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DECENTRALISED WASTE-TO-ENERGY SYSTEMS FOR INDIA: AN ECOLOGICAL APPROACH TO PRODUCING RENEWABLE ENERGY FROM LIVESTOCK AND AGRICULTURAL WASTE

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ABSTRACT

This study investigates the viability of setting up a decentralized network of waste-to-energy facilities in India with special reference to Kerala, using cow dung and agricultural waste to generate renewable electricity. This study employed a comprehensive approach focusing on data collection on waste generation (cattle dung and agricultural waste), data on Installed Capacity and consumption of energy from Kerala State Electricity Board, estimating energy potential and financial evaluation and component analysis of a suitable Waste-to-Energy (WTE) plant were conducted. In order to guarantee a steady supply of feedstock and regional advantages, this study identified a model that gives priority to a large number of smaller plants. Every year, each 1 MW biogas-powered Combined Heat and Power (CHP) plant can produce about 8,300,000 kWh of electricity and needs about 57,000 metric tonnes of cattle dung, or the production of 7,800 cattle. Based on Kerala's 2022–2023 consumption data, a carefully planned network of 100 of these plants, running for a conservative 6,000 hours annually, could generate 600 GWh of renewable electricity, potentially powering over 870,000 people. This shows considerable scalability as it accounts for less than 10% of the state's overall waste-to-energy potential. Clean energy, decent work, and environmental sustainability are among the 12 UN Sustainable Development Goals that the project supports. Each plant will require about one acre of land, in addition to a feedstock storage area for ten days. In order to maximize social development, sustainable waste management, greenhouse gas reduction, and renewable energy generation, we advise a public-private partnership with the Kerala government.

KEY WORDS: Agriculture waste, Cattle manure, Environmental sustainability, Green energy, Greenhouse gas, Renewable energy, Solid waste management

INTRODUCTION

India, a country with a largest bovine population and a long history of agriculture, faces the twin challenges of managing enormous amounts of organic waste and supplying its expanding energy needs. Conventional waste disposal techniques frequently result in lost opportunities for resource recovery and environmental degradation. Adopting decentralized waste-to-energy (WTE) systems, especially those that use agricultural residues and livestock manure, is a promising remedy.

The state of Kerala in India is targeted to achieve net-zero emissions by 2050 and fulfill 100% of its energy needs through renewable energy sources by 2040 (CSTEP 2024). This goal calls for a pattern change away from reliance on conventional fossil fuels and towards creative and sustainable energy sources. One of the most promising approaches is waste-to-energy (WTE) technology, which provides a two fold advantage by producing clean energy and tackling the growing waste management issues.

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The development of biomass-based energy systems can facilitate rural economic development by providing farmers with new income sources and creating job opportunities in the bioenergy sector (Mizsey and Racz, 2010). The environmental impact of open dumping and uncontrolled organic waste decomposition, which contribute to greenhouse gas emissions and soil and water contamination, can be mitigated through the implementation of waste-to-energy technologies (Tauseef *et al.*, 2013).

By using microorganisms like bacteria and archaea, anaerobic digestion (AD), a vital biological process, makes it easier for organic materials to break down in oxygen-deficient environments. This procedure is essential for the development of a sustainable bioeconomy and for the management of organic waste. The resource recovery and waste minimization are in line with the use of AD in WTE plants. The circular economy, which promotes systems where waste is planned out and resources are kept in circulation, seeks to decouple economic growth from limited resource consumption (Ellen MacArthur Foundation, 2013). The anaerobic digestion helps close the gap between circular economy principles and the achievement of sustainable development goals (Bernstad *et al.*, 2013).

The Kerala state's internal power generation currently fulfils only 30-35% of its energy needs, with the remainder being met through imports, primarily from coal-based sources. This scenario highlights the necessity of comprehending the state's energy dynamics and formulating a strategic plan to decrease reliance on thermal imports while facilitating a seamless transition to renewable energy. This study investigates the feasibility of establishing a network of strategically located waste-to-energy (WTE) plants across the state, demonstrating how Kerala can simultaneously address its energy requirements, mitigate environmental pollution, and foster economic growth. This study focuses on utilising diverse waste streams, including cattle manure and agricultural residues like paddy straw, coconut waste, and banana stems, as feedstocks for electricity generation.

