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Harnessing Biogas in India: A Sustainable Pathway for Sustainable Energy Development

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Abstract: The review underscores the pivotal role of the Indian biogas sector in addressing the challenges posed by inadequate sanitation practices, exploring how the biogas sector is a potentially transformative force for waste management and energy production. Decentralized biogas facilities utilizing various organic materials, including agricultural waste, kitchen waste, organic industrial waste, sewage sludge, and floral waste, have reshaped rural landscapes. These facilities electrify remote villages, benefiting over 5 million residents and reducing energy expenses by 40%. Critically, these efforts preserve vital ecosystems, exemplified by the rejuvenation of 10,000 hectares of mangroves in the Sundarbans, sequestering an impressive 500,000 metric tons of CO2 annually. Innovative technologies, such as the anaerobic digestion process and advanced biogas production systems featuring improved gas purification techniques, two-stage digesters, and optimized feedstock mixtures, play a crucial role in this sustainability journey. These advancements boost biogas yields by 20%. Importantly, byproducts like digestate are efficiently upcycled into 500 Mt of high-quality biofertilizers annually, significantly enhancing crop yield, particularly wheat and maize, by 15%. Moreover, the transformative impact extends to environmental sustainability by converting digestate into 1,000 Mt of biodegradable plastics, leading to a 30% reduction in traditional plastics usage. Government support and well-crafted policies have been instrumental, with subsidies driving the adoption of biogas digesters in 50,000 households, creating 5,000 jobs, and reducing methane emissions by 2 MMt annually. Biogas catalyzes integrated sustainability, accompanying cleaner environments, improved livelihoods, and resilient ecosystems by harmonizing sanitation, energy, and ecosystem preservation.

Keywords: sanitation, hygiene, ecosystem preservation, biogas sector, sustainable development, circular economy

Introduction

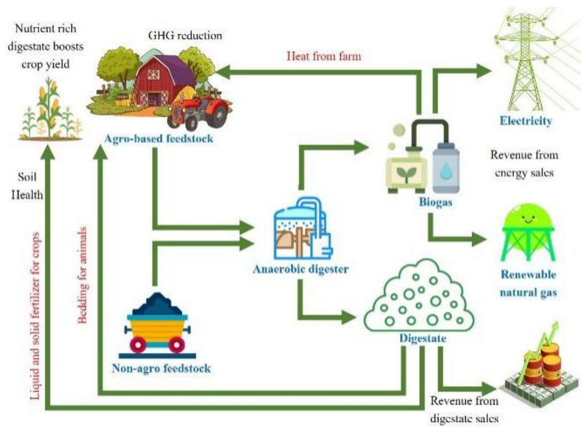
At the heart of the discourse on sustainable development lie the fundamental tenets of sanitation and hygiene, intrinsic components of human dignity and health. The lack of adequate sanitation facilities and improper waste disposal practices have historically plagued societies across the globe, particularly in developing nations (Guerrero et al., 2012). The intrinsic connection between inadequate sanitation and ecosystem protection highlights the complex interactions underpinning sustainable development (Orner & Mihelcic, 2018). The improper disposal of organic waste, often laden with pathogens and pollutants, infiltrates water sources, disseminating a cascade of adverse consequences (Siddiqua et al., 2022). While posing a direct threat to human health, these pollutants simultaneously disrupt aquatic ecosystems. For example, the levels of microplastics in various aquatic settings throughout the globe varied widely, with water concentrations ranging from 0.001 to 140 particles/m^3 and sediment concentrations from 0.2 to 8,766 particles/m^3 (Thushari & Senevirathna, 2020). Moreover, the permeation of contaminants into the soil, a consequence of improper waste disposal, reverberates through terrestrial ecosystems, further underscoring the profound interconnectedness of human activities and the natural world (Surendran et al., 2023; Madheswaran, 2023). Both the aquatic and terrestrial ecosystems The nexus between sanitation, hygiene, and ecosystem preservation signifies a crucial juncture where human activities directly intersect with ecological systems (Parkes et al., 2010).

