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Green Energy Concept for Uttarakhand: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Biogas technology, which utilizes the anaerobic digestion of organic matter to produce methane and carbon dioxide, has gained traction as a sustainable solution for energy needs, waste management, and environmental protection. This review explores the feasibility, implementation, and benefits of biogas technology in hilly regions, where unique geographical and climatic conditions present both opportunities and challenges. The paper discusses types of feedstock, biogas plant designs, socio-economic impacts, and policy frameworks pertinent to hilly areas, supplemented by case studies from various regions worldwide. Through a comprehensive analysis, this review aims to provide insights into the potential of biogas technology to contribute to sustainable development in hilly terrains. Biogas, in its raw form, that is without any purification can be used as clean cooking fuel like LPG, lighting, motive power and generation of electricity. It can be used in diesel engines to substitute diesel up to 80% and up to 100% replacement of diesel by using 100% Biogas Engines. Further, Biogas can be purified and upgraded up to 98% purity of methane content to make it suitable to be used as a green and clean fuel for transportation or filling in cylinders at high pressure of 250 bar or so and called as Compressed Bio-Gas (CBG).

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1. INTRODUCTION

In recent decades, biogas technology has emerged as a transformative solution in both rural and urban settings, particularly in regions like Uttarakhand, India. Uttarakhand, known for its diverse terrain ranging from the Himalayan foothills to the fertile plains, faces unique challenges in energy access and environmental sustainability [1]. The adoption of biogas technology in this region represents a promising advancement towards addressing these challenges while promoting socio-economic development. Biogas technology involves the anaerobic digestion of organic matter such as agricultural residues, animal dung, and kitchen waste to produce methane-rich gas [2]. This renewable energy source not only provides a clean and sustainable alternative to traditional fuels but also offers various environmental and economic benefits. In Uttarakhand, where agriculture forms the backbone of the economy and rural livelihoods, biogas technology plays a crucial role in converting organic waste into energy, thereby reducing dependence on conventional energy sources and mitigating environmental degradation [3,4-6].

2. ENERGY SECURITY AND RURAL DEVELOPMENT

In rural Uttarakhand, where access to electricity and clean cooking fuels remains limited, biogas technology has significantly improved energy security and household incomes. By utilizing locally available biomass resources, predominantly agricultural residues and animal dung, rural households can generate biogas for cooking and lighting [7]. This not only reduces the reliance on firewood and fossil fuels but also alleviates the drudgery of fuel collection, predominantly borne by women and children in traditional households.

Moreover, the installation of biogas plants has created opportunities for rural entrepreneurship and employment [8-10]. Local technicians are trained in plant installation, maintenance, and repair, fostering a self-sustaining ecosystem of biogas production within communities. This decentralized approach not only enhances energy access but also empowers rural populations economically, contributing to overall rural development and poverty alleviation [11-14].

2.1 Environmental Sustainability

In urban areas of Uttarakhand, particularly in rapidly growing towns and cities, biogas technology offers a sustainable waste management solution. Urban centers generate substantial amounts of organic waste, including food scraps and sewage, which if left untreated, contribute to pollution and public health hazards. Biogas plants installed in urban settings facilitate the efficient disposal of organic waste while producing biogas and organic fertilizer as valuable by-products [2].

The utilization of biogas as a cooking fuel in urban households reduces indoor air pollution, a significant health concern in densely populated areas. Furthermore, the use of biogas displaces fossil fuels, thereby lowering greenhouse gas emissions and contributing to climate change mitigation efforts at the local level [3].

2.2 Government Initiatives and Policy Support

Recognizing the multifaceted benefits of biogas technology, both the central and state governments in India have implemented various policies and initiatives to promote its adoption. Subsidies and financial incentives are provided to rural households and institutions for the installation of biogas plants, making the technology more accessible and affordable [1]. In Uttarakhand, specific schemes such as the Chief Minister's Solar and Biogas Energy Scheme underscore the government's commitment to expanding renewable energy infrastructure and enhancing energy security in rural areas [15].