MATERIALS AND METHODS

This study employed a comprehensive approach focussing on data collection, analysis across technical, economic and social aspects to assess the feasibility of establishing a decentralised network of waste-to-energy (WTE) plants in India with special reference to Kerala.

Data Collection on Waste Generation

The Animal Husbandry Department, livestock census reports from 2003 onwards, and Departmental publications were the sources of information on the number of cattle and the rates at which waste is generated. Data on the production of agricultural residues, such as banana stems, paddy straw, and coconut fronds, was gathered from the Department of Agriculture Development & Farmers' Welfare of Kerala and Kerala agricultural university. To obtain information on regional waste generation trends and current waste management techniques, local municipal corporations and panchayats were consulted.

Data on Installed Capacity and Consumption of Energy

The Kerala State Electricity Board (KSEB) provided information on the state's current grid infrastructure, consumption trends, and electricity generation capacity. This included past information on peak loads, electricity demand and regional differences in energy use.

Estimating Energy Potential

The energy potential of each waste stream was estimated using established conversion factors for the production of biogas from agricultural residues and cattle waste. These elements were taken from industry best practices and scientific literature. Anaerobic digestion's potential for producing electricity was estimated using energy yield models that took into account variables like digester efficiency, feedstock composition, and moisture content. The standard calorific value of methane was used to calculate the energy yield from the biogas.

Financial Assessment and Mechanisms

The financial evaluation and component analysis of a suitable Waste-to-Energy (WTE) plant were conducted based on a techno-economic feasibility approach tailored for processing cow dung and agricultural waste. The methodology involved the identification, classification, and cost estimation of all major subsystems required for plant installation and operation. The model for implementation is also accessed.

RESULTS

The energy potential of livestock manure and agricultural residues is examined in this study. A substantial untapped resource for the production of biogas is revealed by our analysis. Cattle manure exhibits the most promising qualities among the evaluated feedstocks because of its high calorific value and wide availability. For estimating dug availability as feedstock total bovine population is assessed.The bovine population of Kerala is shown in Table 1.

The total bovine population as per 2019 livestock census is 1.4 million and it will produce 28 million Kg cow dung per day considering the production of 20.0 Kg day^{-1} cow^{-1}. The estimate of annual Agriculture waste is depicted in Figure 1.

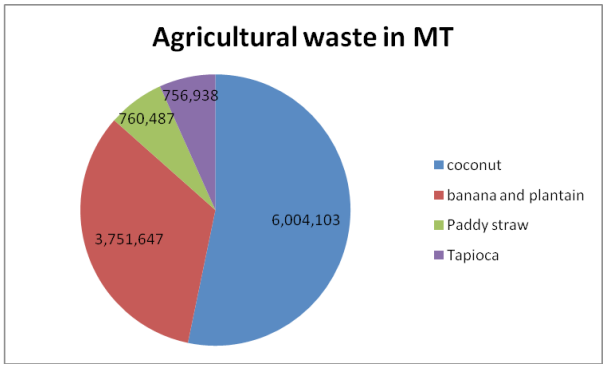

Fig. 1. Availability of annual Agriculture waste

Temporal Dynamics of Kerala's Electricity Supply, Consumption, and Infrastructure (2000-01 to 2022-23)

Distinct sequential trends in installed generation capacity, per capita electricity consumption, and the interaction between internal generation and external power procurement are revealed by analysing Kerala's power sector from the financial year 2000-01 to 2022-23.

Throughout the study period, the installed power generation capacity showed an overall upward trend. The capacity began at about 2.5 GW in 2000-01, increased gradually until 2011-12, then accelerated more sharply, reaching about 3.5 GW by 2022-23. This expansion most likely reflects calculated capital expenditures meant to increase the state's electrical infrastructure in order to meet the growing demand for energy. The notable expansion noted in the latter half of the time frame might suggest a concentrated attempt to improve energy security and diversify the energy mix, possibly including a larger proportion of renewable energy sources. Kerala's installed power generation capacity is illustrated in Figure 2