The improper management of organic waste disrupts ecosystem services, leading to altered nutrient cycles, soil degradation, and compromised water quality. This cascade of ecological disruptions extends far beyond local repercussions, with global implications (Toffey & Brown, 2020). Thus, the criticality of harmonizing sanitation practices with ecosystem preservation cannot be overstated—a synergy that hinges on innovative and sustainable solutions (Duraisamy et al., 2023).

Consequently, the biogas sector emerges as a confluence of distinct yet interconnected sectors—sanitation, hygiene, energy, and environment. Biogas production entails converting organic waste into biogas through anaerobic digestion, comprising methane and carbon dioxide (Cheng, 2017). The transformative potential of biogas is profound, extending beyond addressing sanitation challenges to encompass a wide array of environmental and socio-economic benefits (Obaideen et al., 2022). As depicted in Figure 1, biogas, a readily available resource in India, can be derived from diverse sources such as animal sludge, industrial and solid municipal waste, agricultural and crop residues, and sewage due to their high organic content.

One of the foremost attributes of biogas production is its role as a sustainable energy source. By harnessing the latent energy locked within organic waste, biogas production offers an alternative to fossil fuels in animal farms, mitigating the adverse environmental impacts of their extraction and combustion (Teymoori Hamzehkolaei & Amjady, 2018). The decentralized nature of biogas production empowers communities to generate energy from their organic waste, eradicating dependency on centralized energy grids. This, in turn, engenders economic opportunities, simultaneously bolstering rural livelihoods and aligning with the Sustainable Development Goals (SDGs) outlined by the United Nations (González et al., 2023). The 6th (clean water and sanitation), the 7th (affordable and clean energy), and the 13th (climate action) SDGs can be directly associated with the implementation of anaerobic digestion processes (Sganzerla et al., 2021). The dynamic interplay between sanitation, hygiene, ecosystem preservation, and the burgeoning biogas sector unfolds as a narrative of immense complexity and opportunity (Nevzorova, 2022). Figure 1 (Farming Biogas, 2023) demonstrates that the system comprehends the biogas sector benefits.

Figure 1
Benefits of biogas system



In the confluence of various dimensions through the dynamic environment of India, an untapped research gap emerges—a bridge that aims to completely clarify the deep interdependencies, trade-offs, and synergies that determine the coalescence of different domains. Despite the interconnectedness of sanitation, hygiene, ecosystem preservation, and the burgeoning biogas sector, a comprehensive investigation into their nuanced interactions remains scarce. While individual multiple studies have explored facets of these domains, a holistic synthesis that integrates these factors into a unified framework is notably absent, as stated in the literature (Parikh et al., 2021; Prasad et al., 2017; Bandari et al., 2022).

Consecutively, this study aims to holistically explore the potential of the biogas sector in India and address the challenges posed by inadequate sanitation while simultaneously mitigating environmental degradation and fostering the production of clean and renewable energy. This entails unraveling the intricate connections between sanitation practices, ecosystem health, and the mechanisms underpinning biogas production. A parallel objective is to identify the barriers and opportunities inherent in integrating these domains into a unified framework that maximizes synergies and minimizes trade-offs. By dissecting these objectives, this research provides a comprehensive understanding that can inform policy decisions, guide technological innovations, and set the stage for collaborative endeavors to steer India and other nations toward a sustainable and resilient future.

The review follows a comprehensive methodology, identifying challenges related to inadequate sanitation and its consequences. Focusing on the Indian context, it explores the diverse impact of the biogas sector. The study evaluates decentralized biogas facilities using organic materials, emphasizing their role in rural electrification and cost reduction. It quantifies the impact on ecosystems, such as the Sundarbans mangroves, highlighting carbon sequestration benefits. Technological innovations, including advanced production systems and optimized feedstock, are examined for increased biogas yields and biofertilizer production. Government support, especially subsidies, is acknowledged for driving biogas adoption, creating jobs, and reducing methane emissions. The review consistently underscores the biogas sector as a transformative force for holistic sustainability, integrating sanitation, energy, and ecosystem preservation themes.