2.3 Scope and Objectives of the Paper

By analyzing case studies, statistical data, and policy frameworks, this paper will examine how biogas technology has contributed to sustainable development, energy security, and environmental preservation in the region. It will also highlight opportunities and challenges for further expansion and integration of biogas technology into Uttarakhand's energy landscape. This paper aims to investigate the evolution, impact, and future potential of biogas technology in rural and urban Uttarakhand.

3. TYPES OF FEEDSTOCK AVAILABLE IN UTTARAKHAND

3.1 Agricultural Residues

Agriculture residue, comprising crop residues such as wheat straw, rice husk, and maize stalks, plays a pivotal role in biogas production in Uttarakhand. As an agrarian state, Uttarakhand generates substantial quantities of agricultural waste, which, if managed effectively, can serve as a valuable feedstock for biogas production. This process not only addresses the challenge of waste management but also contributes significantly to renewable energy generation and environmental sustainability.

3.2 Animal Waste

Livestock activity assumes special significance in hilly states like Uttarakhand. Over 80% of the all livestock species and cent per cent of indigenous poultry population are owned by marginal and small holders. Total livestock population in Uttarakhand increased @0.28% per annum during 1993–2003. Bovine population increased from 63% in 1993 to 66.5% in 2003, while during the same period, the share of ovine population declined from 32% per cent to 28% [16]. Livestock farming is prevalent in many hilly areas. Animal waste, particularly from cattle, buffalo, and poultry, serves as a significant feedstock for biogas production in Uttarakhand. Uttarakhand's rural economy is heavily reliant on livestock farming, with a substantial population of cattle and buffaloes [17-20]. The waste produced from these animals, including dung and urine, along with poultry droppings, constitutes a valuable feedstock for biogas production [2]. These organic materials are rich in organic matter and nutrients, making them ideal substrates for anaerobic digestion—the biological process through which biogas is generated. Animal waste is a rich source of organic matter and nutrients, making it an ideal feedstock for biogas production. Utilizing manure not only generates biogas but also reduces greenhouse gas emissions from untreated animal waste.

3.3 Forestry Waste

Hilly regions typically have significant forest cover. Forestry waste, including leaves, twigs, and wood chips, can be utilized as feedstock, contributing to forest management and reducing the risk of forest fires. Effective utilization of this waste in biogas production promotes sustainable forest management practices [21,22]. The utilization of forestry residue for bioenergy production offers several economic and environmental benefits in Uttarakhand. Economically, it provides additional income opportunities for forest-dependent communities through sustainable harvesting and collection of residue biomass [3]. Moreover, bioenergy projects utilizing forestry residue can stimulate local economies by creating jobs in biomass collection, transportation, and plant operation. Environmentally, the sustainable management of forestry residue helps in reducing forest fire hazards and promotes forest health by removing excess biomass that could otherwise contribute to wildfires. Furthermore, utilizing forestry residue for bioenergy reduces greenhouse gas emissions by displacing fossil fuels, thereby contributing to climate change mitigation efforts at both local and global scales [23,24].

3.4 Municipal Solid Waste

The rapid urbanization has led to increased waste generation. MSW, comprising household waste, commercial waste, and institutional waste, can serve as a valuable feedstock for biogas production. In many hilly regions, organic municipal waste, including food waste and green waste, is abundant and often improperly managed. The utilization of MSW for biogas production offers significant economic and environmental benefits in urban areas of Uttarakhand. Economically, it provides a decentralized source of renewable energy, reducing dependency on fossil fuels and mitigating energy costs for municipalities [3,25,26]. Biogas plants utilizing MSW also create opportunities for waste-to-energy projects, generating revenue through the sale of biogas or electricity to the grid. Biogas technology provides a means to efficiently process this waste, reducing landfill burden and producing valuable energy.

