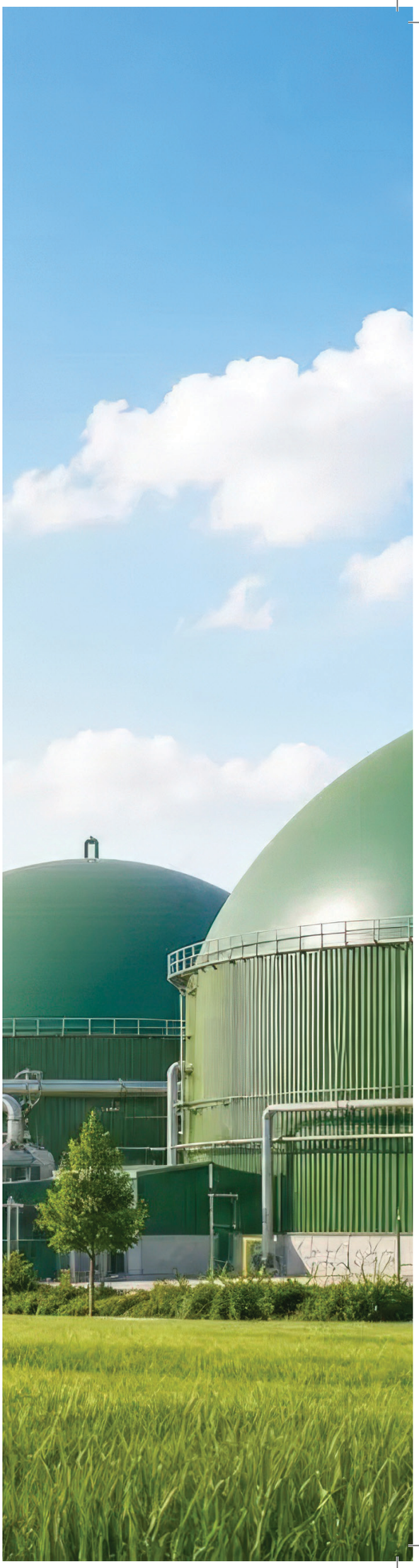






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From the Managing Director's Desk



Munish Madaan
Managing Director
The Catalysts Group

As the world accelerates its shift towards cleaner and more sustainable energy, biogas has emerged as one of the most practical solutions available to us. It turns agricultural residues, food waste, animal manure and industrial organic waste into renewable fuel, while also returning valuable nutrients to the soil. Few technologies address energy, waste and agriculture together in the way biogas does.

For India, this matters more than for most nations. We import a large share of the natural gas we consume. Our fields produce vast quantities of crop residue every season. Our cities generate growing volumes of wet waste. Our soils are losing organic carbon. Biogas sits at the meeting point of all these challenges and offers an answer that is local, circular and scalable.

The Government's approval of the unified GOBARdhan scheme marks a turning point for our industry. For those of us who have worked in this sector for years, it is more than a policy announcement. It is the moment biogas moves from being a promising idea to becoming a national industry.

What makes this framework significant is not the size of the outlay but its design. For the first time, the entire Compressed Biogas value chain, covering demand, pricing, capital, infrastructure and credit, has been brought under one roof. Developers now have assured offtake, long-term price visibility and meaningful financial support. The message from policymakers is clear: India is serious about building a large-scale biogas economy, and it expects the industry to deliver.

Yet one reality concerns me more than it excites me.

Across the country, a large number of CBG plants have been registered, but only a small fraction are commissioned and running. Registration shows intent. Commissioning shows capability. Stable, profitable operation shows excellence. India's biogas ambition will be won or lost in the gap between these three stages.

My view is simple. GOBARdhan has removed most of the market risk from this industry. When price is fixed and offtake is assured, performance becomes the only variable. A plant that converts more of every tonne into methane, runs more days a year and handles feedstock changes without upset will earn more. A plant that cannot do this will have no market conditions left to blame.

The new frontier of bio-waste

What excites me most is how much the feedstock base has grown. Not long ago, biogas meant cattle dung. Today, the economics work for paddy straw that would otherwise be burnt in the fields of Punjab and Haryana, press mud from sugar mills, distillery spent wash, wet municipal waste from our growing cities, dairy, poultry and food-processing residues, and dedicated energy crops such as Napier grass.

The value does not stop at gas. Digestate sold as fermented organic manure returns carbon to depleted soils and creates a second revenue stream, now supported by market development assistance. Biogenic CO_2 recovered during upgrading can be sold to food, beverage and industrial users. The biogas plant of the future is not only a gas plant. It is a rural bio-refinery.

Each of these feedstocks, however, brings its own discipline. Paddy straw is seasonal and rich in lignin. Press mud is available only during the crushing season. Municipal waste changes from one day to the next. The story I hear most often in the field is of a plant designed for one feedstock and forced to run on another. The leaders who succeed will plan for feedstock diversity from day one. They will build year-round supply chains and use biological tools such as enzymes, microbial cultures and process analytics to keep digesters stable through every change.

Underlying all of this is the main issue our industry faces today: feedstock availability. A CBG plant is only as reliable as the supply that feeds it. Too many projects are planned on paper estimates of the biomass within reach, only to discover that collection, aggregation, storage and transport are far harder than expected. Paddy straw must be baled and stored within a narrow window after harvest. Competing uses for residues, from cattle fodder to boiler fuel, push up prices. Fragmented landholdings make aggregation costly, and without assured contracts farmers have little reason to commit. When supply falters, digesters run below capacity, and no amount of policy support can make up for gas that is never produced. Securing feedstock in the right quantity, of consistent quality and at a predictable cost must be treated as the foundation of every project, not an afterthought.

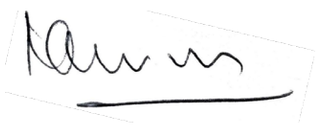
What leadership must now look like

I believe this industry needs three shifts in mindset: from capacity to conversion, from operators to process owners, and from reacting to problems to predicting them. None of these comes from equipment alone. They come from people who understand the biology inside the digester and from partners who stand beside them on the plant floor.

Building this ecosystem will also require partnership well beyond the plant gate. Farmers and aggregators must become reliable feedstock partners, not occasional suppliers. Financial institutions must learn to assess biological risk as carefully as they assess construction risk. Technology providers must be judged by the results they deliver, not by the promises they make.

We learnt these lessons during India's ethanol expansion, and at The Catalysts Group we are applying them to biogas with the same conviction. Our role is to help every plant turn policy support into consistent gas, and consistent gas into lasting value. Put simply, Catalysts' role is to help biogas plants solve the problems that stand in their way, so that every plant attains its maximum output.

The framework is now in place. The feedstock is all around us. What remains is execution, and that is the test of leadership.



Warm regards,
Munish Madan

Analytical and Monitoring Tools for Efficient Biogas Plant Operation





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Introduction

As the world continues its transition toward cleaner and more sustainable energy sources, biogas technology has emerged as an effective solution for converting agricultural residues, food waste and industrial organic waste into renewable energy. However, the success of a biogas plant is not solely determined by the quality of its feedstock or the design of the digester- it depends significantly on how well the biological process is monitored and controlled.

Anaerobic digestion is a complex biological process involving millions of microorganisms working together to convert organic matter into methane-rich biogas. Even small changes in operating conditions can reduce gas production, increase operational costs or, in severe cases, lead to digester failure. This makes continuous monitoring and timely analytical testing essential for maintaining process stability.

The Importance of Process Monitoring

A well-monitored biogas plant offers several advantages:

- Higher methane yield
- Improved digester stability
- Early detection of process imbalance
- Reduced downtime and maintenance costs
- Better digestate quality
- Enhanced plant safety
- Increased operational efficiency

Rather than reacting to process failures, modern biogas plants focus on predictive monitoring, where routine analytical data guide operational decisions.

Key Instrumentations

pH Meter – The First Indicator of Digester Health

One of the simplest yet most critical parameters in anaerobic digestion is pH. Methane-producing microorganisms thrive within a narrow pH range of 6.8–7.5. A sudden drop in pH often indicates excessive accumulation of volatile fatty acids (VFAs), signalling that acid-forming bacteria are producing acids faster than methanogens can convert them into methane. Routine pH monitoring allows operators to identify process instability early and take corrective measures before gas production declines.

Conductivity and ORP Meters – Monitoring Process Stability

Although often overlooked, conductivity and Oxidation Reduction Potential (ORP) provide valuable insights into digester conditions. Conductivity reflects the concentration of dissolved ions, helping detect salt accumulation that may inhibit microbial activity. ORP indicates the reducing environment required for anaerobic digestion. Healthy digesters generally maintain ORP values between −300 and −450 mV, confirming suitable conditions for methane-producing microorganisms.

Portable Gas Analyzers for On-Site Biogas Monitoring

Portable gas analyzers are compact instruments used for rapid on-site monitoring of biogas composition. They measure methane (CH_4), carbon dioxide (CO_2), oxygen (O_2) and hydrogen sulfide (H_2S) using NDIR and electrochemical sensors. These analyzers provide immediate results for assessing biogas quality, optimizing digester performance and supporting routine process monitoring and preventive maintenance.

Portable Gas Analyzer	Principle	Parameters Measured	Application in Biogas Plants
Portable Biogas Analyzer	NDIR + Electrochemical Sensors	CH_4, CO_2, O_2, H_2S	Routine on-site biogas quality analysis and process monitoring
NDIR Methane Sensor	NDIR	CH_4	Continuous monitoring of methane concentration and energy content
Electrochemical Gas Sensor	Electrochemical Cell	O_2, H_2S, CO, H_2	Detects oxygen ingress and corrosive gases for safe plant operation
Laser Methane Detector (TDLAS)	Tunable Diode Laser Absorption Spectroscopy	CH_4	Remote methane leak detection around digesters and pipelines
Photoacoustic Gas Analyzer (PAS)	Photoacoustic Infrared Spectroscopy	CH_4, CO_2	High-sensitivity gas analysis for research and process optimization

Near-Infrared (NIR) Spectroscopy – Fast Feedstock Characterization

NIR is increasingly used in modern biogas plants for rapid feedstock characterization. Unlike conventional laboratory methods, NIR analysis requires minimal sample preparation and provides fast, non-destructive estimation of key feedstock parameters such as moisture, protein, fat, fibre and organic matter. The rapid availability of this information enables operators to optimize feedstock formulation, improve anaerobic digestion efficiency, enhance methane yield and reduce laboratory turnaround time, making NIR a valuable tool for routine process monitoring.

UV-Visible Spectrophotometer – Rapid Chemical Analysis

A UV-Visible (UV-Vis) spectrophotometer is widely used in biogas laboratories for the rapid analysis of Chemical

Oxygen Demand (COD), ammonia nitrogen, phosphate, sulphide and other nutrients. These measurements help assess substrate degradation, nutrient availability and the overall efficiency of the digestion process.

Total Organic Carbon (TOC) Analyzer

A TOC analyzer measures the amount of organic carbon present in feedstock and digestates. It provides a direct indication of how efficiently microorganisms are converting organic matter into biogas. TOC analysis is particularly useful for comparing feedstock quality, monitoring digestion efficiency and evaluating digestate stabilization.

High-Performance Liquid Chromatography (HPLC)

HPLC is an advanced laboratory technique used to monitor the biochemical health of anaerobic digesters. It enables the accurate quantification of volatile fatty acids (VFAs), including acetic, propionic, butyric and lactic acids, as well as sugars, alcohols and other fermentation intermediates. Changes in the concentration of these compounds provide valuable insight into microbial activity and digester stability, allowing operators to identify process disturbances before they impact methane production.

Gas Chromatography with Flame Ionization Detector (GC-FID)

GC-FID is a highly reliable analytical technique used to measure methane (CH_4) and other hydrocarbons in biogas, providing an accurate assessment of biogas quality and energy potential. It can also be used to analyze volatile fatty acids (VFAs) after suitable sample preparation. Routine GC-FID analysis helps monitor digester performance, optimize feedstock utilization, maximize methane production and detect early signs of process imbalance.

Effective analytical and monitoring tools provide the information needed to understand what is happening inside the digester and to support timely operational decisions. From simple pH measurements to advanced HPLC and GC-FID analysis, these tools complement plant-level control by providing rapid and accurate information on feedstock quality, biochemical changes and gas composition.

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From Biomass to Biomethane: A Complete Journey of Biogas Production





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Introduction

Anaerobic digestion is an environmentally friendly technology that converts biodegradable waste into biogas while reducing pollution. Biogas mainly contains methane (50–70%) and carbon dioxide (30–50%), with an energy value of about 21–24 MJ/m^3. Agricultural, industrial and domestic wastes can all be used as feedstocks. The technology has a long history, dating back to ancient civilizations. Today, countries such as China, India, Germany and Denmark use anaerobic digestion on both small and industrial scales. Biogas can also be upgraded to biomethane for use as vehicle fuel.