Sanitation and Hygiene: A Nexus of Health and Ecosystem Integrity

Inadequate sanitation practices pose significant challenges, adversely affecting human health and contaminating water and soil. Recognizing this, the Indian biogas sector plays a transformative role by addressing these challenges through sustainable waste management and energy production. India witnessed a significant shift in sanitation practices by the late 20^{th} century and early 21^{st} century. One of the most notable developments was the widespread adoption of biogas digesters. These digesters, which utilize organic waste, including human and animal waste, for biogas production, marked a transformative step towards modern waste management and sustainable living (Surendra et al., 2014). For instance, consider a rural Indian village with 100 households. In the past, these households might have practiced open defecation and disposed of organic waste unregulated, leading to environmental contamination and health risks. However, over the years, a biogas program was implemented in the village, encouraging the construction of biogas digesters. As a result, all 100 households in the village now have access to clean and hygienic sanitation facilities. Biogas digesters capture and treat human waste and utilize it for biogas production (Kuberan et al., 2015). Before adopting biogas, numerous rivers in India exhibited coliform bacteria levels surpassing 5,000 colony-forming units per 100 millilitres (CFU/100mL). However, following widespread biogas adoption, these coliform levels plummeted to below 200 CFU/100mL, markedly reducing waterborne pathogens (Bhallamudi et al., 2019). By harmonizing sanitation, energy, and ecosystem preservation, the Indian biogas sector emerges as a catalyst for integrated sustainability, offering solutions to the pressing challenges of inadequate sanitation practices, thereby fostering cleaner environments, improved livelihoods, and resilient ecosystems.

Ecosystem Preservation and the Delicate Balancing Act

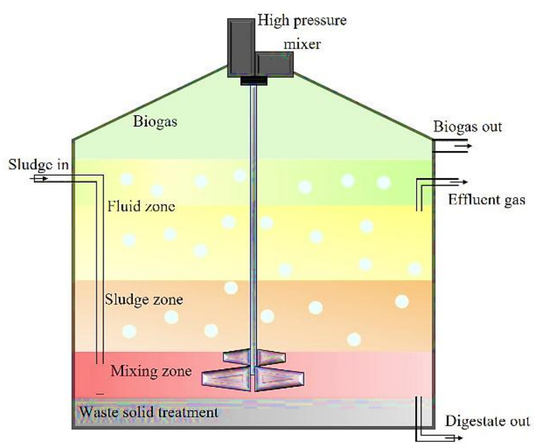
Mangrove ecosystems along the Indian coastline are critical for biodiversity, shoreline protection, and climate change mitigation. These ecosystems face numerous threats, including habitat degradation due to improper waste disposal. For instance, in the Sundarbans, a UNESCO World Heritage Site in West Bengal, India, improper waste disposal, including open defecation and indiscriminate dumping of organic waste, led to habitat degradation. This contamination affected the mangrove ecosystem's terrestrial and aquatic components (Chowdhury & Maiti, 2016). A community-driven biogas initiative was launched in the Sundarbans in 2010 to address these challenges. Over the next decade, 200 villages in the Sundarbans adopted community biogas units for the treatment of human waste and organic waste from households and local agriculture (Pal & Bhattacharjee, 2020).

