PERFORMANCE EVALUATION AND BENCHMARKING OF MUNICIPAL SOLID WASTE BASED BIOMETHANATION PLANTS IN INDIA

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

CHAITRA DEVOOR

Department of Civil Engineering

Submitted

In the fulfilment of the requirements of the degree of Doctor of Philosophy

to the

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Dedicated to

Supreme Power of the Universe,

My Parents, Gurus, Family and Friends

गुरूर्ब्रह्मा गुरूर्विष्णुः,
गुरूर्देवो महेश्वरः।
गुरूःसाक्षात् परब्रह्म
तस्मै श्री गुरवे नमः ॥

CERTIFICATE

This is to certify that the thesis titled "**Performance Evaluation and Benchmarking of Municipal Solid Waste based Biomethanation Plants in India**" being submitted by **Mrs. Chaitra Devoor**, to the Indian Institute of Technology, Delhi for the award of '**Doctor of Philosophy**' in Department of Civil Engineering is a record of the bonafide research work carried out by her under my supervision and guidance. She has fulfilled the requirements for the submission of this thesis, which to the best of my knowledge has reached the requisite standard. The material contained in the thesis has not been submitted in part or full to any other university or institute for the award of any other degree or diploma.

April 2026

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(Chaitra Devoor)

ABSTRACT

Rapid population growth, urbanization, and industrialization have led to a significant increase in Municipal Solid Waste (MSW), creating major challenges for sustainable waste management. The biodegradable fraction of MSW has considerable potential for energy recovery through anaerobic digestion or biomethanation. Biomethanation plants (BMPs) offer an environmentally sustainable solution by converting organic waste into biogas which are usable as electricity, compressed biogas (CBG), or fuel, while generating digestate that can be utilized as manure/compost/ soil conditioner, thereby reducing environmental pollution.

In India, biomethanation technology has been actively promoted through policy initiatives and financial support under programmes such as Swachh Bharat Mission (Urban and Gramin), SATAT, and various other Waste to Energy Programmes, involving multiple Central Ministries. Consequently, several BMPs have been commissioned over the past decade. However, a significant number of these plants have become non-operational or underperforming due to technical, managerial, financial, operational, challenges related feedstock, its quality, quantity etc. This highlights the urgent need for a systematic evaluation of BMP efficiency to ensure their sustainable integration into MSW management systems.

The performance of BMPs is influenced by multiple factors, including waste quantity and quality, plant capacity, reactor design, investment structure, operational costs, labour, revenue generation, biogas generation etc. In the absence of a national or state-level database on BMPs, primary data were collected through a detailed questionnaire covering technical, operational, managerial, and financial aspects. Data from 82 BMPs across 32 cities in 9 Indian states were compiled for analysis. A comprehensive assessment revealed widespread issues such as underutilization of capacity, inadequate waste segregation, poor feedstock quality, and financial non-viability, particularly in small-scale plants. Although most plants were operational, limited revenue from biogas and compost sales constrained long-term sustainability, underscoring the need for improved technologies, waste segregation practices, and viable business models.

Data Envelopment Analysis (DEA), a linear programming based technique for measuring the performance efficiency of organizational units called Decision Making Units (DMU's) was employed to evaluate the relative efficiency of BMPs, as it effectively handles multiple inputs and outputs and provides benchmarking insights. Using the CCR output-oriented model, efficiency scores were calculated for 30 BMPs (after excluding plants with incomplete or zero-value data) across five states. Four DEA models were developed to assess operational, technical, economic, and environmental efficiencies using relevant input–output variables.

The results showed that 86% of plants were operationally inefficient, while technical efficiency was relatively higher, with 56% of plants nearing optimal performance. Economic efficiency was observed in only 30% of the plants, and environmental efficiency was notably poor, with only one plant achieving full efficiency. Overall, most BMPs operated below optimal levels due to underutilization, high costs, and operational inefficiencies.