4. BIOGAS PLANT DESIGNS

4.1 Fixed-Dome Digesters

In Uttarakhand, the implementation of fixed dome biodigesters has emerged as a pivotal strategy for sustainable waste management and energy production, particularly in rural areas where conventional energy sources are scarce. These biodigesters utilize organic waste, predominantly from livestock such as cow dung, to generate biogas, which serves as a renewable energy source for cooking, lighting, and heating purposes. Fixed-dome digesters are commonly used in developing countries due to their simple design and low construction costs. These digesters are buried underground, making them suitable for hilly regions where land space may be limited. Their robust structure can withstand varied climatic conditions prevalent in hilly areas, ensuring durability and long-term functionality. The cow dung producing livestock in Uttarakhand is approximately 32 lac numbers[27,28,29]. 25kg cow dung is required for generation of 1m³ Biogas. Approximate quantity of cow dung is 16 lac kg which can be used for producing 640000 cum biogas generation. There are about 4356 Family Size Biogas plants has been installed in various districts of Uttarakhand till date (UREDA,2024)

4.2 Floating-Dome Digesters

Floating-dome digesters feature a gas holder that floats on the slurry, offering the advantage of easy gas collection and pressure regulation. These digesters are relatively easy to maintain and can be adapted for smaller-scale applications in hilly terrains. The floating dome design also allows for visual inspection and easy cleaning, enhancing operational efficiency. The National Bioenergy Programme will comprise of the following sub-schemes before FY(2025-26) [1].

1. Waste to Energy Programme (Programme on Energy from Urban, Industrial and Agricultural Wastes /Residues)
2. Biomass Programme (Scheme to Support Manufacturing ofBriquettes & Pellets and Promotion of Biomass (non-bagasse) based cogeneration in Industries)
3. Biogas Programme

4.3 Balloon Digesters

Balloon digesters are flexible, portable, and relatively inexpensive. Made from durable plastic or rubber materials, they are suitable for remote and inaccessible areas. Their lightweight nature facilitates transportation and installation even in challenging hilly terrains. Balloon digesters can be quickly set up and relocated, making them ideal for temporary or seasonal use.

4.4 Plug-Flow Digesters

Plug-flow digesters, characterized by a horizontal design where the substrate moves in a plug-flow manner, are suitable for managing fibrous materials such as crop residues and animal manure. These digesters are efficient in biogas production and can be adapted to hilly regions with adequate planning and site selection. Plug flow digesters are primarily used at dairy operations that collect manure by scraping. Mixed plug flow systems have been used at a wider variety of operations because they can tolerate a broader range of solids concentrations.

4.5 Hybrid Systems

Hybrid systems that combine elements of different digester designs offer enhanced flexibility and efficiency. For instance, a combination of fixed-dome and plug-flow designs can optimize the digestion process for varied feedstock types [30]. Hybrid systems can be tailored to specific conditions of hilly regions, maximizing biogas yield and operational efficiency.

4.6 Biogas as a Fuel

Methane (CH_4), carbon dioxide (CO_2), and trace amounts of moisture and hydrogen sulfide (H_2S) make up biogas. The concentration of CH4 in biogas accounts for the majority of its heating value; the presence of other gasses reduces this value and restricts its application. The presence of CO_2 in car fuel is undesirable as it affects engine output and takes up extra space. CO_2 can be eliminated by a variety of techniques, some of which include scrubbing with water or sodium hydroxide. When H_2S in biogas reacts with moisture, sulfuric acid is created. Because sulfuric acid is a very corrosive gas, it can erode metal components such as engine parts, compressors, and burner pipes. Common techniques for eliminating hydrogen sulfide include chemical absorption with an iron sponge, water washing, and iron-based precipitation. When raw biogas is burned, sulfur dioxide (SO_2) is produced, which dissolves in motor oil and reduces the oil's lubricating properties. The biogas produces sulfuric acid, which corrodes the metallic component, by condensing the moisture present and reacting with the SO_2[31,32]. The common methods for removing moisture are adsorption on silica gel, absorption in glycol, or condensate portion removal and passive gas cooling [33]. Biogas must be sent to an upgrading (purification) facility to raise its methane content to over 95% in order to be used as a transportation fuel. Absorption, adsorption, membrane separation, cryogenic, and biological are examples of common upgrading techniques. Every approach has a very different methane slip [34].