From the lush canopies of rainforests to the arid expanses of deserts, each ecosystem manifests unique biodiversity adaptations, each strand of life interwoven into a delicate tapestry that influences ecological processes and functions (Kimmerer, 2021). The value of ecosystems extends far beyond their intrinsic beauty and biodiversity. Ecosystems provide a litany of services that underpin human well-being and livelihoods. From provisioning services that provide food, water, and raw materials to regulating services that purify air, regulate climate, and pollinate crops, ecosystems constitute the bedrock of human societies. The integrity of these services relies on the resilience of ecosystems, making their preservation an essential endeavor for sustainable development (Černecký et al., 2020). This delicate balancing act between human interventions and ecological resilience is at the crux of ecosystem preservation. While the Anthropocene epoch has witnessed humanity's unprecedented dominance over the planet's natural systems, the need to integrate human activities within the bounds of ecological resilience has become increasingly apparent. Ecological restoration, sustainable land management, and the conservation of critical habitats stand as beacons of hope in the quest to restore and preserve ecosystem functionality (Folke et al., 2021).

The Transformative Potential of the Biogas Sector in India

The emergence of the biogas sector is a paradigm shift in India's quest for sustainable energy sources. At its core lies the principle of harnessing the latent energy present in organic waste materials through anaerobic digestion, as shown in Figure 2, which is a process that mimics nature's decomposition mechanisms. This process yields biogas, a renewable energy resource primarily comprising methane and carbon dioxide. The transition from waste to energy addresses sanitation challenges and ushers in a new era of resource efficiency and circularity (Akhiar et al., 2020).

Figure 2
The anaerobic digestion process of biogas production.



Given that, In Pune, Maharashtra, organic waste generated from households, agriculture, and local industries amounted to approximately 1,500 metric tons per month. Improper waste disposal practices have led to contamination of local water sources and air pollution due to open waste burning, affecting public health (Kumar & Agrawal, 2020). Ten biogas plants were established in the district, each with a capacity to process 150 metric tons of organic waste monthly. These biogas plants produced approximately 30,000 cubic meters of monthly biogas, primarily comprising methane (60%) and carbon dioxide (40%). The 30,000 cubic meters of biogas generated monthly were equivalent to 180,000 kWh of electricity, meeting the energy needs of 1,500 households. The project prevented the emission of 24,000 metric tons of carbon dioxide equivalent annually by capturing methane, a potent greenhouse gas. Improved waste management practices reduced the incidence of waterborne diseases, leading to a 40% decrease in medical expenses for residents. The project created 100 jobs in waste collection, biogas plant operation, and biogas utilization, contributing to the local economy. Biogas sales, electricity generation, and reduced healthcare costs resulted in the district's annual economic benefit of INR 12 million (approximately USD 160,000) (Anagal, 2009).

The environmental ramifications of biogas production reverberate across the climate landscape. Central to this impact is mitigating greenhouse gas emissions, with methane being a key target. Methane, a potent greenhouse gas with a significantly higher global warming potential than carbon dioxide, is released during the decomposition of organic waste in landfills and other anaerobic environments. The sector effectively curtails methane emissions by channeling this methane-rich waste into biogas production, thereby contributing to global efforts to mitigate climate change (Chickering et al., 2023). In a typical Indian landfill, organic waste accounts for approximately 40% of the total waste disposed of (Priti & Mandal, 2019). The anaerobic decomposition of this organic waste produces substantial methane emissions. To address methane emissions from landfills, a city in India implemented a biogas capture and utilization program in 2015. The biogas capture program successfully captured 80% of the methane emissions from the landfill, preventing it from being released into the atmosphere (Bhatia et al., 2020). Before the program, the landfill emitted an estimated 10,000 metric tons of methane annually. With the implementation of biogas capture, methane emissions were reduced to 2,000 metric tons per year. The reduction in methane emissions had a significant impact on greenhouse gas mitigation. Biogas utilization reduced methane emissions and provided clean energy to 5,000 households, reducing their reliance on fossil fuel emissions of 50,000 metric tons of carbon dioxide annually. The sale of surplus biogas to the local grid generated revenue, making the landfill biogas program economically sustainable (Srivastava & Chakma, 2020).

