

**DEVELOPMENT OF HIGH-EFFICIENCY ANAEROBIC  
DIGESTION PROCESS OF KITCHEN, VEGETABLE,  
AND FRUIT WASTES FOR BIOGAS PRODUCTION**

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**JULY 2023**

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**DEVELOPMENT OF HIGH-EFFICIENCY ANAEROBIC  
DIGESTION OF KITCHEN, VEGETABLE, AND FRUIT  
WASTES FOR BIOGAS PRODUCTION**

by

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Submitted

*in fulfilment of the requirements of the degree of Doctor of Philosophy*

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**JULY 2023**

Dedicated to my beloved grandparents

“Late. Sh. Shiv Kumar Prasad  
&  
Late. Smt. Prakash Devi”

## ***CERTIFICATE***

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This is to certify that the thesis entitled “**Development of high-efficiency anaerobic digestion process of kitchen, vegetable and fruit wastes for biogas production**” being submitted by **Mrs. Adya Isha** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy**, is a record of bona fide research work carried out by her. She has worked under our supervision and has fulfilled the requirements for the submission of this thesis, which has attained the standard required for a Ph. D. degree of the Institute.

The research results presented in this thesis have not been submitted elsewhere for any degree or diploma award.

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## ACKNOWLEDGEMENTS

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I would like to express my sincere gratitude to the Indian Institute of Technology Delhi for letting me fulfill my dream of being a student here. The work presented in this thesis would not have been possible without my close association with many people. I take this opportunity to extend my sincere gratitude and appreciation to all those who made this thesis possible.

First and foremost, I would like to extend my sincere gratitude to my Ph.D. supervisors, **Prof. Virendra Kumar Vijay**, Centre for Rural Development & Technology, **Prof. P. M. V. Subbarao**, Department of Mechanical Engineering and **Prof. Ram Chandra**, Centre for Rural Development & Technology for introducing me to this exciting field of science and for their kind supervision, extraordinary cooperations, dedicated help, advice, inspiration, encouragement, and continuous support, throughout my Ph.D.

I express my deepest gratitude to the members of Student Research Committee, Prof. K. K. Pant (external examiner), Department of Chemical Engineering, Prof. Anushree Malik, Professor (chairperson), Centre for Rural Development & Technology, Prof. Vivek Kumar (internal examiner), Centre for Rural Development & Technology, Prof. V. M. Chariar (CRC chairperson), Centre for Rural Development & Technology for their valuable suggestions and encouragement at various stages of the present investigation.

I am extremely thankful to Dr. Bhaskar Jha and Mr. Tinku Casper D'Silva for their continuous support and encouragement.

I would also like to thank my seniors, Dr. Abhinav Trivedi, Dr. Supreet Kaur, Dr. Vandit Vijay, Mr. Biju I.K, Dr. Shivali Sahota, Dr. Goldy Shah, Dr. Himanshu Kumar and Dr. Swapna Sagarika.

I thank my fellow labmates, Mr. Anil Singh Tomar, Dr. Praveen Kumar, Mr. Subodh Kumar, Mr. Sameer Ahmed Khan, Mr. Dushyant Kumar, Mrs. Yatih Nupur, Mr. Saptashish Deb, Mr. Saurabh Yadav and Mr. Sandeep Kumar. I must be thankful to the CRDT office staff and our lab staff, Mr. Vinod, Mr. Ramesh, Mrs. Seema, Mr. Ravindra, Mr. Mahesh, Mr. Y. P. Singh, Mr. Adesh and Mr. H. Bose for their timely support shall always be remembered.

I will always be grateful to my grandparents and beloved family for their love and support throughout the journey. I feel a deep sense of gratitude to my father Prof. Birendra Pratap for his unconditional love, inspiration, support and blessings are the prime reasons behind my success in this endeavour. I do not find words to thank my mother Mrs. Snehlata for the love, care, support, and sacrifices for educating and preparing me for my future. My special words of thanks should also go to my uncle Lt. Col. Kumar Mukesh Ranjan for his kind support and inspiration toward my Ph.D. I am very much thankful to my husband Manish Garg for his love, care, understanding, and continuous support to complete this research work. Also, I thank my brothers Aditya Pratap and Abhijeet Pratap for their love, support and valuable prayers.

