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Advancing Rural Development through Innovative biogas optimizations

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***Abstract*—Agriculture remains a pivotal force for employment in India, employing nearly 70% of the rural population. Almost two-thirds of irrigated lands rely on electricity to facilitate pumping groundwater into fields. Consequently, the electrification of rural towns and villages is crucial for the upliftment of the rural populace. Biogas plants, utilizing organic matter to produce methane, are an established technology that holds significant potential for tackling the issue of rural electricitrification.**

This paper addresses the many ways to tailor the operational aspects of biogas plants to suit Indian requirements. Incorporating paddy stubble into biogas production not only facilitates energy generation but also plays a role in mitigating air pollution. Enhancing the efficiency of biogas plants involves the integration of specific additives, pretreatment and bacteria that optimize anaerobic digestion processes, thereby increasing gas production. The residual byproducts derived from biogas generation, rich in nutrients, serve as valuable fertilizer, contributing significantly to the promotion of sustainable agricultural practices. The insights presented in this review highlight the transformative potential of biogas technology, not just in electrifying rural areas, but in fostering an ecologically sustainable agricultural landscape in India.

I. INTRODUCTION

India, often referred to as the land of agriculture, has rich and deep-rooted tradition in farming that can be traced back to over a thousand years. Currently, India is ranked as the second largest producer of rice and the fourth largest producer of wheat in the world. Food grain production has recorded a new high production of 323.55 million tons in 2023 (FSII 2023). Such an increase in production has also come with challenges, the primary challenge being what to do with the stubble leftover post-harvest.

Crop residues or stubble refers to the vegetative part of the plant that is leftover once the grain is harvested. But stubble is not limited to rice and wheat alone. Cotton, sugarcane and other cereal crops also contribute to generating large amounts of agricultural waste residue. Some of this stubble finds use as animal bedding or organic manure. Unfortunately, most don't and are burnt on site. In 2020 - Punjab, 16 tons of stubble was burnt in fields to make room for subsequent planting cycles. This is 80% of the total crop residues generated in Punjab (Pandey, Shailly, and Malhotra 2020).

1.1 Ecological Footprint of Stubble Burning

1.1.1 Air quality

Stubble burning releases a cocktail of air pollutants, including greenhouse gases (GHGs) such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (NOx), as well as carbon monoxide (CO), ammonia (NH3), sulfur dioxide (SO2), volatile organic compounds (VOCs), and particulate matter (PM). The magnitude of emissions is staggering. The annual burning of 15 million tons of paddy residues in Punjab produces an estimated 22 million tons of carbon dioxide, 0.92 million tons of carbon, and 0.03 million tons of sulfur dioxide (Singh et al. 2008). Apart from releasing GHGs and toxic gases, burning also contributes to intense deterioration of air quality by increasing particulate matter (PM). PM in the atmosphere is categorized as PM2.5 and PM10 based on particle size, with PM2.5 referring to fine particles with a diameter less than 2.5µm, and PM10 indicating coarser particles with a diameter less than 10µm. Lighter PM can stay suspended in the air and travel long distances, thus diffusing the detrimental effects to a greater area. The permissible limits for PM2.5 and PM10 are between 60-80µg/m^3. However, according to the Delhi Pollution Control Committee, in 2016 the levels for PM 2.5 and PM10 were about 650 μg/m^3 and 1000μg/m^3 respectively.

1.1.2 Soil quality

The repercussions from stubble burning extend beyond deteriorating air quality. Loss of organic carbon, nitrogen, phosphorus and other micronutrients due to burning leads to gradual reduction in soil fertility. Burning of crop residues in Punjab led to a nearly 100% loss in organic carbon and nitrogen and about a 20-25% loss in phosphorus, calcium and sulfur (Singh et al. 2008). This is dire news it was previously estimated that agricultural soils have lost between 50-66% of historical soil carbon globally (Lal 2004). Soil organic carbon is essential not only to maintaining crop productivity but also helps in retention of soil moisture.

There can be short term benefits to burning crop residues. Burning can kill soil borne pests and pathogens, it also wreaks havoc on the native bacterial and fungal community. Directly burning crop residues on the fields leads to an increase in surface soil temperature leading to loss in bacterial and fungal species richness and alters the microbial members present in the soil. The health of the soil is directly impacted by the living microbial members. These microbes contribute to plant growth and productivity and can also prevent pathogens from spreading. Such dramatic altering of the microbial community can lead to disastrous consequences in the long term.