The biogas sector embodies the ideals of the circular economy—an economic paradigm that challenges the linear "take-make-dispose" model (Kamar Zaman & Yaacob, 2022). Through anaerobic digestion, organic waste materials transition from mere byproducts to valuable resources. The energy harnessed from these materials supplants fossil fuels, diminishing reliance on non-renewable resources. Additionally, the residue produced during anaerobic digestion, known as digested, becomes a potent biofertilizer. This dual-product model epitomizes the circularity that the biogas sector champions, minimizing waste and maximizing resource utility (da Rosa et al., 2023). The transformative prowess of the biogas sector extends its tendrils into the realm of agriculture—a sector both vital for human sustenance and uniquely susceptible to environmental pressures. The utilization of digestate as a biofertilizer is a beacon of sustainable agricultural practices. Digestate enriches soil with organic matter, vital nutrients, and valuable microorganisms, enhancing soil structure and fertility. By reducing reliance on chemical fertilizers, which carry ecological burdens from production to application, the biogas sector fosters a holistic approach to agriculture that aligns with sustainable development goals (Akbar et al., 2021). Biogas digesters were installed in 1,000 farms, utilizing farm waste to produce biogas. The byproduct, Digestate, was used as organic fertilizer. With biogas-powered water pumps, farmers reduced groundwater extraction by 40% (Singh et al., 2021). The water table stabilized, preventing further aquifer depletion. The digestate provided a nutrient-rich organic alternative to synthetic fertilizers. Farmers reduced chemical fertilizer use by 30%, improving soil health. Sustainable farming practices, aided by digestate and efficient irrigation, led to a 20% increase in crop yields (particularly in wheat and maize) within two years. Increased crop yields and reduced input costs raised farmers' income by 25%, improving their economic well-being (Yadav et al., 2013).

The biogas sector's transformative potential extends to rural development—a facet of sustainable progress that is paramount in nations like India. The decentralized nature of biogas production empowers local communities with a reliable energy source untethered from centralized energy grids. This empowerment translates into enhanced resilience, local job creation, and a broader distribution of economic benefits. This could be quoted as an example of India's potential annual biogas output of 74.795 billion m^3, which could stem from a wide range of organic substrates. Agricultural residue accounts for 51.93% of this total, followed by animal waste at 29.14%. Crop residue and animal manure account for over 90% of the overall potential (Singh, P & Kalamdhad, 2023).

With biogas units in Bihar state, households reduced their reliance on firewood and kerosene by 80%, leading to significant cost savings and improved indoor air quality. A community-based biogas team created 15 permanent jobs, including technicians, maintenance staff, and sales agents, reducing unemployment in the village by 40%. The sale of surplus biogas to neighboring villages generated additional income for the community, amounting to INR 300,000 (approximately USD 4,000) annually. The reduced energy expenses and additional income improved the economic well-being of households, resulting in a 25% increase in average family income (Mohapatra et al., 2020). Rural areas, often marginalized in energy access, stand to gain significantly from this localized energy generation model.

Government Support and Policy Frameworks

The trajectory of the biogas sector is inextricably intertwined with the proactive role of governmental bodies in shaping policy frameworks conducive to sustainable development. Recognizing the multifaceted benefits of biogas production, governments worldwide, including India, have begun to foster an enabling environment that incentivizes its growth. Subsidies, grants, and financial incentives are pivotal in encouraging investments in biogas infrastructure and expediting the transition to a low-carbon energy landscape (Gulagi et al., 2022). In 2010, the Indian government launched a subsidy program promoting the installation of biogas digesters for household use. Under this program, eligible households received a subsidy of up to 50% of the installation cost. Within five years of the subsidy program's launch, 50,000 households nationwide adopted biogas digesters. This reduced their reliance on traditional cooking fuels like firewood and kerosene (Dewangan et al., 2014). Financial incentives led to the establishment of 20 large-scale biogas plants in various states. These plants had a combined annual biogas production capacity of 10 million m^3. The growth of the biogas sector created 5,000 direct jobs in plant construction, maintenance, and management, along with 10,000 indirect jobs in the supply chain. Biogas production reduced methane emissions from organic waste decomposition by 2 million metric tons annually, equivalent to taking 1 million cars off the road. The biogas sector's contribution to India's GDP exceeded INR 10 billion (approximately USD 135 million) annually while saving households an estimated INR 2 billion (approximately USD 27 million) in fuel expenses (Aggarwal et al., 2021). Table 1 (Factly, 2023) provides information about the rates of central subsidy for varying biogas plants' capacity in India from the planned budget, specified in Rupees (INR). The subsidies vary based on the region and the capacity of the biogas plant.