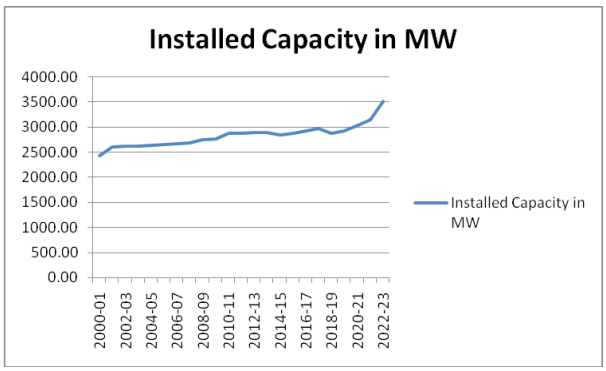

Fig. 2. Kerala's installed power generation capacity

At the same time, there was a general upward trend in the amount of electricity consumed per person. Starting at about 300 kWh in 2000-01, consumption first decreased slightly before beginning a steady rise that reached a peak of almost 700 kWh in 2021-22. In 2022–2023, a minor moderation was noted. This growth highlights the state's rising per capita electricity demand over the past 20 years. The amount of electricity consumed per person is depicted in Figure 3.

The power generated and purchased in Kerala is depicted in Figure 4

Table 1. Bovine population over the years (in thousands)

Category	2003	2007	2012	2019
Crossbreds	1735	1621	1252	1251.58
Indigenous	387	119	77	82.69
Total cattle	2122	1740	1329	1332.51
% increase/ decrease	-37.51	-18.00	-23.62	0.26
Buffaloes	65	58	102	101.50
% increase	-60.60	-10.76	+75.86	-0.49
Total bovines	2187	1798	1431	1434.01
% increasedecrease	-38.58	-17.78	-20.41	0.21

Throughout the study period, there was no discernible sign of consistent growth in the annual internal electricity generation, which fluctuated between roughly 4 and 10 billion units (BU) in terms of power supply. On the other hand, power purchased through imports showed a notable and steady increase. Import volumes began in the early 2000s at levels similar to internal generation (roughly 12-14 BU), increased gradually after 2004-05, and reached over 30 BU by 2022–23. In comparison to the varying internal generation, this significant increase in power imports indicates a growing reliance on outside sources to meet the state's rising electricity demands. The power produced and purchased in Kerala is shown in Figure 3.

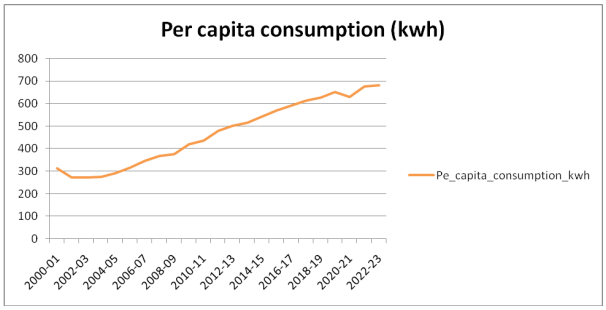

Fig. 3. The amount of electricity consumed per person

Evaluation of Kerala's Waste-to-Energy Potential Using Distributed Generation

A 1 MW biogas plant needs about 57,000 metric tonnes (MT) of cattle manure feedstock per year to run continuously. This amount is equivalent to the estimated 7,800 head of cattle's waste production per year. With this feedstock, a combined heat and power (CHP) biogas plant with a 1 MW capacity could produce about 8,300,000 kWh of electricity annually. Based on the per capita electricity consumption of 682 kWh/year in 2022–2023, this electricity output is adequate to meet the annual domestic energy consumption of over 8700 residential consumers.

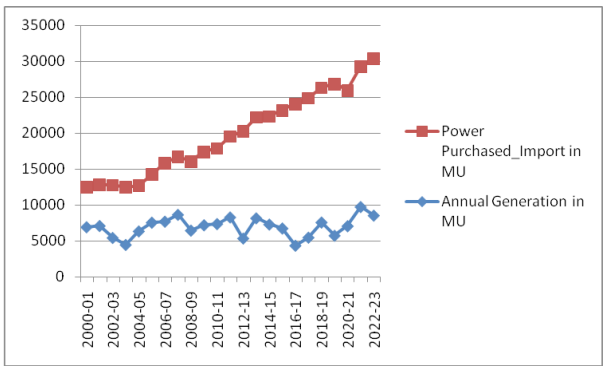

Fig. 4. The power generated and purchased in Kerala

According to preliminary estimates, Kerala's waste streams have a significant potential for producing electricity. The installation of 100 Waste-to-Energy (WTE) plants, each with a 1 MW capacity, could collectively produce about 600 GWh of electricity annually, assuming 6,000 annual operating hours for each plant.A decentralised strategy is an effective method for harnessing energy from locally available waste resources, demonstrated by the feasibility of establishing a minimum of one 1 MW Waste-to-Energy (WTE) plant in 100 of Kerala's 152 administrative blocks. Moreover, a substantial feedstock resource is provided by the annual production of key agricultural wastes, including coconut, banana, plantain, paddy straw, and tapioca.A 1:1 blend of cattle manure and agricultural waste is suggested as a possible feedstock blend for these WTE plants, contingent on local availability.