1.2 Economic consequences of stubble burning.

The impact of stubble burning also hurts economic development across the world. An estimated 5 trillion dollars is lost from the global economy annually (S. Sharma, Khanna, and Ghosh 2019). Open burning results in the loss of about 9 billion tons of carbon and 1.4 billion tons of nitrogen. This translates to nearly 2 billion Indian rupees worth of nutrients [NAS 2017]. Additionally, due to poor visibility and bad air quality leads to the migration of residents out of NCR. Similarly, tourists also do not prefer such conditions. A tourism survey revealed that Delhi had lost about 25-30% of its tourist inflow in 2018 (R. Sharma et al. 2019). Those residents who do stay back in the region face health complications. It is estimated that nearly 35 billion dollars is lost annually managing healthcare due to adverse air quality (Chakrabarti et al. 2019).

II. INNOVATING SUSTAINABILITY: BIOGAS TECHNOLOGY WITH MODERN OPTIMIZATION

Biogas plants use anaerobic digestion (AD) to degrade biomass and produce methane. AD involves a complex sequence of biochemical reactions culminating in the production of biogas, primarily composed of methane, with lesser amounts of carbon dioxide and various trace elements. Depending on the purity of the methane, it can subsequently serve as a versatile fuel for both domestic and industrial purposes.

Historically, in regions like India, biogas plants have predominantly been small-scale operations, primarily catering to local household needs. However, in countries such as Germany, Denmark, and Austria, the landscape of biogas production has evolved into a mature and industrial-level technology. It is estimated that if all the available biomass from crop residues were converted into biogas, a total of 18,000 MW of electricity could be generated. This amount of electricity production accounts for approximately 8% of the country's total electricity demand (Satpathy and Pradhan 2023). It is important to highlight that the majority of biogas production in India originates from small to medium-sized plants designed for household or rural use. India has roughly 5 million small-scale plants (Calero et al. 2023), whereas China has almost 42 million (Giwa et al. 2020). Table 1 summarizes the spread of biogas plants across India's several states. There has been no systematic characterization of all the large-scale industrial biogas plants in India. Finally, the left-over sludge at the end of digestion can also be incorporated as an organic fertilizer, completely closing the loop and thereby improving soil fertility.

Table 1: Distribution of small-scale, domestic biogas plants across the top 4 and bottom 3 states in India.

Year	1990	2002	2007	2010	2012	2022	Percentage increase since 1990
Maharashtra	370662	675177	735196	780527	824203	931313	151.26
Karnataka	65968	340270	396681	418759	445586	512755	677.28
Uttar Pradesh	180806	370219	413052	422269	431631	441180	144.01
Gujrat	92908	351745	387251	411950	420686	435638	368.89
Delhi	578	676	677	679	681	578	0
Dadra & Nagar Haveli	133	169	169	169	169	681	412.03
Chandigarh	77	97	97	97	97	169	119.48
Total	1237390	3369757	3934136	4253561	4545026	5080616	310.59
References	Adapted from (Lohan et al. 2015)					(MNRE 2022)	

While the utilization of crop residues in biogas plants holds considerable promise, its widespread adoption has encountered notable challenges, primarily due to the complex nature of plant biomass. Crop residues consist of complex carbon materials, specifically lignin and cellulose, which pose difficulties in breakdown processes within biogas digesters. Lignin, in particular, forms a rigid structure that inhibits microbial access to cellulose, impeding the breakdown process. Moreover, the production of methane, the primary component of biogas, relies entirely on microbial activity within the anaerobic digester. This process involves a community of microorganisms, including bacteria and archaea, that work synergistically to decompose organic matter and produce methane gas. However, the efficiency of this microbial activity is highly sensitive to various environmental factors. Maintaining optimal conditions within the biogas digester is essential to ensure the efficient functioning of microbial consortia. Factors such as temperature, pH levels, moisture content, and nutrient availability play critical roles in microbial metabolism and methane production. Furthermore, the heterogeneity of crop residues adds another layer of complexity to the digestion process. Variations in biomass composition, particle size, and moisture content can influence the accessibility of substrates to microbial degradation, affecting the overall efficiency of biogas production.