Table:1 Typical Composition and Properties of Biogas -

Components	Unit	Content
CH_4	%	50–80
CO_2	%	15–45
H_2S	mg/m^3	0–5000
NH_3	mg/m^3	0–450
Humidity	-	Saturated
Calorific value	MJ/m^3	20–25
Calorific value	kWh/m^3	5.5–8

Stages of Biogas Production

The four main stages of anaerobic digestion are hydrolysis, acidogenesis, acetogenesis and methanogenesis.

i. Hydrolysis

Hydrolysis is the first stage of anaerobic digestion, in which complex organic compounds such as carbohydrates, proteins and lipids are broken down into simpler molecules that microorganisms can use. Hydrolytic bacteria release enzymes that convert carbohydrates into sugars, proteins into amino acids and lipids into long-chain fatty acids. Complex materials such as lignin and cellulose are difficult to degrade and often require pretreatment or additional enzymes.

Table:2 Chemical reaction in anaerobic digestion –

Stage	Type of conversion
Hydrolysis $(C_6H_{10}O_5)_n + nH_2O = n(C_6H_{12}O_6)$	Proteins to soluble peptides and amino acids Carbohydrates to soluble sugars Lipids to fatty acids or alcohols

Table:3 Enzymes and Their Substrates and Breakdown Products -

Enzymes	Substrate	Breakdown Products
Proteinase	Protein	Amino acids
Cellulase	Cellulose	Cellobiose and glucose
Hemi-cellulase	Hemicellulose	Glucose, Xylose, Mannose
Amylase	Starch	Glucose
Lipase	Fat	Fatty acids and glycerol
Pectinase	Pectin	Galactose, Arabinose

ii. Acidogenesis

During acidogenesis, acidogenic bacteria consume the products of hydrolysis and produce volatile fatty acids (VFAs), such as acetate, propionate and butyrate, along with smaller amounts of ethanol and lactate. Although VFAs are essential intermediates for methane production, their excessive accumulation can lower the pH and lead to digester failure. In protein-rich wastes, amino acids are converted into VFAs through the Stickland reaction, producing ammonia as a by-product. High ammonia concentrations can inhibit anaerobic digestion.

Table:4 Chemical reaction in anaerobic digestion –

Stage	Type of conversion
Acidogenesis 1. $C_6H_{12}O_6 + 2H_2O = 2CH_3COOH + 4H_2 + CO_2$ 2. $C_6H_{12}O_6 + 2H_2 = 2CH_3CH_2COOH + 2H_2O$ 3. $C_6H_{12}O_6 = CH_3CH_2CH_2COOH + 2H_2 + 2CO_2$ 4. $C_6H_{12}O_6 = 2CH_3CH_2OH + 2CO_2$ 5. $C_6H_{12}O_6 = 2CH_3CHOHCOOH$	Amino acids to fatty acids, acetate and NH_3 Sugars to intermediary fermentation products

iii. Acetogenesis

Acetogenesis converts higher volatile fatty acids and other intermediate compounds into acetate and hydrogen, making them suitable substrates for methanogens. Hydrogen produced during this stage must be rapidly consumed by hydrogenotrophic methanogens because high hydrogen concentrations inhibit acetogenic microorganisms. This cooperation between different microorganisms is known as hydrogen interspecies transfer. Lipids follow a separate pathway in which glycerol and long-chain fatty acids are converted into acetate through β-oxidation.

Table:5 Chemical reaction in anaerobic digestion –

Stage	Type of conversion
Acetogenesis 1. CH3CH2OH + H2O = CH3COOH + 2H2 2. CH3CH2OH + 2CO2 = CH4 + 2CH3COOH 3. H3CH2COOH + 2H2O = CH3COOH + 3H2 + CO2 4. H3CH2CH2COOH + 2H2O = 2CH3COOH + 2H2 5. H3CHOHCOOH + H2O = CH3COOH + CO2 + 2H2	Higher fatty acids or alcohols to hydrogen and acetate Volatile fatty acids and alcohols to acetate or hydrogen

iv. Methanogenesis

Methanogenesis is the final stage of anaerobic digestion, where methanogenic archaea convert acetate, hydrogen, carbon dioxide and other compounds into methane. Methanogens are highly sensitive to oxygen and can survive only under strictly anaerobic conditions. Approximately two-thirds of methane production comes from acetate (acetoclastic methanogenesis), while the remaining one-third comes from hydrogen and carbon dioxide (hydrogenotrophic methanogenesis). Some species, such as Methanosarcina, are more resistant to environmental stresses, including high ammonia and acetate concentrations.

Table:6 Chemical reaction in anaerobic digestion –

Stage	Type of conversion
Methanogenesis 1. CH3COOH = CH4 + CO2 2. CO2 + 4 H2 = CH4 + 2H2O	Acetate to methane and carbon-dioxide Hydrogen and carbon-dioxide to methane

Pretreatment Methods in Anaerobic Digestion

Pretreatment methods are used to improve the breakdown of complex organic materials, especially lignocellulosic wastes, thereby increasing hydrolysis and methane production. The four major pretreatment methods are biological, chemical, mechanical and thermal pretreatments.

i. Biological Pretreatments

Biological pretreatment involves the use of microorganisms or enzymes to enhance the degradation and solubilization of organic waste prior to anaerobic digestion. White-rot fungi can effectively degrade lignin through the secretion of ligninolytic enzymes; however, their application is limited by the long treatment periods required and the potential loss of cellulose during treatment. Temperature-phased anaerobic digestion (TPAD), which employs thermophilic or hyper-thermophilic conditions, can enhance hydrolysis and improve methane production by accelerating the breakdown of complex organic matter. Industrial enzymes such as carbohydrases, proteases and lipases can also facilitate degradation of lignocellulosic and complex organic substrates. Despite these advantages, biological pretreatment can be less favourable for large-scale applications because of prolonged retention time, relatively low degradation efficiency and the cost associated with enzyme

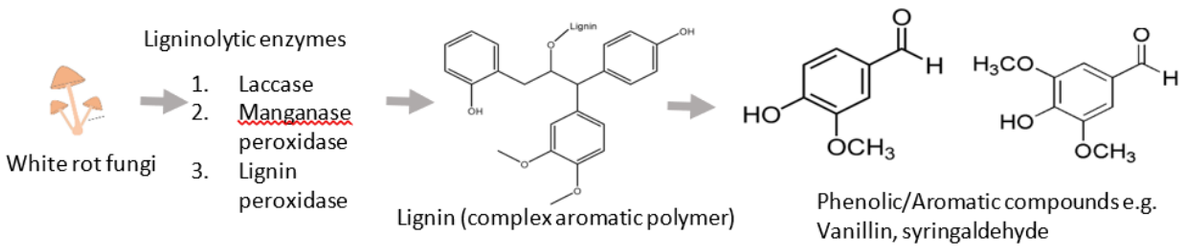


Fig:1 Biological pretreatment of lignin derived polymer

ii. Chemical Pretreatments

Chemical pretreatment involves the application of acidic or alkaline agents to disrupt the complex structure of biomass and enhance its subsequent biodegradation. Acidic pretreatment promotes the breakdown of lignocellulosic materials into simpler sugars, while alkaline pretreatment can induce fibre swelling, disrupt lignin structures and increase the accessibility of cellulose. However, acid treatment can involve higher cost and corrosion concerns, while the choice and concentration of alkaline agents must also be considered carefully.

iii. Mechanical Pretreatments

Mechanical pretreatment enhances the biodegradability of organic substrates primarily by reducing particle size and increasing the surface area available for microbial activity. Ultrasound pretreatment employs acoustic cavitation to disrupt cell structures and promote the release of intracellular organic matter. Collision plate pretreatment can result in cell disruption and improved substrate accessibility, while milling decreases substrate particle size and facilitates microbial degradation. However, excessive size reduction may lead to increased substrate solubility and rapid acidification, which can negatively affect process stability.

Thermal Pretreatments

Thermal pretreatment involves the application of elevated temperatures and pressure to enhance the hydrolysis of complex organic matter while minimizing water evaporation. This approach can improve substrate biodegradability, enhance digestion stability and enable higher organic loading rates in anaerobic digesters. However, excessive temperatures can result in the degradation or loss of volatile solids and may promote the formation of inhibitory compounds. Therefore, optimization of pretreatment temperature is essential to balance pathogen reduction and substrate solubilization with preservation of methane-forming potential.

Important Operating Parameters

The efficiency and stability of anaerobic digestion are influenced by several key operational and physicochemical factors, including temperature, pH, hydraulic retention time (HRT), organic loading rate, mixing and the carbon-to-nitrogen (C/N) ratio. Temperature plays a critical role in determining microbial activity, while pH is important because methanogenic microorganisms perform optimally near neutral conditions. Hydraulic retention time represents the average period for which the liquid substrate remains inside the digester and is determined by the ratio of digester volume to flow rate (HRT = V/Q). Organic loading rate must also be carefully controlled, as excessive substrate loading can result in rapid acidification, VFA accumulation and reduced methane production. Adequate mixing enhances contact between microorganisms and substrates, improves mass transfer and prevents sedimentation and stratification.

Biogas production is therefore a complete journey from biomass preparation and hydrolysis to methane formation. The choice of pretreatment and operating conditions determines how effectively the organic matter moves through these stages and ultimately becomes useful biogas or biomethane.

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Feedstock Selection for Consistent Biogas Production





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Introduction

The increasing demand for renewable energy and sustainable waste management has stimulated interest in anaerobic digestion (AD) as an effective technology for converting organic wastes into renewable biogas. A wide range of feedstocks can be used for anaerobic digestion, including animal manure, crop residues, food waste, sewage sludge, industrial organic waste, wastewater and agricultural processing residues.

However, the availability of biodegradable organic material does not necessarily make it an ideal feedstock. Feedstocks can vary considerably in composition, moisture, biodegradability and inhibitor concentration between batches and seasons. Such variability directly influences microbial activity and digester stability. Therefore, consistent biogas production requires more than selecting a substrate with high theoretical methane potential.

An appropriate feedstock should be available in sufficient quantities, possess relatively predictable characteristics, be compatible with the selected digestion technology and have low concentrations of compounds that inhibit methanogenic microorganisms. This article discusses the major factors governing feedstock selection and proposes a practical framework for identifying feedstocks capable of supporting stable and consistent biogas production.

The Importance of Feedstock

The rate of anaerobic digestion stages is strongly influenced by feedstock composition. Highly biodegradable substrates can undergo rapid hydrolysis and acidification. If methanogens cannot consume the resulting VFAs at a comparable rate, acid accumulation can occur, resulting in reduced pH and methane production. Food waste is a typical example: although it has high biodegradability and considerable methane potential, excessive feeding

can cause rapid acidification, foaming and ammonia accumulation.

Thus, the ideal feedstock is not necessarily the one with the highest methane potential but one that provides a stable balance between biodegradability, nutrient availability, microbial requirements and continuous supply.

Major Feedstock Categories

Table:1 Feedstock for anaerobic digestion

Category	Types of waste
Agricultural waste and crop residues	Crop Stubbles, straw, spoiled fodder, sugar cane trash and bagasse, weeds, tobacco waste, rice and coffee husks, fruit and vegetable processing wastes, oil cakes, etc.
Animal wastes	Cattle dung, goat and sheep manure, pig manure, elephant dune, fishery waste, slaughterhouse wastes.
Aquatic plants	Algae, sea weeds, water hyacinth, etc.
Forest residues	Dead trees, plants, twigs, barks, roots, leaves, etc.

Animal Manure

Animal manure, including cattle, buffalo, pig and poultry manure, is commonly used in anaerobic digestion. It provides microorganisms, nitrogen, minerals and buffering capacity, although its methane productivity may be moderate because some readily degradable organic matter has already been consumed during digestion by the animal. Nevertheless, its relatively stable composition makes manure an excellent base substrate for co-digestion.

Food Waste

Food waste contains readily biodegradable carbohydrates, proteins and lipids and therefore offers high methane-production potential. However, rapid VFA formation, acidification, ammonia generation and foaming can destabilize the digester. Controlled feeding or co-digestion is therefore generally preferable to uncontrolled mono-digestion.

Agricultural Residues

Agricultural residues, including straw, husks, stalks, leaves and processing residues, are widely available in agricultural regions. Their major limitation is the presence of lignocellulosic structures, particularly lignin, which restrict microbial accessibility. Pretreatment may therefore be required to improve the biodegradability of selected residues.

Sewage Sludge

Sewage sludge offers continuous availability because it is generated at wastewater treatment facilities and contains substantial biodegradable organic matter. However, its potential content of heavy metals, pharmaceuticals, contaminants and nitrogen requires appropriate characterization before digestion.

Industrial Organic Wastes

Industrial organic wastes from dairy processing, breweries, distilleries, sugar processing and food industries can provide relatively consistent feedstocks. Nevertheless, these streams may contain salts, cleaning chemicals, acids, alkalis, fats or other inhibitory compounds, making feedstock-specific characterization essential.

Critical Parameters for Feedstock Selection

Table:2 Effect of different pretreatment techniques in biogas production

Pretreatment type	Feedstock used	Results obtained
Ultrasonic (31kHz for 64 sec)	Sewage sludge	Volatile solid removal rate increases from 45.8% to 50.3%
Ultrasonic (20 kHz)	Palm oil mill effluent	16% increase in methane production than untreated effluent
Thermal (microwave, 175°C)	Waste activated sludge	24.25% increase in biogas production than untreated sludge
Chemical (Alkali treated)	Plant residues and cattle dung	31-42% higher digestion efficiency than untreated samples
Chemical (Acid treated)	Waste activated sludge	Increase in biogas production by 21%
Biological (white-rot fungi)	olive mill wastewaters	COD removal was increased from 34 to 65 %

Solids, Organic Matter and Biodegradability

The total solids (TS) and volatile solids (VS) contents provide an initial indication of feedstock characteristics. VS represents the organic fraction that can potentially be biologically converted; however, high VS does not necessarily indicate high methane production because biodegradability varies among substrates. Therefore, TS, VS, COD, biodegradable COD, organic composition and biochemical methane potential should be considered together.