5. CASE STUDY UTTARAKHAND

5.1 Uttarakhand

The state has benefited from a number of favorable factors, such as: (i) strong economic growth and per capita income; (ii) strong social and human development indicators (such as sex ratio and educational attainment); (iii) low poverty, at just 11% in 2011–12 with minimal rural–urban disparity; (iv) lack of severe hunger issues; and (v) the state's general peacefulness. Nonetheless, the state's alarmingly low child-to-sex ratio is one cause for concern. Uttarakhand experienced significant growth during this period as it was established as an independent state after being split from Uttar Pradesh. From 2002 to 2010, the growth rates of biogas plants in these states were 26.66%, 4.05%, 53.15%, 0%, 579.25%, 22.47%, 0.44%, and 14.05%, respectively, with an average growth rate of 87.5% for all states [35]. Uttarakhand witnessed the highest annual growth rate of 1831.93% during this period, mainly due to the establishment of biogas plants in the state. (Meena *et al*,2023).

Poverty: At 11.26% in 2011–12, Uttarakhand's poverty rate is low compared to the country as a whole, which was 21.92% that year. There is also minimal poverty inequality between rural and urban areas.

Education: Good access to education is available, particularly for primary education. At the primary level, the Net Enrollment Ratio (NER) is 89.18%, while at the upper primary level, it is 71%. The percentage of students who complete their education is 100% in elementary school and 96.76% in upper primary school. At the secondary level, NER is substantially lower—just 51.28 percent [36].

With its mostly hilly and mountainous landscape, Uttarakhand has effectively applied biogas technology on a significant scale. More than 300,000 biogas units have been developed nationwide under the Biogas Support Program (BSP), mostly using agricultural leftovers and animal manure. These plants offer a dependable energy source for rural homes while also drastically reducing indoor air pollution and deforestation. Many different designs of biogas digesters are available both in small and large scale operations throughout the world.

i) Health: Owing to the following, biogas plants have been implemented in Nepal with positive health outcomes: lower levels of smoke exposure indoors, fewer acute respiratory infections among the population of all ages, lower infant mortality rates, fewer eye conditions, and lower indoor concentrations of formaldehyde, carbon monoxide, and suspended particles.

ii) Hygiene: Unmanaged human excreta and wastewater are significant issues in rural Nepal since there are no facilities for collecting and treating wastewater. Communicable illnesses diseases like cholera, TB, and diarrhea are frequent occurrences in rural settings. On the other hand, the state of hygiene has improved with the usage of biogas digesters. An estimated 77,000 rural Nepalese households already have toilets connected to biogas generators.

iii) Gender benefits: Women and female children who participate in the firewood collection process have been able to cut down on the three hours a day that they previously spent doing so. Based on the construction of 111,000 biogas plants around the nation, this equates to a savings of over 35,000 woman hours annually. Biogas burning has also resulted in a reduction in the amount of water and time needed to wash cooking utensils because it is not linked to the accumulation of soot particles on their surface.

5.2 India

In the Indian state of Himachal Pradesh, biogas technology has been promoted to manage agricultural waste and reduce reliance on firewood. The implementation of fixed-dome digesters in this hilly region has demonstrated positive impacts on energy access and environmental conservation. Community-based biogas projects have empowered local populations, improved health conditions by reducing indoor air pollution, and provided valuable organic fertilizer for agriculture. Biogas will help cut dependence on imported fossil fuels and support the rural economy by creating local employment opportunities.

The biogas sector in India is undergoing significant development and transformation, driven by government initiatives, technological advancements, and increasing private sector involvement.

5.3 Government Initiatives and Policies

The Indian government has launched several schemes to support the biogas industry. The PM-

PRANAM scheme, for example, promotes the use of organic fertilizers and has allocated significant funds to support biogas production across the value chain, from feedstock procurement to marketing the end products. Additionally, the government has mandated the blending of compressed biogas (CBG) in city gas distribution pipelines starting in 2025, which is expected to boost the uptake of biogas as a clean fuel [27].

The Sustainable Alternative Towards Affordable Transport (SATAT) scheme aims to set up 5,000 CBG plants to provide cleaner and more affordable transport fuel. However, the scheme's progress has been hindered by issues such as the lack of guaranteed offtake and challenges in feedstock collection and processing.

