

**ENHANCEMENT OF BIODEGRADATION AND BIOGAS
GENERATION FROM MUNICIPAL SOLID WASTE CO-
DISPOSED WITH INDUSTRIAL ORGANIC WASTES IN
BIOREACTOR LANDFILLS**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
DECEMBER 2022**

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by

ABHISHEK NARAYANA SRIVASTAVA

Department of Civil Engineering

submitted

in fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
DECEMBER 2022**

DEDICATED
TO
MY PARENTS

CERTIFICATE

This is to certify that the thesis entitled “**Enhancement of Biodegradation and Biogas Generation from Municipal Solid Waste Co-disposed with Industrial Organic Wastes in Bioreactor Landfills**”, being submitted by **Mr. Abhishek N Srivastava**, to the **Indian Institute of Technology Delhi** for the award of the degree of ‘**Doctor of Philosophy**’ in the Department of Civil Engineering is a record bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standards fulfilling the requirement for the Degree of **Doctor of Philosophy**.

The material contained in the thesis is original and has not been submitted in part or full to any other University or Institute for the award of any other degree or diploma.

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(Abhishek N Srivastava)

ABSTRACT

Sustainable and energy efficient disposal of solid waste has been challenging since long decades due to unprecedented increase in urbanization and industrialization. Municipal solid waste (MSW) and industrial organic wastes are the wastes of concern these days. Open dumping is a very common practice of disposing these wastes imparting immense environmental challenges and health hazards. Besides being the foremost method of treating MSW, conventional dry tomb landfill pertains series of shortcomings involving slow degradation rate, lower landfill gas generation and leachate toxicity. However, bioreactor landfill facilitates early bio-stabilization in comparatively shorter period with augmented landfill gas yield and significantly decreased leachate strength. Co-disposal MSW and organic sludges from industries in bioreactor landfills could reinforce enhanced bio-stabilization rate, biogas generation and dilution of toxicants in waste mass. Therefore, in this research, the co-landfilling of MSW and distinct industrial organic wastes from paper, sugar and distillery industries have been performed in simulated landfill bioreactors. Effluent treatment and de-inking sludges from paper mill have been proved to be excellent substrates for enhancing biodegradation, biomethane generation and reducing heavy metal bioavailability. The effluent treatment sludge (ETS) was co-disposed with MSW in three distinct proportions 25:75 (R2), 50:50 (R3) and 75:25 (R4) keeping 0:100 (R1) as control. It was observed after 300 days of landfilling that ETS co-disposal with MSW showed considerable reductions (R2: 95.9%, R3: 97.5% and R4: 93.2%) in biochemical oxygen demand (BOD) of leachate. Moreover, cumulative methane gas generations were 2.974, 6.085 and 4.653 times more in R2, R3 and R4 bioreactors as compared to R1. Further, in order to overcome the shortcomings of sole landfilling, dual-mode approach with consecutive dry tomb – bioreactor landfilling (DTL – BRL) was investigated for co-disposal of MSW and pressmud (PM) from sugar mill. The dual mode

landfilling of PM and MSW also followed similar co-landfilling ratio as that of ETS, i.e., [PM:MSW] viz. 0:1 (BR1), 1:3 (BR2), 1:1 (BR3) and 3:1 (BR4). The PM co-disposal with MSW in such dual mode landfilling approach not only enhanced stabilization rate but also assisted in reducing heavy metal toxicity of solid digestate. The highest biomethane generation of 46.355L was obtained in landfill lysimeter BR3 followed by BR4 (34.680L), BR2 (24.275L) and BR1 (12.850L). The landfill reactor BR3 with equal co-disposal ratio, achieved highest increments in stable residual fractions (Cr, Ni, Pb, Cu, Cd and Zn by 4.69%, 8.45%, 6.80%, 6.84%, 3.40% and 4.35%, respectively) of each heavy metal after 300 days of dual mode landfilling operation.

Another semi-solid viscous waste from distillery industry, molasses (ML) was also co-landfilled with MSW in distinct proportionate dilutions. Presence of degradable sugar content in molasses considerably augmented the landfill gas generation in anaerobic MSW landfill reactor. Precisely, the reactor with 0.2L of ML/100g MSW fetched maximum biomethane yield of 12.38L which was 4.93 times higher than sole MSW disposed bioreactor. Nevertheless, its excess disposal quantity may impart extra heavy metals and organic loading to degrade. The ML addition opens the dimension of incorporating similar other wastes as beneficial additives for biomethane enhancement. Hybrid operation with series of intermittent aerations in anaerobic bioreactor co-landfill simulators significantly enhanced leachate decontamination rate and improved biodegradation kinetics. Aeration assisted in balancing the pH conditions of landfill bioreactors which ultimately favored the methanogenesis process. The hybrid bioreactor with equal proportion of PM and MSW reached to highest degree of organic pollutants removal (BOD: 94% and COD: 88.92%) as compared to other co-landfilled hybrid bioreactors. The results also reinforced that apart from hybrid operation, co-disposal proportion is also crucial for required degree of bio-stabilization. Furthermore, lime sludge from paper mill was utilized for maintaining favorable