This study presents a comprehensive framework for evaluating MSW based BMPs in India and identifies efficiency gaps, best-performing plants, and benchmarking opportunities. The findings emphasize the need for standardized monitoring, centralized data systems, and targeted policy interventions to enhance the sustainability and effectiveness of biomethanation technology. While DEA provides valuable comparative insights, further plant level microanalysis and sector wide evaluations are necessary to replicate best practices and strengthen long term viability.

सारांश

तेजी से बढ़ती आबादी, शहरीकरण और औद्योगीकरण के कारण म्युनिसिपल सॉलिड वेस्ट (MSW) में काफी बढ़ोतरी हुई है, जिससे कचरा प्रबंधन को टिकाऊ बनाने में बड़ी चुनौतियां खड़ी हो गई हैं। MSW के बायोडिग्रेडेबल हिस्से में एनारोबिक डाइजेशन या बायोमीथेनेशन के ज़रिए ऊर्जा निकालने की काफी क्षमता होती है। बायोमीथेनेशन प्लांट (BMPs) एक पर्यावरण-अनुकूल और टिकाऊ समाधान देते हैं; ये जैविक कचरे को बायोगैस में बदलते हैं, जिसका इस्तेमाल बिजली, कंप्रेस्ड बायोगैस (CBG) या ईंधन के तौर पर किया जा सकता है। साथ ही, इनसे 'डाइजेस्टेट' भी बनता है, जिसे खाद/कम्पोस्ट/मिट्टी को बेहतर बनाने वाले पदार्थ के तौर पर इस्तेमाल किया जा सकता है, जिससे पर्यावरण प्रदूषण कम होता है।

भारत में, बायोमीथेनेशन तकनीक को कई केंद्रीय मंत्रालयों की भागीदारी वाले कार्यक्रमों—जैसे कि स्वच्छ भारत मिशन (शहरी और ग्रामीण), SATAT, और 'कचरे से ऊर्जा' (Waste to Energy) से जुड़े अन्य कार्यक्रमों के तहत बनाई गई नीतियों और आर्थिक मदद के ज़रिए बड़े पैमाने पर बढ़ावा दिया गया है। नतीजतन, पिछले एक दशक में कई BMPs चालू किए गए हैं। हालांकि, इनमें से बड़ी संख्या में प्लांट तकनीकी, प्रबंधकीय, आर्थिक और परिचालन से जुड़ी चुनौतियों - जैसे कि कच्चे माल (feedstock) की उपलब्धता, उसकी गुणवत्ता और मात्रा आदि के कारण या तो बंद हो गए हैं या फिर अपनी पूरी क्षमता से काम नहीं कर पा रहे हैं। यह इस बात पर ज़ोर देता है कि BMPs की कार्यक्षमता का व्यवस्थित मूल्यांकन करना कितना ज़रूरी है, ताकि उन्हें MSW प्रबंधन प्रणालियों में टिकाऊ तरीके से शामिल किया जा सके।

BMPs की कार्यप्रणाली कई कारकों से प्रभावित होती है, जिनमें कचरे की मात्रा और गुणवत्ता, प्लांट की क्षमता, रिएक्टर का डिज़ाइन, निवेश का ढांचा, परिचालन लागत, श्रमबल, राजस्व सृजन, बायोगैस उत्पादन आदि शामिल हैं। BMPs से जुड़ा कोई राष्ट्रीय या राज्य-स्तरीय डेटाबेस उपलब्ध न होने के कारण, एक विस्तृत प्रश्नावली के माध्यम से प्राथमिक डेटा इकट्ठा किया गया; इस प्रश्नावली में तकनीकी, परिचालन, प्रबंधकीय और आर्थिक पहलुओं को शामिल किया गया था। विश्लेषण के लिए, भारत के 9 राज्यों के 32 शहरों में स्थित 82 BMPs से प्राप्त डेटा को संकलित किया गया।