5.4 Technological and Financial Developments

Technological advancements are crucial for the biogas sector's growth. Companies like Reliance and Adani are investing heavily in CBG technology, and partnerships between Indian and international firms are facilitating technology transfer and improving feedstock processing methods. Financial support is also growing, with both public and private investments increasing. For instance, Reliance Industries plans to develop 100 CBG plants by 2030, and other large-scale projects are in the pipeline with support from public-private partnerships.

5.5 Private Sector Involvement

Private sector participation is expanding, with companies like Biofuels Junction and SAAF Energy focusing on enhancing the supply chain for biogas production. These companies are addressing supply chain issues by ensuring consistent feedstock supply, which is critical for the viability of biogas plants. Venture funding and private equity investments are also becoming more accessible, encouraging further development in the sector.

5.6 Challenges and Future Prospects

Despite these positive developments, the biogas sector in India faces several challenges, including the high cost of feedstock, non-segregation of municipal solid waste, and the distributed nature of feedstock sources. Addressing these issues requires technological innovation, financial support, and strong partnerships between government bodies and private companies.

The future of biogas in India looks promising, with increased policy clarity, financial incentives, and technological advancements paving the way for growth. The government's support for market development and private sector investments will be crucial in overcoming existing challenges and realizing the full potential of biogas as a sustainable energy source

6. CHALLENGES IN IMPLEMENTING BIOGAS IN UNDEVELOPED NATIONS

Several studies claim that a number of technological obstacles prevent the construction of biogas facilities in developing nations. Among these are householders' lack of knowledge and training, which results in subpar inadequate understanding of feedstock compatibility and upkeep of biogas digesters [37]. Biogas generation can be hampered by inadequate waste collection, improper garbage disposal, and broken supply chains [38]. The lack of animal manure further hinders biogas generation in rural settings because not every household has livestock or poultry (Khan and Martin 2016).

In order to use biogas slurry for organic farming in addition to biogas consumption, farmers at agro-biogas plants must be taught [39]. However, developing long-term biogas facilities is significantly hampered by the dearth of technical skills among biogas operators, especially qualified and experienced staff. It is also difficult to integrate biogas with eco-agriculture and lower biogas output since the majority of operators lack the required technical training and course certifications [40]. Because of a lack of setup and operation experience, the majority of biogas plants are shut down before reaching their full operating capability [41]. Apart from technical obstacles, an excessively negative perspective on biogas technology has resulted from the failure of biogas projects because of inadequate management, insufficient technical expertise, and insufficient experience (Surendra et al. 2014). Other reasons for digester failure include a lack of research and development to produce high-quality digesters, a lack of knowledge regarding efficient digester management, and a delay in embracing technology (Rupf et al. 2015a).

Due to the water constraint that many developing countries encounter, larger-scale biogas generation has proven to be a significant obstacle in many of these countries (Patinvoh and Taher zadeh 2019). Additionally, a biogas digester's daily organic waste-to-water ratio is essential to the production of biogas. If the quantity is too high or too low, it can be entirely halted (Rupf et al. 2015a). Biogas generation is also adversely affected in metropolitan settings when improper organic and inorganic waste segregation occurs.

Furthermore, India's cities, towns, and villages lack enough waste-to-energy infrastructure as a result of municipal and government neglect of garbage collection and segregation. Adopting biogas technologies presents another challenging issue. Due to the high initial cost and market risk associated with biogas technology, many private businesses are hesitant to engage in new construction and technology for biogas plants (Amuzu-Sefordzi et al. 2018; Chen and Liu 2017).