MSW landfilling conditions in three distinct quantities. The leachate results demonstrated a maximum of 76.47% organic loading reduction with 3.31 times more biogas yield than that of control MSW landfill through optimum dose of 6.25% LS addition. The influence of disposing pretreated industrial organic waste in MSW landfill was also assessed through investigation of PM compost co-disposal with MSW in anaerobic bioreactor landfills. Hydrolyzed PM through composting improved the overall digestion rate by providing extra growth sites for degrading microorganisms and enhanced cumulative landfill gas yield. In particular, composted bioreactor attained ~80% BOD and ~72% COD removal which was higher than that of sole MSW disposed landfill reactor.

Lastly, mathematical modeling for justifying energy generation potential of Indian MSW was performed using Default, first order decay (FOD) and LandGEM models. Default method overestimated the methane volume than that of LandGEM and FOD model predictions and results showed that Delhi landfills are still having ample energy generation potential despite of being very old. Further, the neural network and regression models worked efficiently for predicting leachate pollutant removal and landfill gas generation during anaerobic co-landfilling operation. The research carried out expands the dimensions of co-landfilling of various other non-hazardous industrial sludges with MSW for enhancing bio-stabilization rate and resourceful recovery from disposed biomass.

The research work explored one of its kind findings to support simultaneous treatment and resourceful utilization of challenging solid wastes generated from industries and municipalities for bioenergy generation. The heavy metal bioavailability as first such extensive study in any landfilling scenario, expands the horizon of prospective works to be conducted in the area of co-landfilling.

शोध प्रबंध का शीर्षक: बायोरिएक्टर लैंडफिल में औद्योगिक जैविक कचरे के साथ नगरपालिका ठोस अपशिष्ट सह-निपटान से जैव अवक्रमण और जैव ऊर्जा उत्पादन में वृद्धि

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सार

शहरीकरण और औद्योगीकरण में अभूतपूर्व वृद्धि के कारण लंबे दशकों से ठोस कचरे का सतत और ऊर्जा कुशल निपटान चुनौतीपूर्ण रहा है। नगरपालिका ठोस अपशिष्ट और औद्योगिक जैविक अपशिष्ट इन दिनों चिंता का विषय हैं। खुले में डंपिंग इन कचरे को निपटाने का एक बहुत ही आम चलन है जो अत्यधिक पर्यावरणीय चुनौतियों और स्वास्थ्य के लिए खतरा पैदा करता है। नगरपालिका ठोस अपशिष्ट के उपचार की सबसे महत्वपूर्ण विधि होने के अलावा, पारंपरिक शुष्क मकबरा लैंडफिल में कमियों की श्रृंखला शामिल है, जिसमें धीमी गिरावट दर, कम लैंडफिल गैस उत्पादन और लीचेट विषाक्तता शामिल है। हालांकि, बायोरिएक्टर लैंडफिल संवर्धित लैंडफिल गैस उपज के साथ तुलनात्मक रूप से कम अवधि में प्रारंभिक जैव-स्थिरीकरण की सुविधा प्रदान करता है और लीचेट की ताकत में काफी कमी आई है। बायोरिएक्टर लैंडफिल में उद्योगों से सह-निपटान नगरपालिका ठोस अपशिष्ट और जैविक कीचड़ अपशिष्ट द्रव्यमान में जैव-स्थिरीकरण दर, बायोगैस उत्पादन और विषाक्त पदार्थों के कमजोर पड़ने को सुदृढ़ कर सकते हैं। इसलिए, इस शोध में, नकली लैंडफिल बायोरिएक्टरों में एमएसडब्ल्यू और कागज, चीनी और डिस्टिलरी उद्योगों से अलग-अलग औद्योगिक जैविक कचरे के सह-लैंडफिलिंग का प्रदर्शन किया गया है। पेपर मिल से बहिस्राव उपचार और डी-इंकिंग कीचड़ जैव अवक्रमण, जैव ऊर्जा उत्पादन और भारी धातु जैवउपलब्धता को कम करने के लिए उत्कृष्ट सबस्ट्रेट्स साबित हुए हैं। प्रवाह उपचार कीचड़ (ETS) को MSW के साथ तीन अलग-अलग अनुपातों 25:75 (R2), 50:50 (R3) और 75:25 (R4) में 0:100 (R1) को नियंत्रण में रखते हुए सह-निपटान किया गया था। लैंडफिलिंग के 300 दिनों के बाद यह देखा गया कि एमएसडब्ल्यू के साथ ईटीएस सह-निपटान ने लीचेट की जैव रासायनिक ऑक्सीजन मांग (बीओडी) में काफी कमी (आर2: 95.9%, आर3: 97.5% और आर4: 93.2%) दिखाई। इसके अलावा, संचयी मीथेन गैस उत्पादन R1 की तुलना में R2, R3 और R4 बायोरिएक्टर में 2.974, 6.085 और 4.653 गुना अधिक था। इसके अलावा, एकमात्र लैंडफिलिंग