Carbon-to-Nitrogen Ratio

The carbon-to-nitrogen (C/N) ratio is another important indicator. Carbon provides energy, whereas nitrogen supports microbial growth. Excessive nitrogen can increase ammonia concentrations, while extremely carbon-rich substrates may lack sufficient nitrogen. Co-digestion can help balance these characteristics. However, C/N should not be treated as a universal target because its influence depends on ammonia concentration, pH, alkalinity, loading rate and overall substrate composition.

Table:3 Typical C/N ratios of different materials

S.N.	Material	N (%)	C/N ratio
1	Cow, buffalo, sheep, pig and horse manure	1.4-3.8	15-40
2	Poultry manure	6.3	5.2
3	Night soil	6	6-10
4	Fish scarps	6.5	5.1
5	Slaughterhouse waste	7-14	2-4
6	Sawdust	0.1-0.25	200-511
7	Grass clipping and hay	2-4	10-20
8	Bagasse, Wheat and rice straw	0.3-0.5	120-150
9	Corn stalks	0.8	60
10	Kitchen vegetable scraps	3.3	16

Lipids, Proteins and VFAs

Lipids have high theoretical methane potential, but excessive lipid loading can result in the accumulation of long-chain fatty acids (LCFAs), which may inhibit anaerobic microorganisms. Similarly, degradation of protein-rich feedstocks releases ammonia. Moderate ammonia concentrations can provide nutrients and buffering, whereas excessive free ammonia can inhibit methanogens. VFAs, including acetate, propionate and butyrate, are normal intermediates of anaerobic digestion; their accumulation indicates an imbalance between acid production and

consumption and may precede process failure.

Moisture and Solids Concentration

Moisture and solids concentration affect pumping, mixing, reactor volume and mass transfer. Very dilute substrates can increase pumping and reactor costs, whereas highly concentrated substrates may create mixing difficulties and localized accumulation of acids or inhibitors.

Biogas yield from Agricultural and crop residues

Agricultural Residues		Vegetable Wastes	
Residues	**CH4 Yield (m3 /kg of VS)**	**Wastes**	**CH4 Yield**
Sugar beat leaves	0.21	Cauliflower leaves	0.190
Tops of sugar beets	0.32-0.34	Radish shoots	0.304
Maize (whole crop silage)	0.39	Carrot (leaves)	0.241
Maize straw	0.34	Carrot (petiole)	0.309
Sunflower (whole crop silage)	0.3	Cabbage leaves	0.309
Corn cob mix	0.35-0.36	Potato peel	0.267
Wheat grain	0.37-0.4	Lemon pressings	0.473
Wheat straw	0.3	Banana peel	0.24-0.32
Rice husk	0.13	Pomegranate peel	0.312
Rice straw	0.3-0.38	Grape pressings	0.28
Coffee husk	0.20	Coriander leaves	0.325
Grass cuttings	0.3	Coriander stem	0.309
Barley Stalks	0.23		

Practical Feedstock Selection Framework

A systematic selection strategy can significantly improve the reliability of anaerobic digestion. First, an inventory of locally available feedstocks should be prepared, including quantity, seasonal availability, collection frequency, transportation distance and storage requirements. Second, candidate substrates should undergo laboratory characterization for pH, TS, VS, COD, C/N ratio, protein, lipid, carbohydrate, ammonia, alkalinity, sulphur, salinity and potential toxic compounds.

Third, biochemical methane potential (BMP) testing should be performed to compare methane-producing potential under controlled conditions. BMP testing can also be used to evaluate different feedstock mixtures before full-scale implementation. Potential inhibitors such as ammonia, sulphide, salts, heavy metals, antibiotics, disinfectants, pesticides, LCFAs and excessive VFAs should also be assessed.

The next step is blending optimization, where substrates are combined to achieve suitable nutrient balance, moisture, biodegradability, buffering capacity and organic loading characteristics. Finally, long-term supply should be evaluated. A feedstock with excellent methane potential but only short-term availability may be less suitable commercially than a moderately productive substrate available consistently throughout the year.

The plant should also establish quality-control specifications for incoming feedstocks, including acceptable ranges for TS, VS, pH, C/N ratio, ammonia, lipid content, contamination and daily mass flow. Routine monitoring allows unsuitable batches to be identified before they disturb digester operation.

Conclusion

Feedstock selection is a fundamental determinant of the consistency, stability and productivity of anaerobic digestion systems. Selection should not be based solely on theoretical methane potential but should consider organic matter content, biodegradability, C/N ratio, TS and VS, moisture, protein and lipid content, ammonia generation, VFA formation, inhibitory compounds, seasonal variability, transportation requirements and long-term availability.

Co-digestion provides an effective strategy for balancing the limitations of individual substrates and improving process stability. Ultimately, reliable industrial biogas production is best achieved through a systematic approach:

Thus, rather than identifying one universally superior feedstock, commercial biogas plants should develop a stable, well-characterized and continuously available feedstock portfolio that matches the biological and operational requirements of the anaerobic digester.

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Enzyme-Based Pretreatment Technologies: Improving Biogas Yield & Plant Economics





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Introduction

The global transition toward renewable energy and circular waste management has increased interest in anaerobic digestion as a method for converting organic residues into useful energy. Despite its broad applicability, anaerobic digestion is frequently constrained by the hydrolysis of complex organic matter, particularly in agricultural residues, crop straw, forestry residues, food-processing residues and other lignocellulosic materials. The cellulose and hemicellulose contained in these materials are physically and chemically protected by lignin and other structural components, making them less accessible to hydrolytic microorganisms.

Pretreatment is therefore used to modify the structure of biomass and increase the accessibility of biodegradable components. Enzyme-based pretreatment belongs primarily to the biological category and uses hydrolytic or oxidative enzymes to selectively break down specific components of organic matter. Pretreatment should be evaluated not only in terms of methane production but also in terms of energy balance, environmental performance, capital expenditure, operating expenditure and maintenance requirements.

The response of methane yield to pretreatment is strongly dependent on the chemical composition of the substrate. Therefore, a pretreatment that performs well for one feedstock may provide little benefit or even reduce net process performance for another. The objective of this review is to examine enzyme-based pretreatment as a strategy for improving biogas production while evaluating its potential contribution to plant economics.

Anaerobic Digestion and the Hydrolysis Bottleneck

Anaerobic digestion involves four interconnected stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. For this article, hydrolysis is particularly important because complex biomass must first become

accessible to the microbial community. The overall process can be simplified as:

Complex biomass → Soluble compounds → VFAs/intermediates → Acetate + H_2 + CO_2 → CH_4 + CO_2
For lignocellulosic biomass, the structural arrangement can be represented as:
Lignin matrix → Hemicellulose → Cellulose microfibrils
Lignin provides structural rigidity and restricts enzyme and microbial access to cellulose and hemicellulose. Consequently:
High structural recalcitrance → Poor hydrolysis → Lower substrate conversion → Lower methane recovery
Enzymatic pretreatment aims to interrupt this limitation by increasing the accessibility of biodegradable polymers.

Principle of Enzyme-Based Pretreatment

Enzyme-based pretreatment uses biological catalysts to accelerate the breakdown of specific organic compounds. Unlike chemical pretreatment, enzymes generally do not require highly acidic or alkaline conditions. Unlike mechanical pretreatment, their primary action does not depend on physical particle-size reduction. Their principal advantage is specificity.

For example:

- Cellulase + cellulose → soluble sugars
- Hemi-cellulase + hemicellulose → soluble pentoses and hexoses
- Amylase + starch → soluble sugars
- Protease + protein → peptides/amino acids
- Lipase + lipid → glycerol + fatty acids

Ligninolytic enzymes can modify lignin structures and potentially increase the accessibility of cellulose and hemicellulose. The overall objective is not simply to maximize solubilization. Excessive solubilization without adequate downstream conversion can result in accumulation of VFAs or other intermediates. Therefore, the ideal pretreatment produces soluble substrates at a rate that can be efficiently consumed by the subsequent anaerobic microbial community.

Major Enzymes Used in Anaerobic-Digestion Pretreatment

Cellulases and Hemicellulases
Cellulases are key enzymes involved in the hydrolysis of lignocellulosic biomass. The cellulase complex consists mainly of endoglucanases, exoglucanases (cellobiohydrolases) and β-glucosidases, which act synergistically to convert cellulose into cellodextrins, cellobiose and ultimately glucose. Cellulase application is particularly beneficial for crop residues, straw, corn stover, bagasse, paper-containing waste and agricultural processing residues. Similarly, hemicellulases facilitate the breakdown of the heterogeneous hemicellulose fraction through enzymes such as xylanases, β-xylosidases, mannanases, arabinofuranosidases and galactosidases. Their action improves cellulose accessibility and releases additional fermentable sugars, with xylanase being especially important for biomass rich in xylan.

Ligninolytic Enzymes
Lignin is one of the major barriers to the enzymatic hydrolysis of lignocellulosic biomass because it restricts enzyme access to cellulose and hemicellulose. Important ligninolytic enzymes include laccase, lignin peroxidase and manganese peroxidase, which facilitate lignin modification or degradation through different oxidative mechanisms. Their action can improve cellulose accessibility and enhance subsequent enzymatic hydrolysis. However, ligninolytic enzyme systems may be limited by their relatively high cost, while excessive biological treatment can result in the loss of valuable carbohydrates. Therefore, effective lignin pretreatment should aim for selective structural modification or partial removal of lignin while preserving the carbohydrate fraction.

Amylases

Amylases are hydrolytic enzymes that break down starch-based materials into simpler carbohydrates through the sequential conversion of starch to dextrins, maltose and ultimately glucose. They are particularly relevant for food waste, cereal residues, starch-processing waste, potato waste and grain-processing residues. However, for readily biodegradable food waste, additional enzyme application may offer limited economic benefits because native microbial hydrolysis can already occur rapidly. Therefore, amylase-based pretreatment should be selectively applied to substrates where starch hydrolysis represents a significant limitation to overall biodegradation.

Proteases and Lipases

Proteases hydrolyse proteins into peptides and amino acids and are particularly useful for protein-rich substrates such as slaughterhouse waste, dairy-processing residues, animal-processing residues and protein-rich food waste. However, their application should be optimized carefully by considering the overall nitrogen balance, as excessive protein degradation can increase ammonia levels and potentially inhibit methanogenic microorganisms. Lipases hydrolyse triglycerides into glycerol and long-chain fatty acids. Although lipids possess a high theoretical methane potential, excessive accumulation of long-chain fatty acids can inhibit anaerobic microorganisms and adversely affect digester performance.

Enzyme group	Major Enzymes	Mode of action	Primary product/effect
Cellulases	Endoglucanase, Exoglucanase, β-Glucosidase	Internal β-1,4-glycosidic linkages are randomly broken by endoglucanase; cellobiose units are removed from cellulose chain ends by exoglucanase; and cellobiose and short cellodextrins are converted into glucose by β-glucosidase.	Cellodextrins → Cellobiose → Glucose
Hemicelluases	Xylanase, B-Xylosidase, Mannanase, Arabinofuranosidase, Galactosidase	Denature side-chain groups by hydrolyzing the hemicellulose backbone. While β-xylosidase transforms xylo-oligosaccharides into xylose, xylanase breaks the xylan backbone.	Xylose, mannose and other soluble sugars
Ligninolytic	Laccase,Lignin, peroxidase, Manganese peroxidase	Make use of radical-mediated processes to oxidatively alter or partially breakdown lignin. As a result, lignin's structure and interactions with carbohydrates are disrupted.	Modified/partially degraded lignin
Amylases	α-Amylase, β-Amylase, Glucoamylase	Hydrolyze starch's α-glycosidic bonds. Dextrins are produced by α-amylase, maltose is produced by β-amylase, and glucose is produced by glucoamylase from dextrins and oligosaccharides formed from starch.	Dextrins → Maltose → Glucose
Proteases	Endoproteases, Exoproteases	Break down the peptide bonds found in proteins. While exoproteases liberate amino acids or short peptides from chain ends, endoproteases break internal peptide connections.	Peptides+ Amino acids
Lipases	Lipases	Hydrolyze ester bonds in triglycerides and other lipids.	Glycerol +Long-chain fatty acids

Conclusion

Enzyme-based pretreatment can improve the hydrolysis and anaerobic digestion of difficult feedstocks, particularly lignocellulosic agricultural and industrial wastes. Enzymes such as cellulases, hemi-cellulases, ligninolytic enzymes, amylases, proteases and lipases can increase substrate biodegradability and methane production.

However, its commercial success depends on more than methane yield. Feedstock characterization, enzyme selection, dosage optimization, energy consumption and overall treatment cost must be considered. A precision approach—feedstock characterization → enzyme selection → optimization → hydrolysis → anaerobic digestion → methane recovery → economic assessment—offers the greatest potential for industrial application.