My sincere thanks also goes to Dr. Harjit Singh, Senior Lecturer, Mechanical and Aerospace Engineering, Brunel University London for becoming my host supervisor under International fellowship (Newton Bhabha Ph.D. placement programme 2019-2020) leading me working on diverse exciting projects.

I would also like to thank my friends Dr. Meghashree Padhan, Dr. Ayush Gautam, Mrs. Rashmi Rai, Ms. Hina Praveen, Mr. Sagar Dhanushkar, Dr. Rahul, Mrs. Nidhi, Mrs. Bhavna and Mrs. Rekha for their kind friendship and believing in me.

And last but not the least, thanks to God and all my well-wishers, who do not figure in this acknowledgement, however have helped me during the tenure of research work.

**Adya Isha**

## *ABSTRACT*

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Anaerobic digestion of kitchen, vegetable and fruit wastes faces the challenge of frequent composition variation and rapid digester acidification due to its highly degradable nature. Researchers across the globe have generally sorted the problem by the addition of alkaline chemicals, which further harms the environment and adds to the overall cost economics. This study intended to investigate the efficacy of utilizing natural additives to solve this issue. Pongamia de-oiled cake was used in this study which is otherwise non-edible and has less applications. In the first experiment, the kitchen wastes (KW) were segregated according to their pH characteristics as high acidic (pH: 2.00 – 5.00), medium acidic (pH: 5.00 – 7.00) and low alkaline (pH: 7.00 – 8.00) and were treated separately in three digesters (I, II and III) having a total volume of 307 L (working volume: 192 L) for 280 days with organic loading rate (OLR) of 2.80 VS/ m<sup>3</sup> /day for digester I, 2.61 VS/ m<sup>3</sup> /day for digester II and 2.60 kg VS/ m<sup>3</sup> /day for digester III. The digesters I, II and III achieved average biogas yields of 177.82 ± 19.30, 216.57 ± 7.42 and 280.45 ± 2.55 L/kg VS. d, respectively. Maximum synergistic effect of pongamia de-oiled cake was observed in digester I with increased methane production of 46.04% and volatile solids reduction of 11.18%. The principal component analysis and kinetic evaluation revealed that pongamia de-oiled cake addition had a significant positive effect on the AD parameters in all digesters achieving energy efficiencies exceeding 96%. With the success in operation, the study was upscaled to a 25 m<sup>3</sup>/ day capacity anaerobic digester for one year study in the second experiment.

The seasonal variation in KW was studied by classifying the study period of 360 days into six seasons (each season comprising 60 days), namely, spring, summer, monsoon,

autumn, early winter, and prevernal winter. Considering all the properties of kitchen waste, the anaerobic digestion experiment was conducted with the organic loading rate (OLR) of 0.60 – 0.72 kg VS/m<sup>3</sup> /day. The specific biogas production for all the seasons was found to be 0.56 – 0.68 m<sup>3</sup> /kg VS, with the volumetric methane content of 54.3 – 62.8%. The average seasonal specific methane production was observed in the range of 0.30 – 0.41 m<sup>3</sup> /kg VS. The anaerobic digestion conversion efficiency of 55.3 – 67.0% was found for the anaerobic digestion of the wastes. The problem of the rapid acidification of kitchen waste has been rectified with the addition of protein-rich de-oiled pongamia cake in place of alkali chemicals. Furthermore, the digested slurry of biogas plant contained 2.3–2.6% nitrogen, 0.6 – 0.9% phosphorus, and 0.7 – 1.1% potassium, demonstrating rich nutrition value for enhancing the soil quality as an organic manure.

The anaerobic digestion process requires huge amount of water that is to be fed on a daily basis along with the substrates to maintain the required feeding rate. However, the use of freshwater or groundwater for operating the AD process is not a sustainable option, considering its supply is getting very limited in many regions. Based on this concern, the third experiment was conducted on two pilot-scale anaerobic digesters (digesters A and B) having a total volume of 307 L (working volume: 192 L) were used for a study period of 55 days. Digester A was based on anaerobic digestion of kitchen waste with freshwater and digester B was based on anaerobic digestion of kitchen waste with wastewater. The average specific methane production yield from digester A and digester B were estimated as  $273.48 \pm 100$  L/kg VS and  $258.37 \pm 94$  L/kg VS, respectively.