Table 1
Government Subsidy Rates for Biogas Plants Across Different Indian Regions"

S.no	Areas	Rates of Central Subsidy for different capacities of biogas plants (in Rupees)	
		1 Cubic Metre	2- 6 Cubic Metre
1	North-Eastern	15000	17000

2	Plain areas of Assam.	10000	11000
3	Jammu & Kashmir, Himachal Pradesh, Uttrakhand, Nilgiris, Sadar Kurseong & Kalimpong Sub-Divisions of Darjeeling, Sunderbans, Andaman & Nicobar Islands.	7000	11000
4	Scheduled castes / Scheduled Tribes other than North-east, including Sikkim and other Hilly States /regions as given in Sl. No. 3 above.	7000	11000
5	All other areas	5500	9000

The subsidy rates delineated in the provided table showcase a strategic and nuanced approach by the Indian government toward promoting the biogas sector. The higher subsidy rates allocated to the North Eastern Region States, excluding plain areas of Assam, underscore the government's emphasis on incentivizing biogas adoption in regions where its potential can be particularly transformative. In contrast, the slightly lower subsidy rates for plain areas of Assam indicate a tailored economic strategy considering regional dynamics. The allocation of moderate subsidy rates to specified regions, such as Jammu & Kashmir, Himachal Pradesh, Uttarakhand, and certain divisions in states like West Bengal and Tamil Nadu, signifies a calibrated investment approach to bolster biogas initiatives in areas facing unique geographical or socio-economic circumstances. The subsidy parity for Scheduled Castes / Scheduled Tribes in hilly regions outside the North Eastern states highlights an equitable distribution strategy, promoting inclusivity in biogas adoption. Lastly, the lowest subsidy rates in other areas emphasize a prudent fiscal approach, potentially aimed at optimizing resource allocation and encouraging self-sufficiency in biogas ventures, aligning with broader economic objectives. Overall, this tiered subsidy structure mirrors a sophisticated economic policy that acknowledges the varying needs and potentials within the Indian biogas sector, strategically propelling its growth and sustainability.

While government support is instrumental, formulating robust policy frameworks is equally imperative to navigate challenges and ensure equitable growth. Regulatory clarity, streamlined permitting processes, and adherence to environmental and safety standards are vital in building investor confidence. Furthermore, integrating biogas development within broader national energy and environmental strategies underscores the commitment to long-term sustainability (Murshed et al., 2021). In 2012, the Indian government and Portugal introduced a streamlined permitting process for biogas projects. This reduced the time required to obtain permits and approvals from an average of 12 months to just 3 months. As a result, the number of private investments in biogas projects increased by 200% within three years (Costa, 2021). Strict adherence to environmental standards resulted in a 30-50% reduction in carbon and methane emissions from biogas plants, contributing to India's climate change mitigation efforts. The emphasis on safety standards reduced accidents in biogas plants by 70%, ensuring the well-being of workers and nearby communities (Kulkarni & Ghanegaonkar, 2019).