Future research should focus on reducing enzyme costs, improving enzyme stability, developing effective enzyme cocktails and integrating low-energy pretreatment methods to achieve higher net energy and economic returns.

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Integrated Nano-CaO Clarification–Bioenergy Approach for Enhanced Sugar Processing and Biomethane Recovery





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Abstract

This study evaluates a proprietary Nano-CaO-based formulation for enhanced juice clarification, with a focus on improving clarification efficiency and Pressmud characteristics for downstream biomethane recovery. Laboratory-scale evaluation showed a 35% reduction in juice turbidity and a 25% reduction in ICUMSA color compared with conventional treatment. Treatment requirement decreased by 20%, settling time decreased from 25 to 16 minutes, and sugar recovery increased from 10.8% to 11.3%. Beyond clarified-juice quality, the combination of lower treatment loading and improved solids separation may influence the mineral contribution, consolidation, filtration and dewatering characteristics of pressmud. A pressmud stream with reduced treatment-derived mineral loading and improved solids handling could be advantageous for subsequent biological processing and resource recovery. Biomethane enhancement was not measured in the present study; therefore, the bioenergy relevance is presented as a process-integration opportunity requiring direct pressmud characterization and biomethane-potential validation.

Keywords
Nano-CaO; Sugar clarification; Color reduction; Turbidity reduction; Pressmud; Settling efficiency; Sugar recovery; Bioenergy integration; Biomethane recovery

Introduction

Clarification is a critical operation in cane-sugar manufacture because suspended solids, colloids, color-forming impurities and non-sugars can adversely affect evaporation, crystallization, final sugar color and recovery. The

clarification stage also determines the quantity and characteristics of the separated mud subsequently handled as pressmud. Consequently, clarification performance can influence not only sugar-house efficiency but also downstream handling and utilization of pressmud.

This work evaluates an integrated Nano-CaO clarification–bioenergy concept in which clarification performance is considered together with the quality and processability of the resulting pressmud. The study focuses on measurable clarification outcomes—treatment requirement, turbidity, ICUMSA color, settling time and sugar recovery—while considering how improved separation and lower treatment loading may support downstream pressmud processing. Detailed formulation and manufacturing information are outside the scope of this article.

Process Rationale

The Nano-CaO clarification approach is intended to improve interaction with juice impurities and promote effective floc formation, rapid settling and removal of suspended and color-associated material. Improved clarification at a lower treatment requirement may reduce the quantity of treatment-derived inorganic material entering the separated mud. At the same time, stronger solids separation can improve mud consolidation and reduce solids carryover into clarified juice.

These effects are relevant to pressmud management because mineral loading, moisture, solids composition and filterability affect transport, dewatering and downstream processing. A more consolidated pressmud with a lower contribution of treatment-derived mineral solids may provide a more favorable feed characteristic for subsequent biological or resource-recovery operations. This study does not claim increased biomethane yield; rather, it identifies a process pathway that can be validated through direct pressmud and biomethane-potential testing.

Laboratory-Scale Performance Evaluation

Laboratory-scale comparative evaluation was conducted using conventional treatment and the Nano-CaO clarification approach. Clarification performance was assessed using treatment dose, juice turbidity, ICUMSA color, sugar recovery and settling time. The observed values are summarized in Table 1.

Parameter	Conventional Treatment	Nano-CaO Approach	Observed Change
Treatment Dose (% cane)	0.20	0.16	20% reduction
Juice Turbidity (NTU)	450	290	35% reduction
ICUMSA Color	1800	1350	25% reduction
Sugar Recovery (%)	10.8	11.3	+0.5% absolute
Settling Time (min)	25	16	36% faster

Table 1. Comparative laboratory-scale clarification performance.

Clarification and Pressmud Process Impact

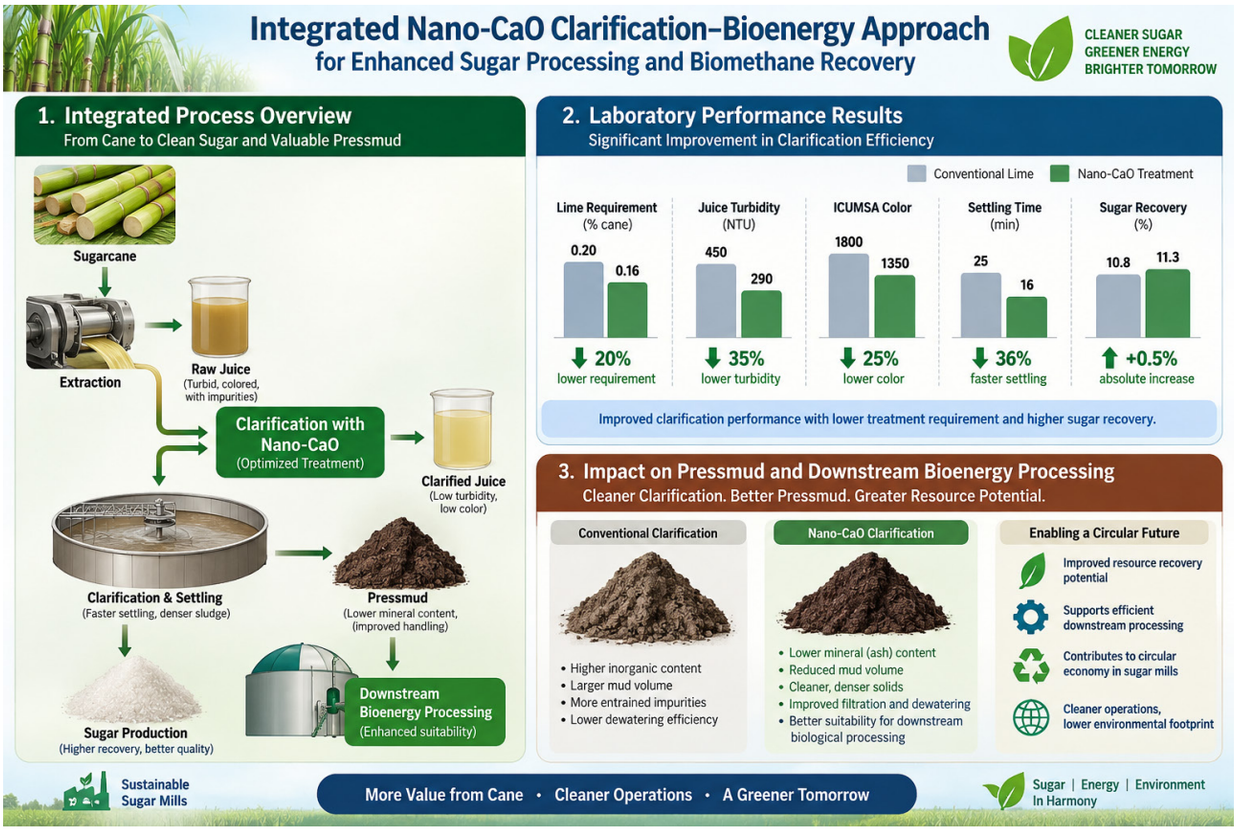
The laboratory data demonstrate a clear improvement in clarification quality. Turbidity decreased from 450 to 290 NTU (35%), while ICUMSA color decreased from 1800 to 1350 (25%). Treatment requirement decreased from 0.20 to 0.16% on cane (20%), and settling time decreased from 25 to 16 minutes (36% faster). Sugar recovery increased from 10.8% to 11.3%, representing an absolute increase of 0.5 percentage points in the evaluated dataset.

The combined reduction in treatment demand and improvement in settling may also influence pressmud

generation and quality. Lower treatment loading can reduce the contribution of treatment-derived mineral solids, while improved settling may support better solids capture, mud consolidation and reduced carryover. Operationally, these effects could support improved filtration and dewatering, lower mud-handling burden and more consistent pressmud characteristics.

Performance Area	Observed / Expected Effect	Process Relevance
Color	25% lower ICUMSA color	Lower color load entering downstream sugar processing
Turbidity	35% reduction	Improved removal of suspended and colloidal impurities
Settling	36% faster	Potentially improved clarifier throughput and solids separation
Treatment demand	20% lower	Lower treatment loading and potentially lower mineral contribution to mud
Pressmud handling	Improved consolidation is anticipated	Potentially improved filtration, dewatering and handling; requires direct validation
Bioenergy integration	Potentially more favorable pressmud characteristics	Supports evaluation as a downstream biological-processing feed; biomethane performance requires BMP testing

Table 2. Integrated clarification and downstream process relevance.



Relevance to Integrated Bioenergy Processing

Pressmud is a process-derived organic residue whose downstream behavior is influenced by moisture, total

solids, volatile solids, ash/mineral fraction, organic carbon and filterability. The present clarification approach may be relevant to an integrated sugar–bioenergy process because it combines improved juice clarification with the possibility of generating a pressmud stream containing less treatment-derived mineral material and exhibiting improved solids-handling characteristics.

Such changes could improve consistency and processability of pressmud before subsequent biological conversion. However, the present clarification dataset does not include pressmud composition, biodegradability or biomethane measurements. Accordingly, enhanced biomethane recovery should be treated as a validation objective rather than a demonstrated outcome. Future work should compare conventional and Nano-CaO-derived pressmud for pressmud mass per tonne cane, moisture, TS, VS, VS/TS, ash, TOC, TKN, C/N ratio, mineral content, filterability, residual sucrose and biochemical methane potential (BMP).

Conclusion

The Nano-CaO clarification approach demonstrated meaningful laboratory-scale improvements in sugarcane juice processing, including 25% lower ICUMSA color, 35% lower turbidity, 20% lower treatment requirement, 36% faster settling and a 0.5 percentage-point increase in sugar recovery. These improvements can strengthen clarification performance while potentially improving pressmud consolidation, reducing treatment-derived mineral loading and supporting filtration, dewatering and downstream processing. The results therefore provide a basis for an integrated clarification–bioenergy approach in which improved sugar processing is linked to improved pressmud processability. Direct pressmud characterization and BMP studies are required before any quantitative claim of enhanced biomethane recovery is made.

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Microbial Ecology of Anaerobic Digestion: The Invisible Workforce Behind Biogas





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Industrial Challenge

As industries face mounting pressure to reduce emissions, minimize waste, cut energy costs, biogas production is emerging as a powerful solution that embodies the principles of the circular economy. By transforming agricultural by products into renewable methane rich gas, biogas enables companies to achieve both sustainability and operational efficiency-while reducing their dependence on fossil fuels. Biogas production from lignocellulosic biomass is generally considered to be challenging due to the recalcitrant nature of this biomass.

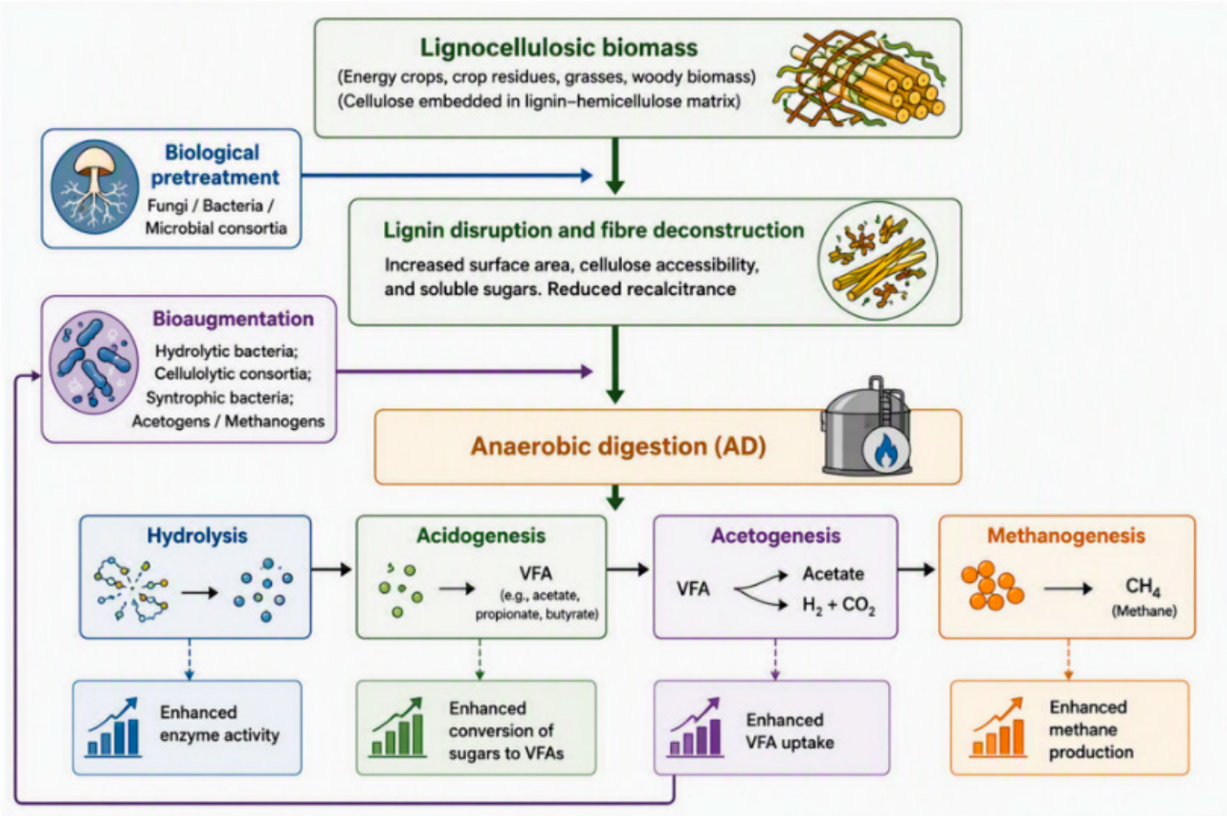
Microbial Community Structure and function

The microbial ecology of Anaerobic Digestion is usually described as a trophic network rather than a simple linear pathway. Rather than a single microorganism, a coordinated microbial consortium carries out a series of interconnected reactions. The efficiency and stability of an anaerobic digester therefore depend on the diversity, activity and interactions of these microorganisms.