2.1 Optimization to improve efficiency of biogas production.

Methane production through AD can be broken down into 4 major phases: hydrolysis, acidogenesis, acetogenesis/dehydrogenation, and methanogenesis. Hydrolysis is the first step, where complex organic polymers are broken down into monomers. Subsequently, acidogenesis takes place leading to the production of hydrogen, carbon-di-oxide and by products like short-chain fatty acids, ammonia and alcohol. The third phase is acetogenesis, where the short-chain fatty acids are further broken down into hydrogen, carbon-di-oxide and acetate. The final phase is methanogenesis where intermediate compounds produced in previous phases are assimilated and converted into methane and carbon-di-oxide. All the 4 phases are completely mediated through microbial metabolism, with acetogenesis and methanogenesis being closely dependent on each other, as methane producing microbes can feed off the hydrogen and acetate produced by acetogenic microbes. The biggest bottleneck in the entire process is hydrolysis as breaking down complex polymers is a slow process (Figure 1).

There are several pretreatment strategies that can be employed to increase the substrate surface area and availability for microbes. Table 2 summarizes the different commonly used pretreatment strategies. In general, both thermal and chemical based methods show high efficiency. However, these methods are also energetically expensive or rely on large amounts of chemicals, which make biogas production economically expensive. One way to overcome this challenge is by separating the phases into two different reactors, where one reactor can be optimized for microbes involved in hydrolysis and acidogenesis, can operate under wide pH conditions (4-9) (Ma et al. 2019) and another reactor optimized for acetogenesis and methanogenesis which require basic pH conditions (6.5-8.5) (Cioabla et al. 2012). Biological pretreatment can be carried out by either using microbes or the enzymes produced by microbes to breakdown crop residues to improve hydrolysis of crop residues. As mentioned above, lignin is a main component of plant cell walls and is difficult to break down. It is also composed of smaller carbohydrate polymers called cellulose and hemicellulose. All these polymers must be completely broken down for efficient biogas production. Fungi have shown great potential in breaking selectively degrading lignin as they produce lignolytic enzymes. Additionally, enzymes can be used at ambient temperatures and require no energy inputs, making this process economically viable. Unfortunately, it's only recently that studies have begun focusing on the use of enzymes to breakdown crop residues to increase methane production. Koupaie et al., reviewed about forty different enzymes that could be used to breakdown crop residues, leading to an increase in biogas production more than 100% in some cases (Hosseini Koupaie et al. 2019). The most popular enzymes were Cellulase, β-glucosidase and xylanase (Leca et al. 2023). Methaplus® L100, sold by DSM, is one of the most efficient and well referenced products and has been used since 2005 to improve breakdown of crop residues in a biogas plant. This product is made up of a cocktail mix of Xylanase, endo-glucanase, exo-glucanase and β-glucosidase. Application of this product led to a 18% increase in biogas production (Gerhardt, Pelenc, and Bäuml 2007). Similarly, Axiase™, also from DSM, is another product that is encouraged to use in biogas plants making use of crop residues from cereals. Presently, studies are focusing on how the cost of production for enzymes can be lowered. Some strategies involve enzyme recycling and enzyme immobilization. In enzyme recycling, active enzymes are collected by harvesting and reusing insoluble biomass from the previous cycle and adding it to the next cycle of hydrolysis. This results in using lesser amounts of enzymes. In enzyme immobilization, specific enzymes can be immobilized onto a support matrix that can be collected at the end of hydrolysis stage.

Table 2: Summary of different pretreatment strategies

Pretreatment	Method	Process
Physical pretreatment	Mechanical	Makes use of grinders, milling, and graters to reduce the size into smaller particles.
	Extrusion	Makes use of high temperature and pressure to force biomass through narrow openings. This causes intense shearing stress and breaks down biomass into smaller particles.
	Irradiation	Biomass is treated with ultrasound, microwave electron beam of gamma rays. This treatment induces chemical changes in the biomass and breaks down complex polymers.
	Liquid hot water	Water is pressurized and maintained at temperatures ranging from 140°C to 240°C. Under these conditions, the high pressure forces the water into the biomass, effectively breaking it down and enhancing its surface area.
	Steam explosion	Biomass undergoes high-pressure heating with saturated steam for a brief duration, followed by rapid pressure reduction.
Thermochemical pretreatment	Alkali based	The ester bonds of lignin, cellulose and hemicellulose are broken down and dissolved using strong bases like sodium hydroxide or potassium hydroxide.
	Acid based	Instead of bases, acids like nitric acid, phosphoric acid or sulfuric acid can be used to breakdown the biomass.
	Oxidative	Oxidizing agents like hydrogen peroxide or Ozone are used to breakdown the biomass.
Biological pretreatment	Microbial consortia	Different microbes including bacteria and fungi are added to the biomass. This process takes longer than physical and chemical methods but is low energy and environmentally friendly.
	Enzyme based	Instead of using microbes, enzymes derived from these microbes can be added directly to the biomass to break it down.