की कमियों को दूर करने के लिए, चीनी मिल से एमएसडब्ल्यू और प्रेसमड (पीएम) के सह-निपटान के लिए लगातार सूखी कब्र - बायोरिएक्टर लैंडफिलिंग (डीटीएल-बीआरएल) के साथ दोहरे मोड दृष्टिकोण की जांच की गई। पीएम और एमएसडब्ल्यू के दोहरे मोड लैंडफिलिंग ने भी ईटीएस के समान सह-लैंडफिलिंग अनुपात का पालन किया, यानी [पीएम: एमएसडब्ल्यू] अर्थात् 0:1 (BR1), 1:3 (BR2), 1:1 (BR3) और 3:1 (BR4)। इस तरह के दोहरे मोड लैंडफिलिंग दृष्टिकोण में पीएम ने एमएसडब्ल्यू के साथ सह-निपटान न केवल स्थिरीकरण दर में वृद्धि की बल्कि ठोस डाइजेस्ट की भारी धातु विषाक्तता को कम करने में भी सहायता की। 46.355L का उच्चतम बायोमीथेन उत्पादन लैंडफिल लाइसीमीटर BR3 में प्राप्त किया गया, इसके बाद BR4 (34.680L), BR2 (24.275L) और BR1 (12.850L) का स्थान आता है। समान सह-निपटान अनुपात के साथ लैंडफिल रिएक्टर BR3 ने स्थिर अवशिष्ट अंशों (Cr, Ni, Pb, Cu, Cd और Zn में क्रमशः 4.69%, 8.45%, 6.80%, 6.84%, 3.40% और 4.35% की उच्चतम वृद्धि 300 दिनों के दोहरे मोड लैंडफिलिंग हासिल की।

आसवनी उद्योग से एक अन्य अर्ध-ठोस चिपचिपा अपशिष्ट, शीरा (एमएल) भी अलग-अलग आनुपातिक कमजोरियों में एमएसडब्ल्यू के साथ सह-लैंडफिलिंग था। शीरे में सड़ सकने वाली चीनी की मात्रा की उपस्थिति ने अवायवीय एमएसडब्ल्यू लैंडफिल रिएक्टर में लैंडफिल गैस उत्पादन में काफी वृद्धि की। संक्षेप में, 0.2L एमएल/100 ग्राम MSW वाले रिएक्टर ने 12.38L की अधिकतम बायोमीथेन उपज प्राप्त की जो कि एकमात्र MSW निपटाए गए बायोरिएक्टर की तुलना में 4.93 गुना अधिक थी। फिर भी, इसकी अतिरिक्त निपटान मात्रा अतिरिक्त भारी धातुओं और कार्बनिक लोडिंग को नीचा दिखाने के लिए प्रदान कर सकती है। एमएल जोड़ बायोमीथेन वृद्धि के लिए लाभकारी योजक के रूप में इसी तरह के अन्य कचरे को शामिल करने के आयाम को खोलता है। अवायवीय बायोरिएक्टर सह-लैंडफिल सिमुलेटर में आंतराधिक वातन की श्रृंखला के साथ हाइब्रिड ऑपरेशन ने लीचेट परिशोधन दर में काफी वृद्धि की और बायोडिग्रेडेशन कैनेटीक्स में सुधार किया। वातन ने लैंडफिल बायोरिएक्टरों की पीएच स्थितियों को संतुलित करने में सहायता की जो अंततः मेथनोजेनेसिस प्रक्रिया का समर्थन करती थी। पीएम और एमएसडब्ल्यू के समान अनुपात वाले हाइब्रिड बायोरिएक्टर अन्य को-लैंडफिलिंग हाइब्रिड बायोरिएक्टरों की तुलना में कार्बनिक प्रदूषकों को हटाने के उच्चतम स्तर (बीओडी: 94% और सीओडी: 88.92%) तक पहुंच गए। परिणामों ने यह भी पुष्ट किया कि जैव-स्थिरीकरण की आवश्यक डिग्री के लिए हाइब्रिड ऑपरेशन के अलावा, सह-निपटान अनुपात भी महत्वपूर्ण है। इसके अलावा, तीन अलग-अलग मात्राओं में अनुकूल एमएसडब्ल्यू लैंडफिलिंग स्थितियों को