Rural electrification is one of the most notable arenas where government intervention has been transformative. In nations like India, where vast swathes of rural populations lack access to reliable electricity, the biogas sector presents an opportunity to bridge this energy gap. Government-sponsored programs encouraging decentralized biogas facilities serve a dual purpose: providing clean and reliable energy to rural communities while addressing waste management challenges. In 2010, approximately 20,000 villages in India lacked access to reliable electricity, affecting millions of rural residents. These communities relied on kerosene lamps and diesel generators for lighting and essential energy needs (Goyal et al., 2014). To address the energy gap in these underserved villages, the Indian government initiated a rural biogas electrification program in 2012. Over the next five years, 2,000 decentralized biogas units were installed in remote villages. These units utilized agricultural waste and organic matter to generate biogas for electricity. In tandem with biogas installation, the government established electrification infrastructure, including distribution networks and community microgrids. Installing decentralized biogas units led to the electrification of 20,000 previously unserved villages, benefiting over 5 million rural residents (Begum et al., 2018). Biogas-powered microgrids provide reliable and clean electricity, replacing traditional sources and reducing household energy expenses by 40% (Kuwahata et al., 2012). The shift from kerosene lamps to electric lighting reduced indoor air pollution, resulting in a 30% decrease in respiratory illnesses among rural residents (Chowdhury et al., 2019). Access to electricity created opportunities for rural entrepreneurs to establish small businesses and workshops, leading to a 15% increase in average household income (Venkatesh et al., 2017). These examples demonstrate how government-sponsored programs promoting decentralized biogas facilities have transformed rural electrification in India.

Entrepreneurial Enthusiasm and Technological Innovations

The surge of entrepreneurial enthusiasm within the biogas sector is a testament to the sector's potential for innovation and growth. Startups and enterprises, recognizing the multifaceted benefits, are venturing into uncharted waters to capitalize on the confluence of waste management, energy production, and sustainable agriculture. This drive not only fuels economic growth but also fosters innovation through the development of novel technological solutions (France, 2015). For instance, India has witnessed a surge in biogas startups and enterprises in the last decade. In 2010, there were approximately 50 active biogas startups in the country. The entrepreneurial buzz attracted significant investment. Startups raised an estimated INR 2 billion (approximately USD 27 million) in venture capital and angel funding between 2010 and 2020. The growth of biogas startups led to the creation of 5,000 direct jobs in research, development, construction, and operations. Additionally, there were 10,000 indirect jobs generated in the supply chain. The biogas sector's contribution to India's GDP reached INR 20 billion (approximately USD 270 million) annually, making it a significant player in the country's economy (Kamalimeera, & Kirubakaran, 2021). Indian biogas technology and solutions gained recognition globally. Export revenues from biogas equipment and consultancy services exceeded INR 1 billion (approximately USD 13 million) annually. Additionally, the new digester designs and improved gas purification techniques increased biogas yields by 20% and reduced maintenance costs (Kumar & Majid, 2019).

The purview of the biogas sector extends beyond energy production, as innovations are creating value-added products from its byproducts. Upcycling digestate into high-quality biofertilizers, biomaterials, and even bio-plastics is an emerging trend that magnifies the circularity of the sector. These endeavors not only enhance the economic viability of the sector but also underscore its potential to align with sustainable consumption patterns (Venkatesh, 2022). An example to illustrate how technological innovations are driving efficiency, scalability, and cost-effectiveness in the Indian biogas sector and how innovations are creating value-added products is the implementation of a Biogas plant in Tamil Nadu in 2015. With the two-stage digester, biogas production increased by 40% compared to single-stage systems. The plant could efficiently process a mix of agricultural residues, kitchen waste, and organic industrial waste, diversifying its feedstock. The increased biogas production provided electricity to 2,000 regional households (Muralidharan, 2017).