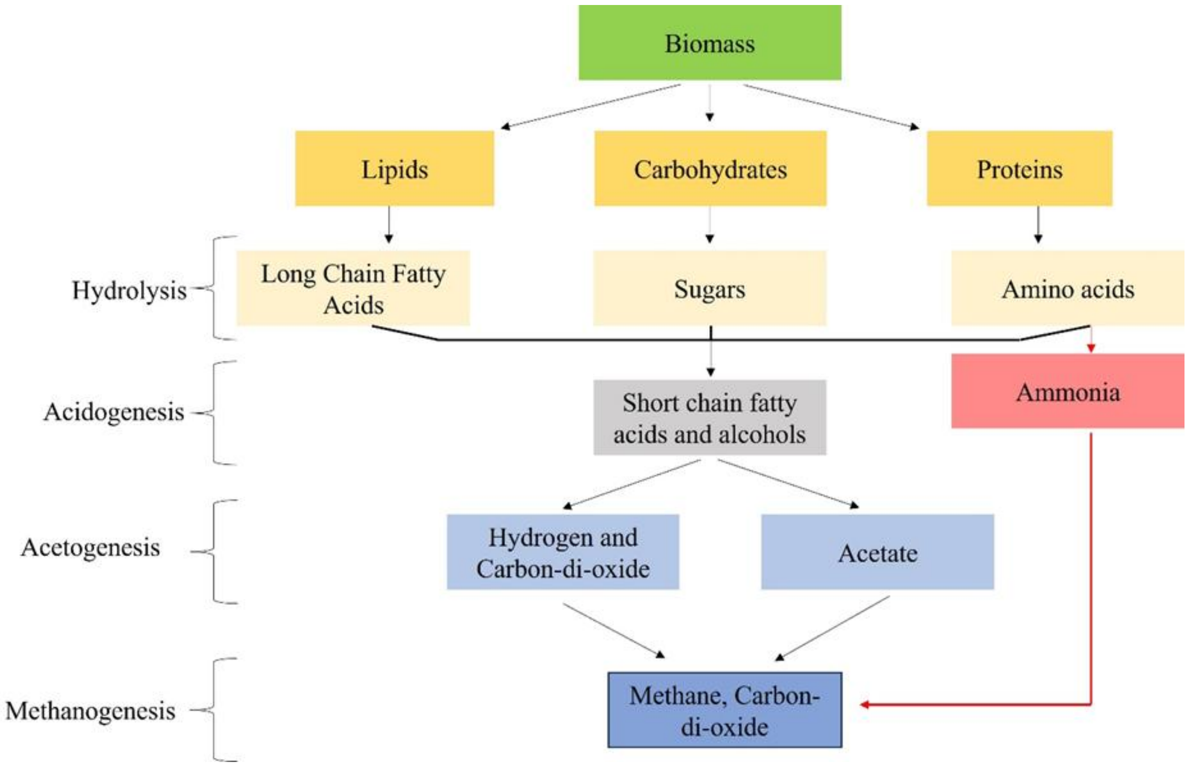

Figure 1: The different stages in AD. High ammonia concentrations can be inhibitory to methane production, and is marked in red. This occurs if the digestor is fed with biomass containing high nitrogen source.

2.2 Co-digestion and additives

The Carbon to Nitrogen ratio is critical for achieving high biogas production. When the substrates utilized have a low C/N ratio, i.e substrates have greater organic nitrogen content, accumulation of ammonia and rising pH levels (8.5 or above) may occur. These circumstances can interfere with methane-producing bacteria, preventing methanogenesis and lowering biogas production. When the C/N ratio is excessively high, i.e substrates have a low organic nitrogen concentration, methanogens may utilize nitrogen more quickly, resulting in nitrogen deficiency. This deficiency may also result in reduced biogas output.