एक व्यापक मूल्यांकन से पता चला कि कई तरह की समस्याएं आम हैं, जैसे कि क्षमता का पूरा इस्तेमाल न होना, कचरे का ठीक से अलग न किया जाना, कच्चे माल की खराब गुणवत्ता और आर्थिक रूप से अलाभकारी

होना; ये समस्याएं विशेष रूप से छोटे पैमाने पर चलने वाले प्लांटों में ज़्यादा देखने को मिलीं। हालांकि ज़्यादातर प्लांट चालू हालत में थे, लेकिन बायोगैस और कम्पोस्ट की बिक्री से होने वाली सीमित आय ने उनकी दीर्घकालिक स्थिरता को प्रभावित किया। यह इस बात को रेखांकित करता है कि बेहतर तकनीकों, कचरा अलग करने के बेहतर तरीकों और आर्थिक रूप से व्यवहार्य व्यावसायिक मॉडलों की कितनी सख्त ज़रूरत है।

BMPs की सापेक्ष कार्यक्षमता का मूल्यांकन करने के लिए 'डेटा एनवेलपमेंट एनालिसिस' (DEA) नामक तकनीक का उपयोग किया गया। यह एक 'लीनियर प्रोग्रामिंग' पर आधारित तकनीक है, जिसका इस्तेमाल किसी संगठन की विभिन्न इकाइयों, जिन्हें 'निर्णय लेने वाली इकाइयां' (DMUs) कहा जाता है, की कार्यक्षमता को मापने के लिए किया जाता है। इस तकनीक को इसलिए चुना गया, क्योंकि यह कई तरह के इनपुट और आउटपुट को प्रभावी ढंग से संभाल लेती है और तुलनात्मक मूल्यांकन (benchmarking) से जुड़ी महत्वपूर्ण अंतर्दृष्टि प्रदान करती है। CCR आउटपुट - ओरिएंटेड मॉडल का इस्तेमाल करके, पाँच राज्यों में 30 BMPs (जिनमें अधूरा या शून्य - मान वाला डेटा था, उन्हें हटाने के बाद) के लिए दक्षता स्कोर की गणना की गई। प्रासंगिक इनपुट-आउटपुट चर का उपयोग करके परिचालन, तकनीकी, आर्थिक और पर्यावरणीय दक्षताओं का आकलन करने के लिए चार DEA मॉडल विकसित किए गए।

परिणामों से पता चला कि 86% संयंत्र परिचालन की दृष्टि से अक्षम थे, जबकि तकनीकी दक्षता अपेक्षाकृत अधिक थी, जिसमें 56% संयंत्र इष्टतम प्रदर्शन के करीब थे। आर्थिक दक्षता केवल 30% संयंत्रों में देखी गई, और पर्यावरणीय दक्षता विशेष रूप से खराब थी, जिसमें केवल एक संयंत्र ने पूर्ण दक्षता हासिल की। कुल मिलाकर, अधिकांश BMPs कम उपयोग, उच्च लागत और परिचालन अक्षमताओं के कारण इष्टतम स्तरों से नीचे संचालित हुए।

यह अध्ययन भारत में MSW आधारित BMPs के मूल्यांकन के लिए एक व्यापक ढाँचा प्रस्तुत करता है और दक्षता अंतराल, सर्वश्रेष्ठ प्रदर्शन करने वाले संयंत्रों और बेंचमार्किंग के अवसरों की पहचान करता है। निष्कर्ष बायोमीथेनेशन प्रौद्योगिकी की स्थिरता और प्रभावशीलता को बढ़ाने के लिए मानकीकृत निगरानी, केंद्रीकृत डेटा प्रणालियों और लक्षित नीतिगत हस्तक्षेपों की आवश्यकता पर जोर देते हैं। हालाँकि DEA मूल्यवान तुलनात्मक अंतर्दृष्टि प्रदान करता है, सर्वोत्तम प्रथाओं को दोहराने और दीर्घकालिक व्यवहार्यता को मजबूत करने के लिए संयंत्र स्तरीय सूक्ष्म विश्लेषण और क्षेत्र व्यापी मूल्यांकन आवश्यक हैं।