Biogas production is a cooperative process involving hydrolytic, acidogenic, acetogenic and methanogenic microorganisms. Each group depends on the products of the previous stage, and this syntrophic relationship ensures the efficient conversion of complex organic matter into methane and carbon dioxide.

Sulphate-reducing bacteria (SRB) also constitute an important functional group in anaerobic digesters. SRB utilize sulphate as a terminal electron acceptor and compete with methanogens for common substrates, such as acetate, lactate, and hydrogen. While methanogens convert these substrates into methane, SRB reduce sulphate to hydrogen sulphide (H_2S), influencing both microbial ecology and biogas quality.

Stages of Anaerobic Digestion



Hydrolysis

During hydrolysis, bacteria use extracellular enzymes to break down complex polymers such as carbohydrates, proteins, lipids and lignocellulose into simpler compounds. This is often the rate-limiting step, especially for lignin-rich substrates.

Bioaugmentation can accelerate hydrolysis through the addition of cellulolytic, hemicellulolytic and lignin-degrading bacteria or consortia, thereby improving substrate degradation and methane production from lignocellulosic feedstocks such as wheat straw.

Acidogenesis (Acidification Phase)

During acidogenesis, hydrolysis products such as sugars, amino acids and fatty acids are converted by acid-producing bacteria into volatile fatty acids (VFAs), alcohols, hydrogen (H_2) and carbon dioxide (CO_2). These products serve as substrates for the next stage of anaerobic digestion. Common acidogenic bacteria include Clostridium, Bacillus, Pseudomonas and Flavobacterium.

Acetogenesis

In the acetogenesis stage, acetogenic bacteria convert VFAs and alcohols into acetic acid, hydrogen and carbon dioxide, which are the primary substrates for methanogens. Important acetogenic bacteria include Syntrophomonas and Syntrophobacter.

Methanogenesis

Methanogenesis is the final stage of anaerobic digestion, where methanogenic archaea convert acetic acid, hydrogen and carbon dioxide into methane (CH_4) and carbon dioxide. Approximately 70% of methane is produced from acetate, while the remaining 30% is produced from hydrogen and carbon dioxide. This stage determines the overall biogas yield.

Role of Methanogens in Methane Production

Methanogens are strict anaerobic archaea that thrive at pH 6.8–7.2 and mesophilic (28–42°C) or thermophilic (55–72°C) temperatures. They are essential for methane production in biogas plants and wastewater treatment systems.

Biochemical Pathways of Methanogenesis

Methane is produced in anaerobic digestion through two main pathways:

i. Acetoclastic methanogenesis: Acetic acid is directly converted into methane (CH_4) and carbon dioxide (CO_2) by acetotrophic methanogens. This pathway produces about 70% of the total methane under normal conditions.
ii. Hydrogenotrophic methanogenesis: Hydrogen (H_2) and carbon dioxide (CO_2) are converted into methane by hydrogenotrophic methanogens. This pathway becomes dominant under high ammonia, high organic loading or thermophilic conditions.

When acetate accumulates or methanogens are stressed, syntrophic acetate-oxidizing (SAO) bacteria convert acetate into H_2 and CO_2, which are then utilized by hydrogenotrophic methanogens. Methanosarcina is highly adaptable because it can use both acetoclastic and hydrogenotrophic pathways, making it important for stable biogas production.

Syntrophic interaction among Microorganisms

A key ecological feature of Anaerobic Digestion is syntrophy, meaning the growth of one organism depends on another organism removing its metabolic products. This is especially important for the oxidation of fatty acids and alcohols, where reactions remain thermodynamically feasible only when hydrogen or formate is kept very low by methanogens.

Competitive Interaction between Microorganisms

Sulphate-Reducing Bacteria (SRB) are obligate anaerobic microorganisms that perform dissimilatory sulphate reduction. They oxidize compounds such as lactate and acetate or utilize hydrogen as an electron donor while reducing sulphate (SO_4^{2-}) to hydrogen sulphide (H_2S). Common SRB associated with anaerobic digesters include Desulfovibrio, Desulfotomaculum and Desulfobacter.

Although anaerobic digestion is largely based on syntrophic interactions, SRB establishes a strong competitive relationship with methanogens. Both groups utilize common electron donors such as hydrogen, acetate and other organic compounds; however, SRB use sulphate as the terminal electron acceptor and convert it to H_2S rather than methane. When sulphate is abundant, SRB can outcompete methanogens for these substrates, diverting carbon and electrons away from methanogenesis. This can reduce methane yield, increase H_2S concentration in biogas and create additional operational challenges due to H_2S toxicity and corrosion.

Factors Impacting the Microbiology of Anaerobic Digestion

The microbial community inside an anaerobic digester is highly influenced by environmental conditions such as temperature, pH, carbon/nitrogen ratio, loading rate, nutrient availability, toxic compounds and mixing intensity. These process parameters shape digester community structure significantly.

Sulphate concentration is an important ecological factor that determines the abundance of SRB within anaerobic digesters. Elevated sulphate levels promote sulphate reductio and increase hydrogen sulphide production.

Excess H_2S not only lowers biogas quality but may also inhibit methanogenic activity, interfere with syntrophic interactions and increase corrosion of pipelines, storage systems and biogas engine. Therefore, maintaining a balanced microbial community and controlling SRB activity are essential for efficient methane production.

Thermophilic digestion at 55°C favours groups such as Thermotogales and Clostridiales through selective adaptation. Optimal pH ranges differ for hydrolytic bacteria (pH 5.5–7), acidogens (pH 5–7.5) and methanogens (pH 6.5–8), hence maintaining overall pH balance is important.

Excessive substrate loading can accelerate acid production, leading to accumulation of VFAs, reduction in pH and inhibition of methanogenic activity. Similarly, compounds such as ammonia, sulfide, heavy metals and high concentrations of salts can disturb microbial interactions and reduce methane yield.

Conclusion

The stability of a biogas plant therefore depends not only on the amount of substrate supplied, but also on maintaining the ecological balance between the microorganisms that convert it into methane. Understanding the ecological balance between methanogens and sulphate-reducing bacteria provides the foundation for developing selective strategies that suppress H_2S formation while preserving methane production, thereby improving both biogas quality and process stability.

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Optimizing Biogas Plant Performance: Key Operating Parameters and Process Control





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Introduction

Utilization of byproducts is key to the sustainability of any industry, and creation of wealth from industrial waste and byproducts is gaining momentum. Generation of biogas using anaerobic digestion is one such innovation and has been seen as an alternative source to petroleum products. Apart from generating green fuel, anaerobic digestion enables considerable reduction in environmental pollution from industrial waste while providing organic fertilizer. However, operational and maintenance challenges of anaerobic digesters can limit biogas production capabilities.

Therefore, proper understanding of the parameters that need to be controlled to optimize biogas yields is essential. Maintaining optimal digester efficiency involves continuous monitoring of important physical, operational, chemical and biological parameters, including temperature, loading, nutrients and inhibitors.

Physical Parameters

Temperature

Temperature is the most critical operational parameter for the optimization of a biogas plant. Bioreactors generally operate under two kinetic modalities, mesophilic and thermophilic.

- Mesophilic range (30–40°C): Most anaerobic digestion processes occur in the mesophilic temperature range. The optimal temperature for mesophilic bacteria is around 35–37°C. Every 2°C temperature drop will impact the methanogens bacteria activity resulting in 3-5% drop in methane production (ref). Hence, below 30 °C there can be up to 15-20% drop in methane production, and the balance between acid producing fermentative bacteria and methanogens become strained, as acidogenic tolerate lower temperature better than methanogens. It can also lead to increased HRT and digester souring, which significantly affects the methanogens activity.

- Thermophilic range (45–65°C): Thermophilic bacteria are active at higher temperatures, typically between 50–60°C. Biogas production in the thermophilic range is faster than in the mesophilic range, but the process can be more sensitive to fluctuations in temperature and pH. Due to the high temperature, in thermophilic conditions HRT can be reduced up to 2-3 times more as compared to the mesophilic condition but every temperature drop from the optimum range (53-57°C) increase the HRT and biogas productions of the digester.

Temperature affects not only the rate of biogas production but also the composition of the biogas. Higher temperatures can favour the production of methane over carbon dioxide, resulting in biogas with a higher methane content. However, extreme temperatures can inhibit microbial activity and lead to process instability.

Organic Loading Rate (OLR)

The ideal organic loading rate of anaerobic digesters for biogas production is between 2.0 and 7.0 kg/m^3/day, depending on the characteristics of the feedstock and design of the digester. The organic loading rate in terms of COD kg/m^3/day can be calculated using the COD value of the feed, the flow rate and the working volume of the digester. Higher organic load rate (4-7 kg/m3/day) may help to increase the biogas production and reduce the HRT of the digester, however excessive OLR may decrease the digester efficiency, due to increased osmotic, nutrients and inhibitor stress on the bacteria.

Food-to-Mass (F:M) Ratio

The 'food' available for microorganisms in wastewater treatment systems is represented in terms of COD or BOD, while the microorganism level in the digester is generally estimated in terms of mixed liquor volatile suspended solids (MLVSS). Therefore, the F/M ratio can be calculated as the ratio of the total COD fed to the digester to the total amount of microorganisms (MLVSS) present in the digester. A low F/M ratio indicates excessive microorganisms and limited food supply, while a high F/M ratio indicates excessive food compared to microorganisms. In general, an F/M ratio of 0.2 to 0.4 is optimum; under certain circumstances, a ratio of 0.5 may be allowed for maximum digester efficiency and methane formation but excessive food and mass ratio above 0.8 can stress the methanogenesis bacteria and system failure.

Mixing and Agitation

Mixing plays a pivotal role in the anaerobic digestion process. Effective mixing fosters substrate homogeneity, ensuring equitable nutrient access for microorganisms and facilitating the breakdown of complex organic matter. Key benefits include:

- Enhanced degradation rate
- Prevention of scum
- Temperature control
- Reduction of dead zones

Chemical and Biological Parameters

Nutrient Balance (C: N:P Ratio)

Nitrogen is essential for microbial proteins, including the enzymes required to hydrolyze complex substrates such as starch, fats and proteins. As nitrogenous compounds degrade, they release ammonium and contribute to bicarbonate alkalinity, helping buffer VFA-induced acidification.

Phosphorus is critical for cellular energy transfer through ATP and for maintaining the structural integrity of phospholipid membranes. Adequate phosphorus therefore supports microbial metabolism, nutrient uptake and cell growth.

Hence, carbon (C), nitrogen (N) and phosphorus (P) are vital for microbial processes, and the optimum ratio for biogas production is 100:5:1. Press mud is a carbon-rich feedstock, where the C: N and C:P ratios may be more than 25:1 and 100:1, respectively. In such cases, maintaining the optimum C: N:P ratio becomes necessary by co-digestion or adding nutrients.

pH

The pH of the digester should be between 6.8 and 7.5 because most methane-generating bacteria can function in this range. Methane-forming bacteria break down fewer volatile acids outside the optimal pH range, hence reducing methane yield. Below pH 6.5, acidogenic bacteria rapidly produce VFA, while pH-sensitive methanogens cannot consume them fast enough, causing VFA accumulation and digester souring. Low pH also depletes bicarbonate alkalinity, reducing the digester's natural buffering capacity.

At high pH (>8), the ammonium–ammonia equilibrium shifts toward free ammonia (NH_3), which can penetrate microbial cell membranes and inhibit methanogens. Excessively alkaline conditions also disrupt membrane integrity and enzyme activity, significantly slowing microbial growth and digestion.

Volatile Fatty Acid-to-Alkalinity (VFA/Alk) Ratio

Alkalinity is represented by the carbonate/bicarbonate ions, which act like buffering system to neutralize the acids. As alkalinity is reduced, the digester loses its ability to resist pH drops. Also, at elevated VFA/Alk, accumulation of undissociated VFAs (generated during acidogenesis) increases, enhancing proton diffusion across cell membranes and imposing additional intracellular pH-regulation stress. Consequently, cellular electron flow and ATP conservation become energetically constrained, reducing conversion of acetate/H_2–CO_2 to CH_4 and further accelerating VFA accumulation. Generally, an optimal VFA-to-alkalinity ratio between 0.20 and 0.30 supports continuous methane yield and stable microbial activity. Ratios exceeding 0.4 - 0.5 signify stress due to acid accumulation outpacing the buffer and may require a reduction in organic feed rates. Ratios climbing past 0.8 indicate that the system is souring and methane-forming bacteria may shut down, requiring emergency buffering such as sodium bicarbonate. Methane production is significantly hindered when VFA concentrations cross 4,000–8,000 mg/L.