6.1 Environmental Impact

The process of producing biogas is without any risks to the environment. The requirement for a significant volume of water is one major issue biogas plants face. This is required for both maintaining the optimal water-to-manure ratio of 1:1 and anaerobic digestion [42]. In dry seasons or in places with limited water supplies, producing biogas might be difficult [43]. Additionally, the production of biogas may be adversely affected by lower temperatures. For example, biogas output can be reduced below 15 °C, which makes it difficult for farmers in colder regions to use biogas as an energy source [44] n addition, there is a chance that gas leaks, odor problems, and noise pollution will negatively impact the environment. Broken digester lids and leaking gas valves in particular can emit a combination of hydrogen, carbon dioxide, and methane sulfide, leading to a rise in greenhouse gas emissions and groundwater contamination [45,46]. Some African nations, like Zambia, might experience a lack of water, which could make running biogas plants more difficult (Shane et al. 2015b). It is crucial to identify hazardous spots and use leak-proof feedstock and digester storage areas in order to reduce these environmental concerns. In order to save groundwater and avoid offensive odors, waste gas outlets should also be properly handled [45].

6.2 Reduction of Greenhouse Gas Emissions

Biogas production significantly reduces greenhouse gas emissions by capturing methane, a potent greenhouse gas, that would otherwise be released from decomposing organic matter. The use of biogas as a fuel also offsets carbon dioxide emissions from traditional fossil fuels. In hilly regions, where traditional waste management practices may lead to uncontrolled methane emissions, biogas technology offers a sustainable solution for mitigating climate change.

6.2.1 Mitigation of deforestation

Hilly regions often face severe deforestation due to the high demand for firewood. Biogas technology provides an alternative energy source, reducing the need for firewood and helping to conserve forest resources. By alleviating pressure on forest ecosystems, biogas production contributes to biodiversity conservation and soil stability, which are critical for maintaining the ecological balance in hilly terrains [47].

6.2.2 Soil Conservation

The byproduct of biogas production, known as digestate, is a nutrient-rich organic fertilizer. Its application improves soil fertility and structure, promoting sustainable agricultural practices and preventing soil erosion common in hilly areas [47]. The use of digestate enhances soil organic matter content, water retention capacity, and microbial activity, leading to improved crop yields and soil health.

6.2.3 Water resource management

Biogas technology contributes to water resource management by reducing organic waste pollution in water bodies. Properly managed biogas plants prevent the runoff of untreated waste into rivers and streams, thus protecting water quality. In hilly regions, where water sources are often limited and vulnerable to contamination, biogas technology plays a crucial role in safeguarding water resources [48].

6.2.4 Biodiversity conservation

By reducing deforestation and promoting sustainable waste management, biogas technology indirectly supports biodiversity conservation. Preserving forest cover and preventing soil degradation create a favorable habitat for various flora and fauna. Additionally, the reduction in chemical fertilizer use due to the availability of organic digestate contributes to healthier ecosystems.

6.2.5Air quality improvement

The use of biogas reduces indoor air pollution caused by traditional biomass fuels, leading to improved respiratory health among rural households. This is especially important in hilly regions where access to healthcare may be limited. Cleaner air from biogas use also benefits the broader environment by reducing emissions of particulate matter and other pollutants.

7. STATUS OF BIOGAS AS AN ENERGY SOURCE WORLDWIDE

Although the benefits of biogas have been known about since the 19th century, the depletion of natural gas sources and growing concern over greenhouse gas emissions are the main reasons for the present surge in interest in the technology. In the 20th century, high-value fertilizer was first used. Biogas output increased from approximately 7,934 TOE (9:298 × 10 9 L) in 2009 to 14,120 TOE (1:6548 × 10 10 L) in 2016, indicating the widespread use of biogas technology in Europe [49]. One practical route toward the switch to a low-carbon grid power is the production of electricity from biogas. Most of the accessible technologies are simple to implement on a home and business level. Biodegradable biomass resources, such as animal and human waste, industrial and municipal waste, are readily accessible as a substitute source of energy. Biodigesters, which are categorized into two primary designs—the fixed dome design and the floating dome design—are where biogas is produced under controlled conditions. However, because there is a growing need to produce more practical, affordable, and sustainable bio-gas designs, new designs are being developed to improve on the current concepts [50]. Due to factors like low conversion efficiencies, high production costs, the availability of cheaper fossil fuel sources, and a lack of urgency in implementing biogas technology, biogas production and use globally have not yet reached their full potential [32].