Financial Estimate and model for 1 MW WTE plant

The installation cost of a 1 MW waste-to-energy plant utilizing cow dung and agricultural waste is estimated at Rs. 16 crore. The financial estimate of 1 MW WTE plant is shown in Table 2.

Table 2. The financial estimate of 1 MW WTE plant

Sl. No.	Components	Amount (Rs in lakh)
1	Core Conversion Technology	640
2	Power Generation Equipment	400
3	Waste management and preliminary processing	200
4	Civil Works	240
5	EPC and Project Management	120
	Total	1600

Core Conversion Technology includes Anaerobic Digestion Systems, which consist of digesters (tanks), feeding and mixing systems, and gas collection and treatment components. Power generation equipment consists of biogas engines or turbines, which convert biogas into electricity, as well as generators and the associated equipment for connecting the plant to the electrical grid. Waste management and preliminary processing units include waste reception and storage for the reception, storage, and management of cow dung

and agricultural waste. Civil Works and Construction includes construction of civil structures such as buildings, roads etc. Engineering Procurement and Construction (EPC) as well as Project Management is the key component which include engineering design, equipment procurement, construction management, water treatment systems, auxiliary power supply, instrumentation and control systems, pollution control equipment, and commissioning and startup processes.

Public-Private Partnerships (PPPs) can help Kerala deploy WTE plant on a large scale, requiring a substantial capital investment of 1600 crore rupees. Long-term contractual agreements, risk-sharing procedures, and clearly defined project structures are essential success factors for these PPPs. The private sector provides funding, technological knowledge and operational efficiency while the public sector usually supplies the regulatory framework, guarantees feedstock supply, and maintains grid connectivity. One of the state's most important opportunities for the green energy transition is WTE plants.

DISCUSSION

The suggested plan to build Waste-to-Energy (WTE) plants in Kerala based on feedstock type emphasizes a key idea in the development of bioenergy: supply chain optimization. For WTE facilities to remain economically viable and continue operating, a steady and dependable supply of waste matter must be secured (Su *et al*., 2012; Rogovskii *et al.,* 2021). By distributing smaller plants throughout the state, this strategy promotes a decentralised model that reduces transportation distances and related expenses while boosting regional energy security.

According to the findings, Kerala has two opportunities to improve its energy sustainability, by strategically developing its power infrastructure and by tapping into untapped bioenergy resources. The analysis of livestock manure and agricultural wastesunderline a significant although mostly underutilized potential for biogas production.Due to its high calorific value and abundance, cattle manure stands out as a promising feedstock. This is in line with international research that highlights the potential of livestock waste in the production of bio energy (Abbasi *et al*., 2020). The estimated 600 GWh of energy produced annually by 100 WTE plants running 6000 hours a year makes a substantial contribution to Kerala's electricity production. This output could theoretically power about 870,000 people annually based on the 682 kWh/year per capita electricity consumption in 2022–2023. This number, however, only accounts for a small portion (less than 10%) of Kerala's estimated total energy potential from available waste, suggesting that there is a significant opportunity to increase WTE capacity. The economic viability of WTE plants can be increased and biogas production optimised by combining livestock manure with other organic wastes, such as food waste and agricultural residues (Mata-Alvarez *et al*., 2000). Co-digestion has been demonstrated to improve process stability, boost biogas yield, and improve nutrient balance. The region's bioenergy potential and livestock farming are closely related, as evidenced by the significant feedstock requirement of 57,000 MT of cattle waste annually for a 1 MW biogas plant.A 1 MW combined heat and power (CHP) biogas plant can produce about 8,300,000 kWh of electricity annually, which can meet the annual domestic energy needs of about 12,000 people.' This waste is generated from approximately 7,800 head of dairy cattle. This study supports 12 of the Sustainable Development Goals (SDGs) of the United Nations, including clean energy, decent work, gender equality, and environmental sustainability.