After the three sets of experiments, the final objective was to estimate the techno-economics and greenhouse gas (GHG) mitigation potential of the system if the proposed strategy is applied. In order to simulate the results, a 200 m<sup>3</sup> kitchen waste-based biogas system for various commercial applications (cooking, electricity and vehicular applications) was considered. According to the results, the strategy is profitable with a payback period of 2.6 years, 6.5 years and 7.4 years, respectively for cooking, electricity and vehicular applications.

Thus, it can be summarized that the successful long-term operation of anaerobic digestion of KW is possible using natural additives and reduced freshwater requirement. Moreover, the study shows the prospects for resolving the shortcomings generally observed in existing KW based biogas plants and set an example for operating new biogas plants without the need for any design modifications.

रसोई, सब्जी और फलों के अपशिष्टों के अवायवीय पाचन को इसकी अत्यधिक निम्नीकरणीय प्रकृति के कारण बार-बार संरचना परिवर्तन और तेजी से पचने वाले अम्लीकरण की चुनौती का सामना करना पड़ता है। दुनिया भर के शोधकर्ताओं ने आम तौर पर क्षारीय रसायनों को शामिल करके समस्या का समाधान किया है, जो पर्यावरण को और नुकसान पहुंचाता है और समग्र लागत अर्थशास्त्र में जोड़ता है। इस अध्ययन का उद्देश्य इस समस्या को हल करने के लिए प्राकृतिक योजकों के उपयोग की प्रभावकारिता की जांच करना है। इस अध्ययन में करंज की खली का उपयोग किया गया जो अन्यथा अखाद्य है और इसका उपयोग कम होता है। पहले प्रयोग में, रसोई के अपशिष्टों को उनकी pH विशेषताओं के अनुसार उच्च अम्लीय (pH: 2.00 - 5.00), मध्यम अम्लीय (pH: 5.00 - 7.00) और निम्न क्षारीय (pH: 7.00 - 8.00) के रूप में अलग किया गया था और तीन बायोगैस संयंत्र (I, II और III) में अलग-अलग अध्ययन किया गया था, जिनकी कुल मात्रा 307 L (कार्यशील मात्रा: 192 L) थी। बायोगैस संयंत्र I के लिए 2.80 VS/ m<sup>3</sup>/दिन, बायोगैस संयंत्र II के लिए 2.61 VS/ m<sup>3</sup>/दिन और बायोगैस संयंत्र III के लिए 2.60 kg VS/ m<sup>3</sup>/दिन की जैविक लोडिंग दर के साथ 280 दिन तक अध्ययन किया। बायोगैस संयंत्र I, II और III ने 177.82 ± 19.30, 216.57 ± 7.42 और 280.45 ± 2.55 L/kg VS की औसत बायोगैस पैदावार हासिल की। बायोगैस संयंत्र I में करंज की खली का अधिकतम सहक्रियात्मक प्रभाव देखा गया, जिसमें 46.04% की वृद्धि हुई मीथेन उत्पादन और 11.18% की अस्थिर ठोस कमी हुई। प्रमुख घटक विश्लेषण और गतिज मूल्यांकन से पता चला कि करंज की खली के संयोजन से 96% से अधिक ऊर्जा दक्षता प्राप्त करने वाले सभी डाइजेस्टर में अवायवीय पाचन मापदंडों पर महत्वपूर्ण सकारात्मक प्रभाव पड़ा। अध्ययन में सफलता के साथ, दूसरे प्रयोग में एक साल के अध्ययन के लिए 25 m<sup>3</sup>/दिन क्षमता वाले बायोगैस संयंत्र तक बढ़ा दिया गया।

रसोई अपशिष्ट में मौसमी भिन्नता का अध्ययन 360 दिनों की अध्ययन अवधि को छह मौसमों (प्रत्येक मौसम में 60 दिन) में वर्गीकृत करके किया गया था, अर्थात्, वसंत, ग्रीष्म, मानसून, शरद ऋतु, प्रारंभिक सर्दी और पूर्ववर्ती सर्दी। रसोई अपशिष्ट के सभी गुणों को ध्यान में रखते हुए, अवायवीय पाचन प्रयोग 0.60