8. GROWTH OF BIOGAS ENERGY RESOURCES WORLDWIDE

About 0.25% of the worldwide energy market and 27% of the biofuel industry were made up of biogas in 2011 (Hahn,2015). Because biogas can be produced and used to power rural communities, it can raise living conditions there. This is especially true when organic manure is used to produce higher-quality agricultural goods and sell power to the grid. Biogas can be used to heat, cook, light, and power diesel engines, which in turn run household and educational machinery. These days, biogas can be processed to produce biomethane, which can be injected into natural gas networks to replace natural gas, utilized as a car fuel, and substituted for natural gas in commercial, industrial, and residential settings. Carbon dioxide can be separated from biogas and utilized as a raw material to produce chemical fuels as well as a feedstock for greenhouses. About 16 million tiny household biogas digesters were in use worldwide in 2005, with China and India accounting for the majority of these units [31]. In China, about seven million biogas digesters provided 4% of the country's energy needs in 1996, while in India, biogas replaced the equivalent of 16 million tons of firewood [50]. When heat and electricity are produced concurrently, a process known as cogeneration, biogas utilization efficiency can be significantly boosted. By replacing generation from fossil fuels, excess power can be sold to the grid, helping to stabilize it and reducing global warming [51].

8.1 Future Prospects

8.1.1 Technological innovations

Ongoing research and development are crucial for advancing biogas technology. Innovations such as improved digester designs, enhanced microbial cultures for better digestion efficiency, and integration with other renewable energy systems can increase the viability and effectiveness of biogas technology in hilly regions [52]. Future technological advancements should focus on adaptability, cost reduction, and maximizing biogas yield from diverse feedstock types.

8.1.2 Integration with sustainable practices

Integrating biogas technology with sustainable agricultural and environmental practices can amplify its benefits. Combining biogas production with organic farming, agroforestry, and conservation efforts can create synergistic effects that enhance overall sustainability. Such integrated approaches can contribute to the holistic development of hilly regions, addressing energy, environmental, and socio-economic challenges concurrently [53].

8.1.3 Policy development

Continued policy support is essential for scaling up biogas technology. Governments should develop comprehensive policies that address technical, financial, and social aspects of biogas implementation. Policies should promote research and innovation, provide financial incentives, and support capacity-building initiatives. Collaborative efforts between governments, NGOs, and international organizations can create a conducive environment for the widespread adoption of biogas technology.

8.1.4 Community-led initiatives

Empowering local communities to lead biogas projects can enhance their sustainability and impact. Community-led initiatives that involve participatory planning, local ownership, and management can ensure that biogas systems meet the specific needs and conditions of hilly regions. Such approaches can foster a sense of responsibility and commitment among community members, leading to successful and sustainable biogas projects.

9. CONCLUSION

Biogas technology offers a promising solution to the energy, environmental, and socio-economic challenges faced by hilly regions. By leveraging locally available organic waste, biogas systems can provide a reliable source of renewable energy, improve waste management, and contribute to environmental conservation. The successful implementation of biogas technology in hilly terrains requires a comprehensive approach that addresses technical feasibility, environmental impact, socio-economic benefits, and policy support. Future efforts should focus on technological innovations, integration with sustainable practices, and community-led initiatives to maximize the benefits of biogas technology.

By fostering a collaborative and inclusive approach, biogas technology can contribute to the sustainable development of hilly regions, enhancing energy security, environmental health, and socio-economic well-being.

This thorough analysis emphasizes the crucial elements of biogas technology in hilly environments, providing insightful information for scholars, decision-makers, and practitioners who wish to advance sustainable development in these areas. In conclusion, biogas technology stands as a beacon of sustainable development in Uttarakhand, offering a pathway towards cleaner energy, enhanced rural livelihoods, and resilient urban infrastructure. As the state continues to grapple with energy access and environmental sustainability, biogas technology presents itself as a pivotal tool for achieving inclusive growth and mitigating the adverse impacts of climate change. This comprehensive review highlights the critical aspects of biogas technology in hilly terrains, offering valuable insights for researchers, policymakers, and practitioners aiming to promote sustainable development in these regions.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

I, hereby declare that NO generative AI technologies such as large language models (chatGPT, COPILOT, etc) and text to image generators have been used during writing or editing of manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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