Additionally, the feasibility of a distributed generation approach is suggested by the initial evaluation of Kerala's waste-to-energy (WTE) potential. A substantial feedstock resource for WTE plants is presented by the estimated yearly generation of large amounts of agricultural waste from important crops like coconut, banana/plantain, rice, and tapioca, as well as the possible integration of cattle manure (Demirbas *et al*., 2009). Given the increasing interest in decentralised energy systems worldwide for improved energy access and resilience, it is feasible to install 1 MW WTE plants in a significant number of Kerala's administrative blocks (Sovacool *et al*., 2019). This strategy could help generate electricity while also addressing waste management issues and adhering to the principles of the circular economy (Korhonen *et al*., 2018).

However, a critical context for incorporating these bioenergy strategies is revealed by the temporal analysis of Kerala's electricity supply, consumption, and infrastructure. Although installed power generation capacity in the state has been increasing, especially in recent years, this growth has not kept up with the rising per capita electricity

consumption. As a result, during the previous 20 years, Kerala has become much more dependent on outside power procurement. This increasing reliance highlights the pressing need to improve energy self-sufficiency by implementing domestic renewable energy sources and diversifying the state's energy mix.

Significant capital investment is required for the development of WTE infrastructure; the proposed project in Kerala is estimated to cost roughly 16000 crore rupees. This substantial financial investment emphasises the necessity of creative financing strategies to support the broad implementation of WTE technologies. For large-scale infrastructure projects, such as those in the waste management and energy sectors, public-private partnerships, or PPPs, have become a key tool for enlisting the resources and experience of the private sector (World Bank, 2022). PPPs provide a framework for joint project delivery and risk sharing where the public and private sectors combine their strengths. While the private sector provides funding, technological know-how, and operational efficiency, the public sector usually supplies the regulatory framework, guarantees feedstock supply, and maintains grid connectivity. Clear project planning, risk distribution, and long-term contractual agreements are essential components of PPP success. For projects to be implemented successfully, a robust and cooperative PPP model is essential (ADB, 2023).

According to Fagerström *et al*. (2018), anaerobic digestion is essential to the circular economy for the management of organic waste and is a vital connection between the bio economy, the circular economy, and the accomplishment of sustainable development goals. The characteristics of the feedstock essentially determine the performance of anaerobic digestion in terms of initiation, stability, and biogas yield (Lohani and Havukainen, 2018). There are two advantages to using livestock manure for energy production from an environmental standpoint. First of all, it supports the global shift to sustainable energy systems by offering a renewable substitute for finite fossil fuels. Second, methane, a powerful greenhouse gas with a 25-fold greater potential for global warming than carbon dioxide over a 100-year period, is greatly reduced by anaerobic digestion of livestock manure (Su *et al.*, 2012; Burg *et al*., 2018; Xu *et al.*, 2018; Hoang and Kato, 2021; IPCC, 2021; Pertiwiningrum *et al.*, 2020; Timofeev and Erk, 2021). Therefore, generating biogas for efficient manure management is essential for reducing climate change and advancing sustainable farming methods. Utilising cutting-edge anaerobic digestion technologies, like membrane bioreactors, thermophilic digestion, or two-stage digestion, can improve the quality of the digestate, a valuable biofertilizer, shorten retention periods, and increase the efficiency of biogas production (André *et al*., 2017). With feedstock supply chains and local power generation, using locally accessible biomass resources can improve energy security, lessen reliance on imported power, and support rural economic development (Müller *et al*., 2019). Furthermore, by replacing fossil fuel-based electricity generation and lowering greenhouse gas emissions from waste decomposition, these bioenergy pathways can help mitigate climate change (IPCC, 2022).

CONCLUSION

Kerala's large reserves of unused bioenergy from livestock manure and agricultural residuesoffer a calculated chance to strengthen energy independence and lessen the state's growing dependency on outside power supplies. Decentralised WTE deployment is made possible by Kerala's plentiful livestock manure resources and other organic waste streams. These resources also fit with the principles of the circular economy and global trends in sustainable energy development. This approach not only improves energy independence and lessens dependency on fossil fuels, but it also helps mitigate climate change and encourages sustainable farming methods. A viable path to a more robust and sustainable energy future for Kerala is to combine these bioenergy pathways with the continuous development of the state's electrical infrastructure.

Conflict of interest

The authors declare no conflicts of interest.

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