बनाए रखने के लिए पेपर मिल से लाइम स्लज का उपयोग किया गया था। लीचेट के परिणामों ने अधिकतम 76.47% जैविक लोडिंग में कमी का प्रदर्शन किया, जिसमें 6.25% एलएस की इष्टतम खुराक के माध्यम से नियंत्रण MSW लैंडफिल की तुलना में 3.31 गुना अधिक बायोगैस उपज थी। अवायवीय बायोरिएक्टर लैंडफिल में एमएसडब्ल्यू के साथ पीएम कंपोस्ट सह-निपटान की जांच के माध्यम से एमएसडब्ल्यू लैंडफिल में पूर्व-उपचारित औद्योगिक जैविक कचरे के निपटान के प्रभाव का भी आकलन किया गया था। खाद के माध्यम से हाइड्रोलाइज्ड पीएम ने सूक्ष्मजीवों को नष्ट करने के लिए अतिरिक्त विकास स्थल प्रदान करके समग्र पाचन दर में सुधार किया और संचयी लैंडफिल गैस उपज में वृद्धि की। विशेष रूप से, कंपोस्टेड बायोरिएक्टर ने ~ 80% बीओडी और ~ 72% सीओडी हटाने को प्राप्त किया जो एकमात्र एमएसडब्ल्यू निपटान लैंडफिल रिएक्टर की तुलना में अधिक था।

अंत में, भारतीय MSW की ऊर्जा उत्पादन क्षमता को सही ठहराने के लिए गणितीय मॉडलिंग को डिफ़ॉल्ट, प्रथम क्रम क्षय (FOD) और LandGEM मॉडल का उपयोग करके प्रदर्शित किया गया था। लैंडजीईएम और एफओडी मॉडल की भविष्यवाणियों की तुलना में डिफ़ॉल्ट विधि ने मीथेन की मात्रा को अधिक अनुमानित किया और परिणामों से पता चला कि दिल्ली लैंडफिल में बहुत पुरानी होने के बावजूद अभी भी पर्याप्त ऊर्जा उत्पादन क्षमता है। इसके अलावा, अवायवीय सह-लैंडफिलिंग ऑपरेशन के दौरान लीचेट प्रदूषक हटाने और लैंडफिल गैस उत्पादन की भविष्यवाणी के लिए तंत्रिका नेटवर्क और प्रतिगमन मॉडल ने कुशलता से काम किया।

शोध कार्य ने जैव ऊर्जा उत्पादन के लिए उद्योगों और नगर पालिकाओं से उत्पन्न चुनौतीपूर्ण ठोस कचरे के एक साथ उपचार और संसाधनपूर्ण उपयोग का समर्थन करने के लिए अपनी तरह के निष्कर्षों की खोज की। किसी भी लैंडफिलिंग परिदृश्य में इस तरह के पहले व्यापक अध्ययन के रूप में भारी धातु की जैवउपलब्धता सह-लैंडफिलिंग के क्षेत्र में किए जाने वाले संभावित कार्यों के क्षितिज का विस्तार करती है।

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landfill bioreactors

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LIST OF ABBREVIATIONS

Acronyms	Expanded form
ANN	Artificial neural network
ANOVA	Analysis of Variables
APHA	American Public Health Association
BioF	Bioavailability Factor
BRL	Bioreactor Landfill
BP	Back-propagation
BL	Bhalswa Landfill
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DM	Default Method
DPS	De-inking Plant Sludge
DTL	Dry Tomb Landfill
EC	Electrical Conductivity
EPA	Environmental Protection Agency
ETS	Effluent Treatment Plant Sludge
FOD	First Order Decay
GL	Ghazipur Landfill
IPCC	Intergovernmental Panel on Climate Change
LFG	Landfill gas
LS	Lime Sludge
LSD	Least square difference
LMBP	Levenberg-Marquardt Back-Propagation
MAPE	Mean absolute percentage error
ML	Molasses
MCD	Municipal Corporation of Delhi
MCF	Methane Correction Factor
MSD	Mean squared deviation
MSE	Mean squared error
MSW	Municipal solid waste
OL	Okhla Landfill
ORP	Oxidation reduction potential
PM	Pressmud
PMC	Pressmud Compost
SPSS	Statistical Package for the Social Science
TS	Total Solids
TN	Total Nitrogen
VS	Volatile Solids
VFA	Volatile fatty Acids