Ammonia

Ammonia is produced by the degradation of nitrogen-rich organic matter such as proteins, urea and food waste. While nitrogen is essential for microbial growth, excessive ammonia, particularly in its free or un ionized NH3 form, can diffuse through the membrane of methanogens, affects the acid-base equilibria and K+ ion balance, which forces the cells to spend more energy (ATP) to maintain the cellular pH, ion transport and homeostasis, leaving behind less energy for methanogenesis. Mild inhibition begins above 1,500 mg/L, with severe methane suppression occurring at 3,000–4,000 mg/L. Higher operating temperatures can push the equilibrium towards toxic free ammonia, magnifying its inhibitory effects. Maintaining the digester pH below 7.4 can help reduce this risk.

Hydrogen Sulphide

Sulfide concentration is a critical indicator of anaerobic digester health. Sulphate-reducing bacteria (SRB) can outcompete methanogens for available hydrogen, reducing sulphur substrates into dissolved sulphide and gaseous hydrogen sulphide. Hydrogen sulphide is toxic to methane-producing microorganisms, because undissociated H_2S can penetrate microbial membranes, inhibit key metalloenzymes, and disrupt cellular energy metabolism, particularly in methanogens. H2S can also form acids with water that corrode plant machinery. Sulfide levels of > 50 ppm in liquid phase and > 2,000 ppm in gas phase is generally considered as an alarming situation, and measures should be taken to minimize the sulfide levels.

Inhibitors

Common in livestock manures such as cattle or poultry waste, and even in some industrial and municipal solid waste, antibiotics and other chemicals can suppress or gradually wipe out critical bacterial and archaeal populations, extending the lag phase and reducing biogas output. Some common inhibitors present in poultry waste – Ammonia, antibiotics or antimicrobials (sulfonamides, fluoroquinolones, tetracyclines, lasalocid, monensin etc.)

Inoculum

In AD, the proportion of inoculum refers to the proportion of anaerobic activated sludge or other microbial communities added relative to the mass of the raw material. Insufficient inoculum results in poor system stability,

making it more vulnerable to environmental fluctuations such as pH and temperature changes. An inoculation ratio of 10-30% can provide sufficient active microorganisms to enable rapid system start-up. Excess inoculum occupies reactor volume, reducing raw material processing capacity and increasing operating costs.

Automation and Process Control

CBG production involves multiple stages that require accurate monitoring and control. Variations in temperature, pressure, gas composition and feedstock quality can directly affect gas production efficiency. Manual operations often lead to inconsistent production, energy losses, human errors, equipment damage and safety hazards. Automated process control may help to minimize these risks.

Distributed Control System (DCS)
Large-scale CBG facilities often use Distributed Control Systems (DCS) for advanced process management. A DCS can monitor the real-time performance of the plant, including temperature, gas pressure, leakage in gas-holder balloons, pH, and digester volume or levels.

Sensors and Instrumentation
Sensors are critical for collecting process data throughout the plant. Common sensors used in CBG plants include temperature and pressure sensors, flow meters, gas analyzers and moisture analyzers, which help monitor plant performance.

Gas Monitoring Systems
Gas quality monitoring is extremely important in CBG plants. Automation systems continuously monitor methane concentration, CO_2 levels, oxygen content, ammonia, sulfides and toxic inhibitors.

Together, these operating parameters and control systems provide the basis for stable digester performance, consistent gas production and safer CBG plant operation.

Unlocking Corn Oil: Technologies for Recovery from Maize based Distilleries





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The rapid growth of maize-based ethanol production and no-revision in the ethanol procurement prices from last several years has increased the importance of maximizing value from every fraction of the grain. Traditionally, the principal co-product of a dry-grind maize distillery has been Distillers Dried Grains with Soluble (DDGS). However, Distillers Corn Oil (DCO) has emerged as an increasingly attractive co-product because of its applications in animal nutrition, biodiesel and other renewable-fuel pathways. Whole maize kernels contain 3-5% oil by weight. Extracting DCO prevents this valuable lipid from being wasted or degrading the quality of dry animal feed fraction.

The recovery of corn oil is therefore likely to become an important area of process optimization in maize-based distilleries, particularly where margins are under pressure and additional coproduct revenue is required to improve the sustainability of the units.

Key uses of Distillers Corn Oil

DCO is a non-food grade co-product which finds application for various purposes viz.:

i. It is a popular, cost effective and sustainable lipid source for bio-fuel manufacturing viz. bio-diesel and renewable diesel.
ii. DCO also serves as a valuable, nutrient dense fat supplement in live-stock & poultry diets.
iii. DCO or its derivatives can be utilized in manufacturing soaps, rubber items, inks & rust inhibiting compounds.

Where is the Oil Located?

In a conventional dry-grind process, maize is milled, liquefied, saccharified and fermented before distillation. Following ethanol recovery, the resulting whole stillage is separated into wet cake and thin stillage. A portion of the thin stillage is normally recycled as back set, while the balance is concentrated and eventually incorporated into DDGS. Corn oil is distributed between these fractions. Some oil is present as relatively free oil, while a significant quantity remains associated with cell walls, protein matrices and fine solids. Oil can also occur as very small droplets in an oil-in-water emulsion, making its recovery by conventional gravity separation difficult. Research has shown that the amount of oil transferred into thin stillage is strongly influenced by corn preparation

and the degree to which the oil is released from the grain matrix.

Consequently, future oil-recovery systems are likely to focus not only on separation equipment but also on liberating more oil upstream and destabilizing emulsions before separation.

Decanter and Three-Phase Centrifugal Separation

The simplest approach is to recover oil from the stillage stream by centrifugal separation. Conventional decanters separate whole stillage into wet cake and thin stillage, and this first separation is important because oil remaining with the wet cake is generally difficult to recover later. Modern decanters can be configured to improve oil transfer into the liquid phase. Threephase centrifuges or tri-canters can simultaneously separate solids, aqueous liquid and an oilrich phase.





This technology is particularly attractive for existing distilleries because it can be integrated with the existing stillage separation system.

Disc-Stack Centrifuges

High-speed disc-stack centrifuges represent as another most promising technology for improving DCO recovery. Their high centrifugal forces and large effective separation area enable them to capture smaller oil droplets than conventional equipment. Commercial systems are already being used for oil skimming from thin stillage or concentrated syrup.





An important process configuration is to partially concentrate thin stillage through evaporation and then pass it through a disc-stack separator before completing evaporation. Concentrating the stream increases the concentration of oil and can improve the economics and effectiveness of centrifugal separation. Patented processes have specifically proposed placing the centrifuge between stages of a multi-effect evaporator.

Approximately 57% of US corn ethanol plant use this technology, however, average recovery rates capture only 50-60% of total potential corn oil yield, thus leaving room for further technological optimization.

Thermal Treatment and Emulsion Breaking

A major limitation in oil recovery is the presence of stable oil-water emulsions. Temperature, pH and emulsion-breaking treatment can therefore play a major role in improving recovery. Research and commercial experience indicate that appropriate conditioning of thin stillage before centrifugal separation can release oil from the emulsion and increase the quantity available for recovery.

Thermal conditioning has also been investigated, including pressurized heating followed by cooling and

centrifugal separation. Such treatment can alter the physical characteristics of the stillage and facilitate subsequent oil separation.

The practical opportunity is to optimize temperature–residence time–pH–centrifugal force as an integrated system rather than treating the centrifuge as an isolated piece of equipment.

Enzyme-Assisted Oil Recovery

A more advanced approach is to increase oil recovery by using enzymes during fermentation or downstream processing. Cellulases, pectinases and other hydrolytic enzymes can break down components of the cell-wall and solids matrix, thereby releasing oil that would otherwise remain with the wet cake.

Studies have demonstrated that hydrolysing enzymes can shift more oil from wet cake into thin stillage, where it becomes easier to recover. A synergistic effect has also been observed when enzymes are combined with suitable surfactant treatment. However, enzyme selection and dosage require careful optimization because some treatments, particularly inappropriate protease application, can increase emulsification and actually reduce recoverable free oil.

Thus, enzyme-assisted recovery should be considered as a process-specific optimization rather than a universal additive solution.

Aqueous Enzymatic Extraction

Aqueous enzymatic extraction is another promising solvent-free technology. Instead of relying on hexane or other organic solvents, enzymes are used to disrupt the grain or germ matrix, followed by separation of liberated oil through centrifugation. Studies on corn germ have demonstrated substantial oil recovery using combinations of cellulases and other enzymes.

For a conventional dry-grind distillery, however, the economics and integration of such a system need careful evaluation. It may become more attractive in plants adopting grain fractionation or germ recovery upstream of fermentation.

Membrane and Advanced Separation Technologies

Membrane technology offers another potential future route. Research has demonstrated the concentration of corn oil from ethanol extracts using nanofiltration membranes, with simultaneous concentration of other valuable ethanol-soluble components such as proteins and lecithin.

Although such systems are less established for mainstream DCO recovery than centrifugation, they could become relevant in integrated biorefineries where multiple high-value products are recovered from maize.

The Way Forward

For most existing maize-based distilleries, the immediate opportunity is likely to lie in optimizing conventional centrifugal recovery rather than adopting a completely new extraction process. A combination of efficient whole-stillage separation, controlled evaporation, oil skimming, disc-stack centrifugation and appropriate emulsion-breaking technology can potentially provide a practical retrofit pathway.

The next generation of plants may go further by combining enzyme-assisted oil recovery, advanced centrifugation, process analytics and automated control. Online monitoring of stillage characteristics, oil concentration, temperature, pH and centrifuge performance could allow continuous optimization of oil recovery.

Ultimately, corn oil recovery should be viewed as part of an integrated maize biorefinery strategy. The objective should not merely be to extract oil, but to maximize the combined value of ethanol, corn oil, DDGS and other co-products while minimizing energy consumption and maintaining the desired quality of each product. With shifting ethanol margins & fixed procurement pricing, recovery of DCO provides an additional revenue stream that can help in improving the financial capabilities of the plants.

The Modern Brewery: From Brewing Beer to Engineering Efficiency





Mahendra Verma
BMS- Head

Why the future of brewing excellence will be defined not only by the beer in the glass, but by how intelligently it is produced

Brewing has always been a balance of science, craftsmanship and experience. Malt, water, hops and yeast come together through a carefully controlled process to create a product that consumers experience simply as a glass of beer.

But behind that glass, the modern brewery faces a much more complex challenge.

Breweries today must deliver **consistent quality, process efficiency, resource optimization and commercial competitiveness—often at the same time**.

This is changing the way we look at brewing. The question is no longer only *"How do we make great beer?"* but increasingly, *"How do we make great beer more consistently, efficiently and sustainably?"*

From Individual Processes to the Complete Brewing System

A brewery is an interconnected system. Decisions made during mashing can influence wort separation; wort characteristics can affect fermentation; fermentation performance can influence maturation and filtration; and filtration efficiency can ultimately affect tank availability and production capacity.

This means that solving one process problem in isolation may not always deliver the best overall result.

For example, a filtration challenge may appear to be a filtration problem, but its underlying causes can originate much earlier in the process—through raw-material characteristics, mash conditions, viscosity or wort composition.

The modern approach therefore needs to focus on **root-cause analysis and total process performance**, rather than simply correcting the visible problem.

Technology Should Solve a Problem—Not Create One

Enzymes, yeast, processing aids and analytical technologies can provide valuable tools for modern breweries. Their real value, however, comes from how intelligently they are applied.

Enzyme technology, for instance, can support breweries in areas such as starch conversion, viscosity management, filtration and raw-material flexibility. But the decision to use an enzyme should begin with the process requirement—not with the product.

A useful technical trial should answer three questions:
Does it work technically?
Does it create measurable value?
Can the benefit be sustained commercially?

This is where technical expertise becomes important. A solution that performs well in a laboratory trial may require further evaluation under actual brewery conditions before it can be considered a reliable commercial solution.

The Hidden Value of Time

One resource that is often underestimated in brewery economics is **time**.

Brewhouse cycles, fermentation vessels, filtration systems and packaging operations all have finite capacity. Every unnecessary hour can have an opportunity cost.

If a process improvement reduces cycle time while maintaining quality, the benefit may extend beyond the immediate saving. It can potentially improve equipment utilization, production planning and available capacity.

Similarly, better filtration performance can influence tank turnaround and downstream scheduling.

Therefore, technology should increasingly be evaluated not only on **cost per kilogram or cost per hectoliter, but by the broader value it creates for the brewery**.

Efficiency and Sustainability Can Work Together

Sustainability is becoming an operational priority across the brewing industry. Water, energy, waste and resource utilization are no longer only environmental considerations, they are also business considerations.

Reducing unnecessary heating, improving extract recovery, minimizing product losses or optimizing process time can potentially contribute to both operational efficiency and resource conservation.

The opportunity is to make sustainability part of everyday process improvement rather than treating it as a completely separate initiative.

Brewer's Perspective: Five Questions Before Adopting Technology

Before introducing a new enzyme, yeast, additive or process technology, every brewery should ask:

1. What problem are we actually trying to solve?
2. Can the improvement be measured?
3. What is the total economic benefit—not just the product price?
4. Will the solution perform consistently at plant scale?
5. Does it improve the overall brewery process, rather than just one process step?