- 0.72 kg VS/ m<sup>3</sup>/दिन की जैविक लोडिंग दर के साथ आयोजित किया गया था। सभी मौसमों के लिए विशिष्ट बायोगैस उत्पादन 0.56 - 0.68 m<sup>3</sup> /kg VS पाया गया, जिसमें वॉल्यूमेट्रिक मीथेन सामग्री 54.3 - 62.8% थी। औसत मौसमी विशिष्ट मीथेन उत्पादन 0.30 - 0.41 m<sup>3</sup> /kg VS की सीमा में देखा गया। अपशिष्टों के अवायवीय पाचन के लिए अवायवीय पाचन रूपांतरण दक्षता 55.3 - 67.0% पाई गई। क्षार रसायनों के स्थान पर प्रोटीन युक्त करंज की खली को शामिल करने से रसोई अपशिष्ट के तेजी से अम्लीकरण की समस्या को ठीक किया गया है। इसके अलावा, बायोगैस संयंत्र के पचे हुए घोल में 2.3-2.6% नाइट्रोजन, 0.6 - 0.9% फॉस्फोरस और 0.7 - 1.1% पोटेशियम पाया गया है, जो जैविक खाद के रूप में मिट्टी की गुणवत्ता बढ़ाने के लिए समृद्ध पोषण मूल्य का प्रदर्शन करता है।

अवायवीय पाचन प्रक्रिया के लिए बड़ी मात्रा में पानी की आवश्यकता होती है जिसे आवश्यक भोजन दर को बनाए रखने के लिए सब्सट्रेट के साथ दैनिक आधार पर पिलाया जाता है। हालाँकि, अवायवीय पाचन प्रक्रिया के संचालन के लिए मीठे पानी या भूजल का उपयोग एक स्थायी विकल्प नहीं है, क्योंकि कई क्षेत्रों में इसकी आपूर्ति बहुत सीमित हो रही है। इस चिंता के आधार पर, तीसरा प्रयोग दो पायलट-स्केल बायोगैस संयंत्र (बायोगैस संयंत्र ए और बी) पर आयोजित किया गया था, जिनकी कुल मात्रा 307 L (कार्य मात्रा: 192 L) थी, जिसका उपयोग 55 दिनों की अध्ययन अवधि के लिए किया गया था। बायोगैस संयंत्र ए ताजे पानी के साथ रसोई अपशिष्ट के अवायवीय पाचन पर आधारित था और बायोगैस संयंत्र बी अपशिष्ट जल के साथ रसोई अपशिष्ट के अवायवीय पाचन पर आधारित था। बायोगैस संयंत्र ए और बायोगैस संयंत्र बी से औसत विशिष्ट मीथेन उत्पादन उपज क्रमशः 273.48 ± 100 L/kg TS और 258.37 ± 94 L/kg VS अनुमानित की गई थी।

प्रयोगों के तीन समूह के बाद, अंतिम उद्देश्य प्रस्तावित रणनीति लागू होने पर सिस्टम की तकनीकी-अर्थशास्त्र और ग्रीनहाउस गैस शमन क्षमता का अनुमान लगाना था। परिणामों का अनुकरण करने के लिए, विभिन्न व्यावसायिक अनुप्रयोगों (खाना पकाने, बिजली और वाहन अनुप्रयोगों) के लिए 200 m<sup>3</sup> रसोई अपशिष्ट-आधारित बायोगैस प्रणाली पर विचार किया गया। परिणामों के अनुसार, यह कार्यनीति खाना

पकाने, बिजली और वाहन अनुप्रयोगों के लिए क्रमशः 2.6 वर्ष, 6.5 वर्ष और 7.4 वर्ष की भुगतान अवधि के साथ लाभदायक है।

इस प्रकार, यह संक्षेप में कहा जा सकता है कि प्राकृतिक योजक और कम मीठे पानी की आवश्यकता का उपयोग करके रसोई अपशिष्ट के अवायवीय पाचन का सफल दीर्घकालिक संचालन संभव है। इसके अलावा, अध्ययन आम तौर पर मौजूदा रसोई अपशिष्ट आधारित बायोगैस संयंत्रों में देखी जाने वाली कमियों को हल करने की संभावनाओं को दर्शाया है और किसी भी डिजाइन संशोधन की आवश्यकता के बिना नए बायोगैस संयंत्रों के संचालन के लिए एक उदाहरण स्थापित करता है।

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## ***SYMBOLS AND ABBREVIATIONS***