Several studies have explored the utility of mixing animal manure, which is typically rich in nitrogen with crop residues, which tends to be rich in carbon. For example, chicken manure was mixed with Maize crop residue improved methane production by 600%, compared to mono digestion with chicken manure (Feng et al. 2018). Similarly, mixed crop residues amended with cow manure led to a greater than 100% increase in methane production, compared to mono digestion with manure (Comino, Rosso, and Riggio 2010). Finally, wheat straw mixed with sludge leftover from sewage degradation led to an increase in methane production by close to 160% (Potdukhe et al. 2021). All these studies made use of increased carbon loading through amendment of crop residues.

Apart from optimizing C/N ratios, biogas production can also be increased by addition of crucial trace elements. Microelements such as Iron, Boron, Nickel, Calcium, Cobalt, Copper, Selenium, Sulfur and Zinc all play an integral role in maintaining sustained methane production. These micronutrients play many roles in biogas production including improving rate of hydrolysis, promoting enzyme activities (Romero-Güiza et al. 2016), increasing growth of methanogens (Abdallah et al. 2019; Romero-Güiza et al. 2016), increasing methane production (Kaneko et al. 2014; Hansen, Angelidaki, and Ahring 1999) and reducing odor (Choong et al. 2016).

2.3 Role of electrically conductive materials

The conventional model of methane production involves methane-producing microbes utilizing hydrogen and other byproducts such as formate generated by non-methane-producing microbes. However, recent studies propose that hydrogen and formate serve as electron sources, acting as electron donors. An alternative mechanism, known as Direct Interspecies Electron Transfer (DIET), bypasses interspecies hydrogen/formate transfer (Summers et al. 2010). In DIET, electron-donating partners transfer electrons directly to electron-accepting partners through electrical contacts, rather than relying on intermediary soluble electron carriers such as hydrogen and formate. Thus, addition of electrically conductive materials can lead to the increase in efficiency of electron transport and thereby increase methane production. Table 3 describes the different materials that have been tested and their benefits.

Table 3: The advantages and disadvantages of different conductive materials

Material	Advantage	Disadvantage	Results
Activated Carbon	High surface area and electrical conductivity Enrichment of microbes contributing to DIET (Lee, Lee, and Park 2016)	1. Expensive material Difficult to remove from digested sludge. Must be replenished	Methane production increased from 20% (Peng et al. 2018) - 1000% (Dang et al. 2017)
Biochar	1. Low cost and economically favorable Can adsorb heavy metals which can inhibit methane producing microbes. Can promote nutrient retention by adsorbing organic nutrients like phosphate and ammonium (Fagbohungbe et al. 2017) Enrichment of microbes contributing to methane production (Luo et al. 2015)	1. Less electrically conductive compared to activated carbon. Difficult to remove from digested sludge. Must be replenished every day	Increase in methane production (Jang, Choi, and Kan 2018) Decrease in time to produce methane (G. Wang et al. 2018) Can handle higher organic loads (Luo et al. 2015)
Carbon fibers/ cloth	1. Highly conductive Creates a support system to grow microbes	High cost of application	Increase in methane production (Dang et al. 2016)
Magnetite	2. Highly conductive	Is consumed by microbes and needs to be continually replaced	Increase in methane production (C. Wang et al. 2019)

2.4 Use of AI to monitor and optimize biogas production in plants.

As mentioned above, several parameters can constrain or destabilize optimal biogas production. Temperature, pH, C/N ratio, additives added, distribution of different microbes are just among the few. Monitoring all these variables in real time can be exceedingly challenging and cumbersome, if limited to human intervention alone. Automation, with the help of machine learning tools to track and correlate complex non-linear associations between the plethora of variables and stable biogas production. Machine learning was used collected data from the various sensors of within biogas plant and uploaded into a microcontroller and used to optimize biogas production (Sureshkumar and Tamilselvan 2020). Once uploaded, the microcontroller made use of Support Vector Machine algorithm to identify suitable parameters that needed to be modified to improve biogas production. The system decided the amount of water needed to be mixed and temperature to be maintained for optimal production. This led to an increase in biogas production by 15% and increased the operational lifetime of the plant.