These questions help shift the conversation from *"Which product should we buy?"* to *"Which process challenge are we trying to solve?"*

Tomorrow's Brewery

The brewery of tomorrow will not necessarily be the one using the most technology. It will be the one using the right technology, at **the right point in the process, supported by data and brewing expertise.**

Brewing will always remain a combination of science and craftsmanship. Technology should not replace the brewer's experience; it should provide better tools to apply that experience.

For me, this is where the future of brewing becomes particularly exciting: **moving from simply making beer efficiently to engineering the entire brewing process for quality, consistency, sustainability and value.**

The ultimate objective is not merely to produce more beer.

It is to produce better—with greater intelligence, greater consistency and greater value.

Stresses in Fermentation





Soham Sanyal
Leaf Technical Service Representative



Dr. Furqan Ali
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India's achievement of the E20 ethanol blending marks a significant milestone for the industry and signals a clear inflection point in the ethanol landscape. It reflects sustained policy decisions and significant investments made by ethanol producers across India.

As the industry moves into a new phase, the focus naturally shifts from target attainment towards long-term operational and commercial performance. In an environment of volatile feedstock costs and rising operational costs, profitability is ever so significant. Therefore, fermentation efficiency is no longer just a technical consideration – it is now a key lever for plant competitiveness and long-term plant performance.

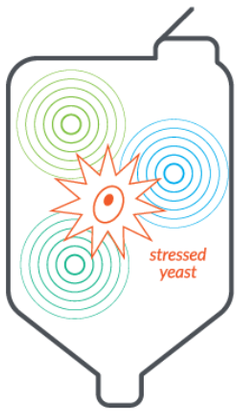
One of the key drivers of fermentation efficiency is yeast health. The yeast is subjected to a combination of stresses - biological, chemical, and physical - in the fermenter that affect yeast health. Understanding these stresses and how they interact is essential for managing and protecting fermentation efficiency and, in the long term, sustaining plant profitability.

Biological stresses :

- bacteria
- wild yeast
- ageing
- mutation

Physical stresses :

- temperature
- osmotic pressure
- pressure



Chemical stresses :

- organic acids
- pH
- toxic compounds
- nutrition lack
- ethanol

Biological stress during fermentation

Bacterial contamination in a fermenter initiates a critical competition for resources between the pitched yeast and bacteria. Due to their faster replication rate, doubling approximately every 20 minutes, bacterial populations can increase eightfold per hour. In contrast, yeast typically requires two hours to double its population, resulting in a growth rate roughly six times slower than that of common contaminants. The disparity creates a biological race where even a minor initial contamination can quickly overwhelm the fermentation. Therefore, strategically minimizing the initial contaminant load through optimized process parameters (such as pH, temperature, and sanitation protocols) is essential. This approach directly reduces the bacterial growth rate and biological stress on the yeast, and ultimately safeguards fermentation yield and plant profitability.

Another occurring stressor is yeast aging, a phenomenon happening after 10 to 20 yeast generations. Each reproductive cycle leaves budding scars, which cumulatively reduce growth rate and, in turn, ethanol productivity. This is negligible in batch processes but is a key limitation in continuous fermentation, where yeasts undergo extensive replication. To overcome the resulting slowdown in fermentation kinetics, adapting yeast pitching in continuous processes is required to periodically introduce fresh yeast and sustain process efficiency.

Physical stress

Yeast's optimal temperature for growth is 30°C, and industrial ethanol production's is 33°C. With an increased temperature – between 35 to 38°C – the yeast's growth rate will be lower, and ethanol toxicity will increase. There is a cumulative effect of both high temperature and ethanol concentration on yeast inhibition. Choosing a robust yeast able to manage such temperature levels is essential to optimize the fermentation performance.

Osmotic pressure can also further stress yeasts during fermentation: it arises from a difference between the fermentation medium and the inner part of the yeast. Primary contributors to osmotic pressure in the medium are sugars, including monomeric (glucose, fructose), dimeric (maltose, sucrose), and trimeric (maltotriose). Osmotic pressure in a medium will affect ethanol yield, as glycerol can be overproduced under osmotic stress conditions. It will also affect ethanol productivity by partially inhibiting yeast growth. Maintaining a level of osmotic stress below a critical value will lead to fermentation performance improvement.

Chemical stressors in fermentation

Organic acids – mainly lactic and acetic – can be produced by the contaminants or present in the raw material itself. Acids will inhibit the yeast and affect ethanol productivity and yield. The associated pH is also an important parameter to consider, as a lower pH can also increase the toxicity of certain organic acids, such as acetic acid. The optimal pH for the yeast is between 4 and 5.5.

Lastly, nutrient deficiency also affects yeast growth, creating an additional stress factor. As this impairs growth, it also affects both yield and productivity. For instance, a nitrogen deficiency can stall fermentation, leading to yield losses. It will also have a direct impact on ethanol productivity, as the yeast population is limited and kinetics are slowed. Working on optimal nutrition to avoid limitations will help to have a robust yeast to maintain a high ethanol productivity and yield even at high ethanol concentration.

Managing the stresses

While none of these stresses can be eliminated outright, each can be managed through some stress management measures. One of the key lever will be the choice of yeast: choosing a robust yeast for tolerance to inhibitors, ethanol, and temperature swings will act on various stress factors in order to secure fermentations. Opting for a continuous optimization approach, refining parameters like enzyme dosing pattern, mash flow, and mash gravity will reduce osmotic stress and its impact on fermentation. Going hand-in-hand with fermentation parameter optimization is a robust CIP and close pH monitoring to limit contamination and proactive antibacterial dosing in case of contamination. Finally, nutritional supplementation will ensure there is no deficiency or limitation, ultimately supporting yeast health and optimal fermentation completion.

While all of the above is true, relying on a trusted partner to reduce the effect of stress on your fermentation will ensure you reach your production goals. To discuss your needs, connect with Leaf by Lesaffre today!

https://leaf-lesaffre.com/

Every Litre Counts: Maximizing Value from Every Tonne of Grain





Arindam Mondal
Technical Sales Manager

India's grain-based ethanol industry is entering a new phase of maturity, where success is increasingly defined not just by production volumes, but by production efficiency. As feedstock economics fluctuate and operating margins come under greater scrutiny, ethanol producers are looking beyond capacity utilization and focusing on extracting maximum value from every tonne of grain.

The industry's attention is shifting from simply keeping plants running to optimizing performance across the production process. Every stage, from liquefaction and saccharification through to fermentation, presents an opportunity to improve efficiency, strengthen process reliability, and enhance overall plant economics. In this environment, even incremental improvements can translate into meaningful gains in yield and profitability.

This is where Novonesis' high-performance enzyme portfolio is making a difference. Designed to maximize starch conversion and support consistent process performance, these solutions help distillers achieve greater efficiency without compromising operational stability.

Solutions such as Fortiva® Revo X HP and the Spirizyme® portfolio are helping producers achieve:

- Higher starch-to-ethanol conversion
- Improved liquefaction and saccharification performance
- Greater resilience under challenging operating conditions
- Enhanced process consistency across production cycles
- Improved yield per tonne of grain and stronger plant economics

The result is a production process that delivers more from existing assets, enabling distillers to capture additional value while maintaining reliability and operational excellence.

As the industry continues to evolve, one question becomes increasingly important:

"Are we extracting the maximum value from every tonne of grain?"

The answer often lies not in major process changes, but in continuously identifying opportunities to improve conversion efficiency, reduce variability, and optimize performance throughout the production chain. In a competitive market, these gains can provide a meaningful advantage over time.

At Novonesis, we believe performance is not just a promise. It's engineered into every enzyme we deliver. Let's partner to push the boundaries of what's possible in ethanol production.

Efficiency. Consistency. Yield.
That's the Novonesis advantage

From Ethanol Production to Integrated Biorefinery: A New Value Paradigm





Kartikeya Parashar
Trainee



Abhishek Sharma
Executive - Business Development

India's ethanol industry has moved from being a predominantly sugar-industry by-product business to becoming an important part of the country's energy and agricultural economy. India is now the world's third-largest ethanol producer, behind the United States and Brazil, with its fuel-ethanol production growing at an estimated ~37% CAGR between 2020 and 2025, compared with around 4% globally over the same period. Ethanol production capacity in India reached about 1,953 crore litres as of October 2025, comprising approximately 980 crore litres of grain-based capacity and 973 crore litres from molasses and dual-feed distilleries. Over 2014-15 to 2024-25, sugar mills earned more than ₹1.29 lakh crore from ethanol sales, while the ethanol blending programme has also generated more than ₹1.44 lakh crore in foreign-exchange savings through reduced crude-oil dependence. With India having achieved 20% ethanol blending, the next question for distillery operators is increasingly different: how much more value can be extracted from the biomass, energy and process streams already entering the plant?

Connecting Feedstocks, Pathways and Value Streams

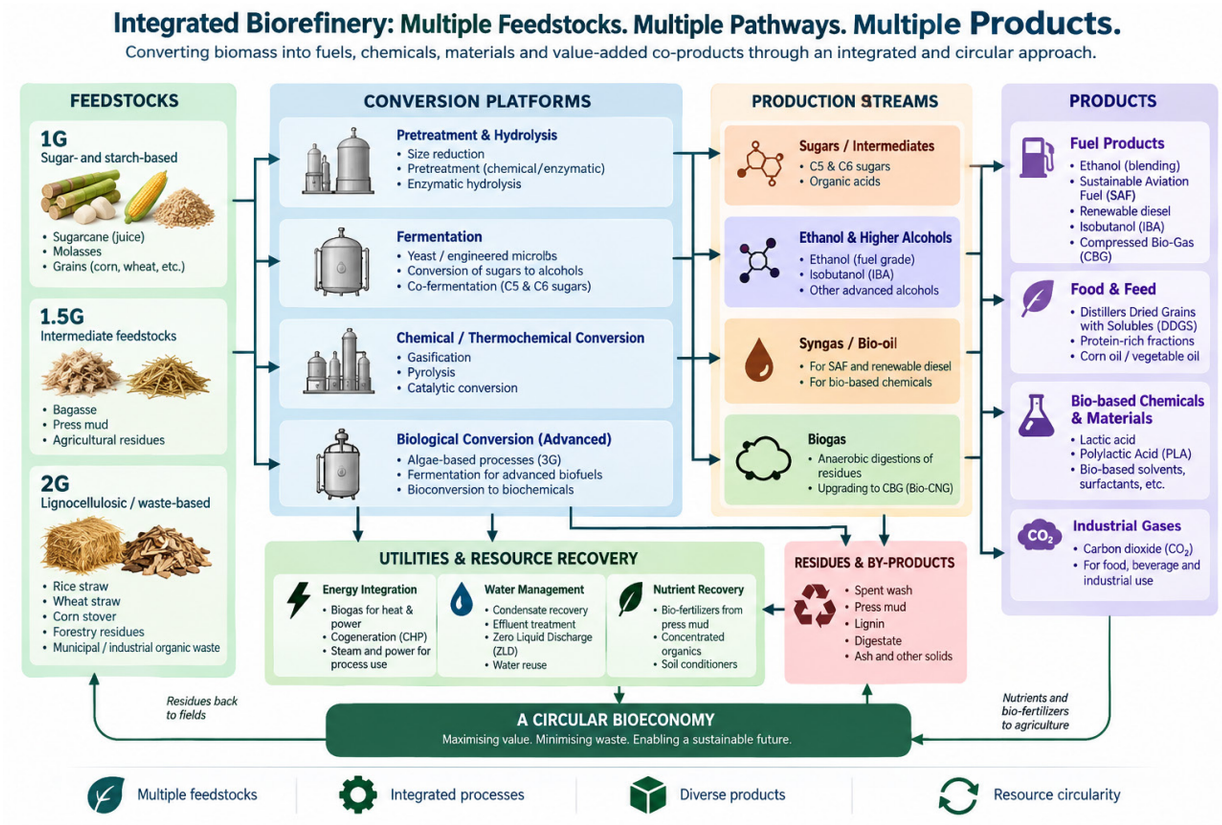
The integrated biorefinery model treats biomass as a portfolio of resources rather than simply as feedstock for ethanol. Different feedstocks, conversion technologies and downstream processes can be integrated to generate multiple products, recover resources and create greater value from the same biomass base.

- Zero Liquid Discharge (ZLD) systems enable greater recovery and reuse of process water and condensates. CPCB's 2023 monitoring reported 4.7 litres of freshwater per litre of alcohol, down from 15 litres in 2016–17—a reduction of about 66%.
- Over the same period, specific spent-wash generation fell by about 41%, reflecting improvements in fermentation, distillation, evaporation and condensate-recovery systems.
- 1G, 1.5G and 2G pathways can integrate sugarcane, molasses, grains and lignocellulosic residues for greater feedstock flexibility.
- Depending on the configuration, outputs can extend well beyond ethanol to include distillers grains, carbon dioxide (CO_2), corn oil, protein-rich fractions, isobutanol, Sustainable Aviation Fuel (SAF) and Polylactic Acid (PLA). This creates opportunities to extract value from both the primary product stream and the carbon, nutrient and material fractions associated with the feedstock.
- Sustainable Aviation Fuel (SAF) can be produced through advanced alcohol-to-jet pathways, creating a route for ethanol-derived carbon to enter the aviation-fuel value chain.
- Isobutanol (IBA) represents another higher-value alcohol pathway, with potential applications as a fuel

component, chemical intermediate and feedstock for further conversion.