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%	=	Percent
&	=	And
/	=	Per
<	=	Lower than
>	=	Greater than
°	=	Degree
₹	=	Rupee
\$	=	Dollar
AAEMs	=	Alkaline earth metals
AD	=	Anaerobic digestion
Ag	=	Silver
Al	=	Aluminium
BC	=	Biochar
BET	=	Brunauer-Emmett-Teller
°C	=	Degree celsius
Ca	=	Calcium
Ca (OH) <sub>2</sub>	=	Calcium hydroxide
CC	=	Capital cost
CBG	=	Compressed biogas
CHP	=	Combined heat and power
Cm	=	Centimeter
C/N	=	Carbon - nitrogen ratio
CH <sub>4</sub>	=	Methane
CO <sub>2</sub>	=	Carbon dioxide
CO <sub>2</sub> eq	=	Carbon dioxide equivalent
Co	=	Cobalt
COD	=	Chemical oxygen demand

Cu	=	Copper
D	=	Day
Db	=	Dry basis
dia	=	Diameter
DIET	=	Direct interspecies electrons transfer
DR	=	Discount rate
Fe	=	Iron
Fe <sub>3</sub> O <sub>4</sub>	=	Iron oxide
Fe <sub>2</sub> NiO <sub>4</sub>	=	Iron nickel oxide
Fig.	=	Figure
FOKM	=	First-order kinetic model
FVW	=	Fruits and vegetable waste
G	=	Gram
GAC	=	Granular activated carbon
GJ	=	Giga Joules
GHG	=	Greenhouse gas
H <sub>2</sub>	=	Hydrogen
HA	=	High acidic
Hcl	=	Hydrochloric acid
H <sub>2</sub> S	=	Hydrogen sulphide
H <sub>2</sub> SO <sub>4</sub>	=	Sulfuric acid
HRT	=	Hydraulic retention time
HTC	=	Hydrothermal carbonization
IRR	=	Internal rate of return
K	=	Potassium
Kg	=	Kilo gram
kJ	=	Kilo joule
KOH	=	Potassium hydroxide
kW	=	Kilo watt
Km	=	Kilo meter

kVA	=	Kilovolt-ampere
KVIC	=	Khadi and village industries commission
KW	=	Kitchen waste
kWh	=	Kilo watt hour
L	=	Litre
LA	=	Low alkaline
LFM	=	Logistic function model
LHV	=	Lower heating value
LPG	=	Liquefied petroleum gas
M	=	Metre
m <sup>3</sup>	=	Cubic metre
MA	=	Medium acidic
Mg	=	Milligram
Mg	=	Magnesium
MGM	=	Modified Gompertz model
mL	=	Milli litre
Mm	=	Milli metre
Mn	=	Manganese
MJ	=	Megajoule
MLD	=	Million L per day
Mo	=	Molybdenum
MP	=	Microwave pyrolysis
MPa	=	Mega pascal
MP	=	Microwave pyrolysis
MW	=	Mega watt
N	=	Nitrogen
Na	=	Sodium
NaOH	=	Sodium hydroxide
NaHCO <sub>3</sub>	=	Ammonium bicarbonate
NH <sub>3</sub>	=	Ammonia

NH <sub>4</sub>	=	Ammonium ion
Ni	=	Nickel
NO <sub>3</sub> -N	=	Nitrate-nitrogen
NO <sub>x</sub>	=	Nitrogen oxides
NPs	=	Nanoparticles
NPV	=	Net present value
NVS	=	Non-volatile solids
O <sub>2</sub>	=	Oxygen
OLR	=	Organic loading rate
O&M	=	Operation and maintenance
P	=	Phosphorous
PCA	=	Principal component analysis
ppm	=	Part per million
rpm	=	Revolutions per minute
S	=	Sulfur
SA	=	Sensitive analysis
Si	=	Silicon
SRB	=	Sequencing batch reactor
STP	=	Standard temperature and pressure
STPs	=	Sewage treatment plants
T	=	Temperature
TAN	=	Total ammonical-nitrogen
TCD	=	Thermal conductivity detector
TDP	=	Total dissolved phosphorus
TMP	=	Theoretical methane potential
TS	=	Total solids
TSS	=	Total suspended solids
TVSMRE	=	Total volatile solids mass removal efficiency

UASB = Upflow anaerobic sludge blanket reactor  
USD = United states dollar  
UV = Ultraviolet  
V = Volume  
VFA = Volatile fatty acids  
VS = Volatile solids  
Yr = Year  
Zn = Zinc