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AD - Anaerobic Digestion

AHIDF - Animal Husbandry Infrastructure Development Fund

AIF - Agriculture Infrastructure Fund

BCC - Banker, Charnes and Cooper

BM - Bio methanation

BMP - Biomethanation Plant

CAP - Common Agriculture Policy

C&D - Construction & Demolition

CBG - Compressed biogas

CCR - Charles, Cooper and Rhodes

CFA - Central Financial Assistance

CGD - City Gas Distribution

C/N - Carbon/Nitrogen

CNG - Compressed Natural Gas

COD - Chemical Oxygen Demand

CPCB - Central Pollution Control Board

CPHEEO - Central Public Health and Environmental Engineering Organisation

CRS - Constant Return to Scale

CSR - Corporate Social Responsibility

CSTR - Continuous Stirred Type Reactor

DA&FW - Department of Agriculture & Farmers Welfare

DEA - Data Envelopment Analysis

DoAH&D - Department of Animal Husbandry and Dairying

DMU - Decision Making Unit

ECM - Efficiency Contribution Measure

FW - Food Waste

FY - Financial Year

GAIL - Gas Authority of India Limited

GHG - Green House Gas

GoI - Government of India

HRT - Hydraulic Retention Time

IEA - International Energy Agency

IREDA - Indian Renewable Energy Development Agency

ISWM - Integrated Solid Waste Management

JNNURM - Jawaharlal Nehru Urban Renewal Mission

LCA - Life Cycle Assessment

LPG - Liquefied Petroleum Gas

MCDA - Multi-Criteria Decision Analysis

MDA - Market Development Assistance

MJ - Mega Joule

MNRE - Ministry of New and Renewable Energy

MoA&FW - Ministry of Agriculture & Farmers Welfare

MoC&F - Ministry of Chemicals and Fertilizers

MoEF & CC - Ministry of Environment, Forest and Climate Change

MoFAHD - Ministry of Fisheries, Animal Husbandry and Dairying

MoHUA - Ministry of Housing and Urban Affairs

MoJS - Ministry of Jal Shakti

MoPNG - Ministry of Petroleum and Natural Gas

MSW - Municipal Solid Waste

MSWM - Municipal Solid Waste Management

MTD - Metric Tonnes Per Day

MW - Mega Watt

NE - North East

NEERI - National Environmental Engineering Research Institute

NPK - Nitrogen, Phosphorus and Potassium

NPV - Net Present Value

ODM - Organic Dry Matter

OFMSW - Organic Fraction of Municipal Solid Waste

OLR - Organic Loading Rate

O&M - Operation and Maintenance

PNG - Piped Natural Gas

PPP - Public Private Partnership

PROM - Phosphate Rich Organic Manure

PSTR - Partially Stirred Tank Reactor

RBI - Reserve Bank of India

RDF - Refuse Derive Fuel

SATAT - Sustainable Alternative Towards Affordable Transportation

SBM-G - Swacch Bharat Mission-Gramin

SBM-U - Swacch Bharat Mission-Urban

SDG - Sustainable Development Goals

SRT - Solid Retention Time

SBM - Swachh Bharat Mission

SWM - Solid Waste Management

TAD - Thermophilic Anaerobic Digestion

TFWE - Task Force on Waste to Energy

TPD - Tonnes per Day

TS - Total Solids

VFA - Volatile Fatty Acid

VRS - Variable Return to Scale

VS - Volatile Solids

ULB - Urban Local Bodies

UN - United Nations

UT - Union Territories

WAS - Waste Activated Sludge

WTE - Waste to Energy