- Polylactic Acid (PLA) can be produced by converting biomass-derived sugars into lactic acid and subsequently into a bio-based polymer, opening a materials pathway alongside fuels.
- Residue-to-CBG pathways are becoming an important part of the integrated biorefinery model: suitable residues and organic streams can undergo anaerobic digestion to produce biogas, containing typically 55–65% methane, which can be used for heat and power or upgraded to around 98% methane for Compressed Bio-Gas (CBG). SATAT (Sustainable Alternative Towards Affordable Transportation), launched in 2018, established an organised CBG ecosystem through long-term offtake arrangements with oil and gas marketing companies. This ecosystem has now reached 217 commissioned CBG plants as of August 2026, with 1,908 plants registered on the national GOBARdhan portal. With the CBG blending obligation currently set at 3% in FY 2026–27, 4% in FY 2027–28 and 5% from FY 2028–29 onwards in the CNG (Transport) and PNG (Domestic) segments, the expanding ecosystem creates further scope for integrating waste, energy, fuel and resource-recovery pathways within the biorefinery model.
- The focus shifts from litres of ethanol per tonne of feedstock to the total value of products, energy and recoverable resources generated from the same biomass.

For a distillery, this creates an opportunity to convert suitable residue streams into energy, fuel and additional revenue, while reducing the burden of waste management. The broader objective is to connect the plant's material, energy and resource streams so that one process output can increasingly become the input or value stream for another.



Measuring Total Resource Value

This points to a broader measure of distillery performance. Ethanol yield will remain critical, but the integrated biorefinery must also measure value recovered per tonne of biomass, energy use, co-product realisation, residue utilisation and process-stream management. With sugarcane contributing around 30–35% of India's ethanol requirement and sugar mills typically operating for only 3–5 months a year, feedstock flexibility and asset utilisation will become increasingly important. The goal, however, is not to add every possible technology, but to integrate the right combination of processes for each plant's feedstock, energy, water, infrastructure and market conditions. The distillery of the future can therefore be seen as a resource-conversion platform—one that goes beyond ethanol to extract greater value from the entire biomass system.

Significant Achievers - June'26
Team Human Resources



Lav Sharma



Archana Kumari



Nishita Tyagi



Muskan Verma

Significant Achievers - July'26
TS Team - East



Sayan Bose



ImanKalyan Nag



Prashant Kushwaha



Arnab Gon



Partha Dey

Significant Achievers - August'26
TS Team - UP



Vikram Yadav



Jatin Sharma

New Joinees



Naimish Pandey
QA/ QC
06-Jul-26



Neekita Jain
R&D
09-Jul-26



Niranjan V
Technical Solutions
13-Jul-26



Prashant Kukreti
R&D
14-Jul-26



Himanshu
HPLC
17-Jul-26



Amrita
CRM
12-Aug-26



Prashant Choudhary
HPLC
13-Aug-26



Deepak Singh
Administration
17-Aug-26



Amandeep
QA/QC
19-Aug-26



Sonali Deep
QA/QC
01-Sep-26



Sourabh Sukumar Patil
Technical Solutions
01-Sep-26



Mukul Kumar
Technical Solutions
01-Sep-26

Anniversaries



Ashwini Agrawal
Business Development
15 Years



Kapil Khandelwal
Business Development
15 Years



Ajay Kumar
Accounts
15 Years



Rana Pratap Singh
Business Development
15 Years



Aarati Gulabchand Ram
CRM
5 years



Shubham Rathaur
Business Development
5 Years



Vikas Choudhary
Technical Solutions
5 Years

Events



DSTA, Mumbai

Events






AIDA, New Delhi

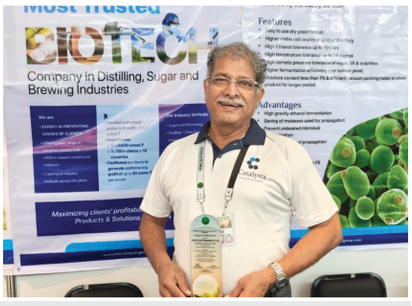






GEMA, New Delhi





PHILSUTECH, Phillipines







SISSTA, Chennai

Events






STAI, Goa






SUGARex Vietnam, Vietnam







SUGARMACH Indonesia, Indonesia






UPDA, New Delhi

Events







Brews & Spirits, Bangalore





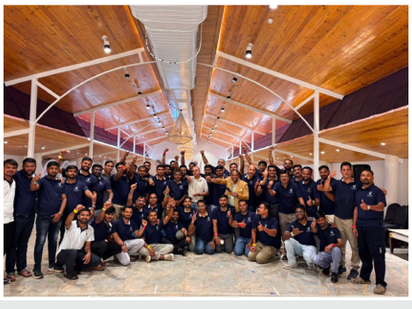
DIY Challenge





Independence Day Celebration







Regional Off Site

Events







Company Off Site







Manager Training

Appreciations

JARANDESHWAR SUGAR MILLS PVT. LTD.

Date- 23/07/206

LETTER OF APPRECIATION

This is to certify that **M/S CATALYSTS BIO TECHNOLOGIES PVT LTD.** has been providing their solutions & technical support to our distillery.

Syrup package solutions from Catalysts have met our expectations. Their package took care of the syrup by controlling the quality of syrup from the mill itself. Dedicated technical person Mr. **Udaysinh Nikam** & his regular guidance & support to our distillery team which is very useful to continue process smoothly and so we achieve production full capacity and visit of senior team from their R&D facility are commendable

With the use of their syrup package, we have observed remarkable results in our syrup/juice fermentation process.

1. Consistent alcohol percentage- 13-13.5% in fermented wash.
2. Consistent productivity- 275 KL production per day.
3. No losses in residual sugars.
4. Very low contamination in syrup and juice with their SOP and solutions.
5. Better fermentation efficiency and yields.
6. Controlled lactic acid contamination in fermentation process.
7. Entire fermentation operations ran on sugar mill condensate water.

We are truly satisfied with their quality products and appreciate their on-site technical support.
We believe that Catalysts Group will keep contributing to our productivity and efficiencies.

We wish them many more success stories.

Authorised Signatory

Distillery Manager
Jarandeshwar Sugar Mills Pvt. Ltd.
Chimangaon,Tal.Koregaon,Dist.Satara

Jarandeshwar Sugar Mills Pvt. Ltd. Chimangaon Tal. Koregaon, Dist. Satara
Reg.No. 15421PN2010 PTC137691 Dt. 20/08/2013

Reg. Office : S.No.15/7 /3. Shop No. 105 &106 Atharva Fariyaz Plaza. Appo. Shankar Maharaj Math. Pune Satara Road, Dhankawadi Pune- 411043.
CIN- U15421PN2010PTC137691 Dt. 20/08/2013
Factory Site : At. Post. Chimangaon. Tal. Koregaon, Dist.Satara. Pin No. 415501 Email - jsmladm@ gmail.com Phone (02163) 236233 /34 /35, 249712 /13 Fax (02163) 236234

Appreciations

कर्मयोगी अंकुशराव टोपे समर्थ सहकारी साखर कारखाना लि.,अंकुशनगर
पो.अंकुशनगर - ४३१ २१२, ता.अंबड, जि.जालना (महाराष्ट्र)
KARMAYOGI ANKUSHRAO TOPE SAMARTH SAHAKARI SAKHAR KARKHANA LTD., ANKUSHNAGAR
Post. Ankushnagar - 431212, Tq. Ambad, Dist. Jalna (Maharashtra)
GSTIN - 27AADAS8482L1ZS, PAN No.AADAS8482L, TAN No. NSKS06848C
Regd. No. JAL/PRG/(A)-1, Date : 10/02/1982, Mob.9623457070, 9623013007
E-mail : samarthsugar@gmail.com, Website: www.samarthsugars.com

Ref.No. Date :-

LETTER OF APPRECIATION **Date: - 23/07/2026**

This is to certify that **M/S CATALYSTS BIO TECHNOLOGIES PVT LTD.** has been providing their solutions & technical support to our distillery **Karmayogi Ankushrao Tope Samarth Sahakari SSK ltd, Ankushnagar. Tq. Ambad, Dist , Jalana. Maharashtra**

Syrup package solutions from Catalysts have met our expectations. Their package took care of the syrup by controlling the quality of syrup. Dedicated technical person **Mr. Shivam Salunkhe**, **Mr. Ajinkya Dagade** and Trainee Executive **Mr. Saurabh Patil** his regularly guidance and support to our distillery team which is very useful to continue process smoothly and so we can achieve production full capacity and visit of senior team from their R&D facility are commendable

With the use of their syrup package, we have observed remarkable results in our syrup fermentation process.

1. *Consistent alcohol percentage*- 12.5-13.0% in fermented wash.
2. *Alcohol Recover* On draw above 14% continuously.
3. *Consistent productivity*- 235 KL production per day both plan.
4. No losses in residual sugars.
5. Very low contamination in syrup and juice with their SOP and solutions.
6. Better fermentation efficiency and yields.
7. Controlled lactic acid contamination in fermentation process.
8. Entire fermentation operations ran on sugar mill condensate water.
9. Spent Wash Recycle In old plant 20% successfully and in new plant 22%.

We are truly satisfied with their quality products and appreciate their on-site technical support.
We believe that Catalysts Group will keep contributing to our productivity and efficiencies.

We wish them many more success stories.

Distillery Incharge

Distillery Incharge
Karmayogi Ankushrao Tope Samarth S.S.K. Ltd.,
Ankushnagar, Tq. Ambad, Dist . Jalna.

Appreciations

The Saswad Mali Sugar Factory Ltd.

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Mob. : 9922993790, 9922993794
E-mail : saswadmali@yahoo.com
saswadmalisugar@gmail.com

Pune Office :
Hotel Central Park,
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Deccan Gymkhana,
Pune - 411 004
Phone : (020) 25531780, 25532891
Mob : 9422531333
E-mail : hotelcentralparkpune@gmail.com

Mumbai Office :
Motlibai Wadia Building,
Ground Floor, Room No. 16,
22-D, S.A. Brelvi Road, Fort,
Mumbai - 400 001
Phone : (022) 22042534

Successfully Moving Towards Centenary

GSTIN : 27AAACT9821D1ZE **CIN : U15424PN1932PLC001904** **Website: www.saswadmalisugar.in**

• Molasses Based Distillery • Grain Based Distillery • Ethanol Plant • Co-generation • Hotel Central Park, Pune

Ref. No. :

Date : 22/07/2026

LETTER OF APPRECIATION

This is to certify that **M/S CATALYSTS BIO TECHNOLOGIES PVT LTD** has been providing their solutions & technical support to our distillery.

Syrup package solutions from Catalysts have met our expectations. Their package took care of the syrup by controlling the quality of syrup from the mill itself. Dedicated technical person **Mr. Udaysinh Nikam** and his regular guidance and support to our distillery team which is very useful to continue process smoothly and so we can achieve production full capacity and visit of senior team from their R&D facility are commendable

With the use of their syrup package we have observed remarkable results in our syrup/juice fermentation process.

1. Consistent alcohol percentage – 13.0 – 13.5 % in fermented wash.
2. Consistent productivity – 45 KL production per day.
3. No losses in residual sugars.
4. Very low Contamination in syrup and juice with their SOP and solutions.
5. Better fermentation efficiency and yields.
6. Controlled lactic acid contamination in fermentation process.
7. Entire fermentation operations ran on sugar mill condensate water.

We are truly satisfied with their quality products and appreciate their on site technical support.

We believe that Catalysts Group will keep contributing to our productivity and efficiencies.

We wish them many more success stories.

For The Saswad Mali Sugar Factory Ltd.

Avinash S. Gaikwad
Distillery Manager

Fermentis by Lesaffre

SafCoffee™ Yeast Strains

Now Available Through

Catalysts

making things happen...

Bringing more control and consistency to coffee fermentation



SafCoffee™ Deep Amber

Developed to provide a complex cup, SafCoffee™ Deep Amber produces strong chocolate notes blended with floral and fruity aromas. This innovative solution also brings a spicy character and long aftertaste to coffee.



SafCoffee™ Sunrise Orange

Selected to enhance fruitiness, SafCoffee™ Sunrise Orange is the ideal choice for a well-balanced cup with mild acidity. This innovative solution enhances passion fruit and tropical fruit aromas, complemented by delicate citrus undertones.



SafCoffee™ Green Origins

SafCoffee™ Green Origins was developed to respect the full expression of coffee's varietal characteristics. This yeast is an excellent choice for producing smooth-bodied coffee with distinct notes of caramel and chocolate.



SafCoffee™ Cool Blue

SafCoffee™ Cool Blue is the solution for producers facing challenging fermentation conditions at high altitudes. Well adapted to temperatures below 10°C, this yeast produces coffee with superb sweetness, hints of vanilla and peanuts, and a long aftertaste.

CATALYSTS GLOBAL PRESENCE



Catalysts
making things happen...

ISO 9001:2015 Certified

THE CATALYSTS GROUP

Catalysts Bio-Technologies Pvt. Ltd. | Naturegen Biotechnologies LLP

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Certifications:

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