III. MUSHROOM CULTIVATION

Mushroom is a protein rich food source, enriched in multivitamins and nutritional components like phosphorus and potassium. Volvariella volvacea is an edible mushroom, commonly known as paddy straw mushroom or straw mushroom. Commercially, these mushrooms can be cultivated directly on rice straw beds. This variety of mushroom also happens to one of the more widely cultivated varieties in the world and accounts for upto 50-60% of the global mushroom production (Ahlawat, Singh, and Kumar 2011). Every kilogram of paddy straw can yield upto 100-150gram of mushroom straw mushroom (Kumar, Kumar, and Joshi 2015). Wheat and rice straw can be utilized as substrate to grow edible mushrooms. Rice straw is a comparatively poor substrate, and to get high productivity, it will be important to mix wheat straw into it (Kaur, Kaur, and Sharma 2019).

The spent mushroom substrate also can be utilized as valuable co-digestion material since raw material is digested by the metabolism of fungi, performing as a pre-treatment, thus facilitating the subsequent anaerobic digestion and increasing the yield of methane production. For every 1kg of mushroom harvested, upto 5 kgs of spent mushroom substrate is generated (Williams, McMullan, and McCahey 2001).

IV IN SITU APPLICATION AS MULCH

Mulching is the even distribution of crop residue across the ground surface. It acts as a protective layer to reduce soil erosion caused by wind and rain, and conserves soil moisture, and discourages weed growth. Mulching using rice straw can provide considerable benefits over non-mulched crops. Mulching with rice straw, for example, has been shown to lower crop water demand by 3 to 11%, increase wheat output, and improve water use efficiency by up to 25% (Gottipati, Burra, and Menon 2021). Mulching also contributes to maintaining a balanced soil temperature as it covers the surface of the soil and is able to keep the soil temperatures low during a hot summer and vice-versa (Kader et al. 2019). This effect is more evident in deserts and arid climate, where mulching can decrease the soil temperature by upto 10 °C (Martin and Poultney 1992).

V. DISCUSSION AND FUTURE PERSPECTIVES

The Government of India's Galvanizing Organic Bio-Agro Resources Dhan (GOBARdhan) initiative stands as a pivotal umbrella effort, embodying a holistic approach across various government sectors. Its primary objective lies in the transformation of animal and agricultural wastes into biogas, thereby championing the principles of a circular economy. GOBARdhan seeks to establish a robust ecosystem conducive to the establishment of Biogas/Compressed Biogas (CBG)/Bio-Compressed Natural Gas (CNG) plants. These facilities are of the utmost importance in assisting India in attaining its ambitious climate action objectives, specifically its aim of achieving net-zero emissions by the year 2070. It integrates initiatives from various ministries and departments, such as the Waste to Energy Scheme spearheaded by the Ministry of New and Renewable Energy and the SATAT (Sustainable Alternative Towards Affordable Transportation) scheme. Initially, SATAT set ambitious goals to establish up to 5000 biogas plants across the country. However, despite these aspirations, the current reality reflects a more modest progress, with only 46 plants operational as of now (Chugh and Goel 2023). Despite this, there is cause for celebration. In 2022, Punjab unveiled Asia' largest biogas plant at Sangrur. Presently, this plant generates 6 metric tons of compressed biogas daily; however, future forecasts suggest that capacity will increase to 33 metric tons per day. Notably, the facility is projected to consume around 100,000 tons of paddy straw that has been procured from eight adjacent villages. Furthermore, an estimated 650 tons of decomposed organic manure are expected to be produced upon completion of the biogas production cycle (Chatterjee 2022). This manure, when applied to agricultural fields, will serve to improve soil fertility. Beyond mitigating stubble burning, the biogas produced can also be utilized for electrification purposes, marking the advent of a new era of sustainable, green energy in India.

The concepts outlined in this review would greatly aid in increasing the effectiveness of future biogas plants. Particularly the use of enzymes and co-digestion with animal manure, conductive additives and amendments with trace metals. It is crucial to emphasize that these strategies are not exclusive to large-scale biogas plants but can also be seamlessly integrated into small and medium-sized digesters prevalent in rural India. By implementing these innovations, biogas facilities can offer a transformative solution to address a pressing environmental challenge: stubble burning. This paradigm shift not only mitigates the adverse impacts of stubble burning on air quality and public health but also unlocks new opportunities for sustainable energy generation, rural livelihood enhancement, and agricultural waste management.

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