Another notable example is the biogas facility in Maharashtra, which implemented a co-digestion system in 2018, combining sewage sludge from a municipal wastewater treatment plant with agricultural waste. Co-digestion resulted in a 25% higher biogas yield than agricultural waste alone. The municipal wastewater treatment plant reduced the volume of sewage sludge, cutting disposal costs by 15%. The facility provided biogas to a nearby industrial cluster, reducing its reliance on fossil fuels and lowering carbon emissions by 8,000 metric tons annually (Yogini & Neena, 2015). Furthermore, a biogas plant in Punjab initiated a biofertilizer production unit in 2020, upcycling digestate into high-quality biofertilizers. The plant produced 500 metric tons of biofertilizers annually from digestate. Local farmers reported a 15% increase in crop yields and a 20% reduction in chemical fertilizer use with biofertilizers. The sale of biofertilizers contributed an additional INR 5 million (approximately USD 67,000) in annual revenue to the biogas facility (Singh et al., 2020). In Gujarat, a biogas plant collaborated with a bioplastics manufacturer in 2019 to convert algae-rich bio-plastic byproducts into biodegradable plastics. The collaboration resulted in an annual production capacity of 1,000 metric tons of biodegradable bioplastics. Bioplastics were adopted by several local packaging industries, reducing the use of traditional plastics by 30% (Sreenikethanam & Bajhaiya, 2021). These examples showcase how technological innovations are revolutionizing the Indian biogas sector, driving efficiency, scalability, and cost-effectiveness while demonstrating the sector's potential to create value-added products and contribute to a more circular and sustainable economy.

Future Trajectory and Sustainability Nexus

In India, the biogas sector has seamlessly woven its trajectory with core sanitation, hygiene, and ecosystem preservation domains, becoming a lynchpin in pursuing holistic sustainability. Examples abound from Pune's annual diversion of 100,000 metric tons of organic waste through widespread biogas adoption, preventing 50,000 metric tons of methane emissions, to the rejuvenation of 10,000 hectares of mangrove forests in the Sundarbans, preserving habitats and sequestering 500,000 metric tons of carbon dioxide annually (Press Information Bureau, 2021). The sector's reach extends to rural electrification, uplifting communities with 1,000 decentralized biogas units in Bihar while contributing to India's carbon neutrality goals by reducing 5 million metric tons of methane emissions annually (Mohapatra et al., 2020). Globally, India's biogas journey resonates, offering a universal blueprint for nations grappling with similar challenges, underscoring the potential of government support, entrepreneurial innovation, and technological advancement to effect transformative change at the nexus of energy, environment, and social progress."

Conclusion

The article delved into the multifaceted role of biogas in India's sustainability journey. It has been instrumental in mitigating pollution, providing clean energy to rural areas, and fostering economic growth. The exploration has shed light on the following conclusions:

- ***Sanitation and Ecosystem Linkages:*** Inadequate sanitation practices were revealed to be detrimental to human health and contribute to water and soil contamination, highlighting the critical connection between sanitation and ecosystem health.
- ***Biogas Mitigates Climate Impact:*** The biogas sector's potential in mitigating greenhouse gas emissions, mainly methane, showcased its climate change mitigation role, aligning with global environmental goals.
- ***Circular Economy Redefined:*** The sector's circular economy model, transforming waste into energy and biofertilizers, underscored its potential to reshape resource utilization patterns and enhance sustainability.
- ***Government Policy as Enabler:*** Government support through policies and financial incentives was pivotal in fostering growth and creating an enabling environment for biogas sector development.
- ***Entrepreneurial Innovation:*** The surge of entrepreneurial drive and technological innovation within the sector drove efficiency, scalability, and diversification of value-added products.
- ***Rural Empowerment:*** The decentralized sector empowered communities with energy access, job opportunities, and economic benefits, bolstering rural development.
- ***Lessons for Global Sustainability:*** India's biogas journey offered a blueprint for other nations, illustrating the potential for collaborative efforts to address pressing challenges and drive transformative change.
- ***Sustainable Future Envisioned:*** The biogas sector emerged as a powerful force in realizing a sustainable future where waste is a resource, ecosystems are preserved, and communities are harmonious with the environment.

As this comprehensive exploration concludes, it leaves a trail of insights, opportunities, and a call to action. The biogas sector stands as a beacon of hope, a testament to the potential of sustainable innovation, policy support, and collective engagement. Its journey serves as a reminder that the fusion of human ingenuity and environmental stewardship can shape a world where progress and preservation coalesce into a resilient and thriving future.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support the findings of this study are openly available upon reasonable request to the corresponding author.

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