

**PROCESS OPTIMIZATION AND PILOT SCALE TESTING OF ALGAL
BIOMETHANATION INTEGRATED WITH WASTEWATER
TREATMENT**

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ALGAL BIOMETHANATION INTEGRATED WITH
WASTEWATER TREATMENT**

by

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Submitted

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Dedicated to My Parents.....

CERTIFICATE

This is to certify that the thesis entitled “**PROCESS OPTIMIZATION AND PILOT SCALE TESTING OF ALGAL BIOMETHANATION INTEGRATED WITH WASTEWATER TREATMENT**” being submitted by **Mr. Pushpendar Kumar** to the Indian Institute of Technology Delhi for the award of “**Doctor of Philosophy**” is a record of bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements for submission of this thesis. To the best of our knowledge the results contained in this thesis have not been submitted in part or full to any other university or institute for award of any degree or diploma.

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ABSTRACT

The commercial potential of algae mediated wastewater treatment and biofuel production technologies is impaired by expensive cultivation systems, low biomass productivity and complex biomass to biofuel conversion routes. The major bottleneck can be overcome by focusing on abundantly occurring natural consortia and selecting simpler, low energy intensive conversion routes. It was hypothesized that the feasibility and energy balance of the algal biomethanation process may be improved through systematic and serious attempts on anaerobic digestion of naturally grown algal biomass, its co-digestion with a suitable carbon rich co-substrate and further process optimization through innovative interventions including identification of suitable inoculum and optimization of volatile solid (VS) loading/digestion time for algal digestion.

In view of the above, the present work was aimed at exploring the wastewater treatment and biomethanation potential of naturally occurring algal consortia designated as HL (collected from eutrophied Hauz Khas lake) through small scale batch studies followed by the pilot level scale up of the cultivation system. Further, sequential optimization of inoculum, co-substrate and VS loading rate was attempted in order to enhance the biomethanation of waste algal biomass. Subsequently, the effect of seasonal variation on biomass productivity (in Hauz Khas lake) and biomethanation in a pilot anaerobic digester (using selected inoculum and co-substrate) was studied over a period of one year to evaluate the practical feasibility of such integrations.

To begin with, the native algal consortia, dominating the nearby Hauz Khas lake was obtained and evaluated for wastewater treatment potential. The dominating algal species in the collected algal consortium were *Chlorella* sp., *Merismopedia* sp., *Closteriopsis* sp. and *Scenedesmus* sp. The consortium grew well in standard media as well as in different wastewaters. Highest biomass productivity ($1.25 \pm 0.28 \text{ g. L}^{-1}$) and nutrient removal was achieved in contaminated and nutrient rich grey water. Subsequently, the process was scaled up in open ponds raceway (800 L). The algal consortium was efficient for the continuous treatment of drainage channel wastewater (DCWW) below discharge limits along with the production of biomass with an average concentration up to $0.68 \pm 0.05 \text{ g. L}^{-1}$. The algal biomass produced during wastewater treatment was rich in lipid (45.87% TS) with an estimated theoretical methane potential of 741 mL. $\text{CH}_4 \text{ g}^{-1}$. VS. However, experimental cumulative yield was up to 277.30 mL. $\text{CH}_4 \text{ g}^{-1}$. VS_{fed}, observed during 30 d anaerobic digestion of algal biomass due to low digestibility (38%) of the

algal biomass with only 44% volatile solid reduction. Overall, the tested consortium had good potential for wastewater treatment coupled with substantial biomass production. However, further attempts must be done to improve the methane yield and digestibility of the tested algal biomass.

Next, sequential optimization of inoculum, co-substrate and VS loading rate was conducted to enhance biomethanation of algal biomass collected from eutrophied Hauz Khas lake. Higher methane yield ($279 \text{ mL. g}^{-1} \cdot \text{VS}_{\text{fed}}$) was observed using inoculum from algae-cattle dung based biogas plant compared to $170 - 200 \text{ mL. g}^{-1} \cdot \text{VS}_{\text{fed}}$ using other inocula (from sewage sludge, *Jatropha*/Karanja cake and cattle dung based plant). Biomethane yield was further enhanced ($312 \text{ mL. g}^{-1} \cdot \text{VS}_{\text{fed}}$) by co-digestion with cattle dung (HL+CD) as compared to $282 \text{ mL. g}^{-1} \cdot \text{VS}_{\text{fed}}$ for HL+WAS (waste activated sludge). Further, VS loading of 5 g. VS. L^{-1} gave highest methane yield of $315 \text{ mL. g}^{-1} \cdot \text{VS}_{\text{fed}}$ while a decrease (240 and $224 \text{ mL. g}^{-1} \cdot \text{VS}_{\text{fed}}$) was observed at 10 and 15 g. VS. L^{-1} , respectively.

To ensure the practical feasibility of the proposed integration, Hauz Khas lake water parameters and algal biomass productivity were studied over a duration of one year (January to December, 2015). Highest nutrient load in Hauz Khas lake water was observed in the month of August and November. The highest algal biomass productivity was observed in the months of April and November. The annual algal biomass productivity was $2.06 \pm 0.21 \text{ g. L}^{-1}$. Pilot-scale anaerobic digester ($\approx 0.5 \text{ m}^3$) was installed for performance evaluation of algal biomass-cattle dung (1:1) co-digestion feedstock for a period of nearly one year from July 2014 to September 2015. The inoculum, co-substrate and VS loading were selected based on batch scale optimization results. The average yield of methane was estimated to be $0.6 - 0.8 \text{ m}^3 \text{ methane m}^{-3} \text{ digester d}^{-1}$ during summer season while it ranged from $0.5 - 0.6 \text{ m}^3 \text{ methane m}^{-3} \text{ digester d}^{-1}$ during winters. The methane content was found to be in the range of 51-60%. Monthly estimation of various wastewater parameters viz., pH, total alkalinity, total volatile fatty acids (TVFA) and ammonia nitrogen ($\text{NH}_4\text{-N}$) indicated the long term stability of the pilot scale process. This study established the feasibility of utilizing wastewater grown native algal consortia for year round biogas production.

(ABSTRACT) सारांश

शैवाल का वाणिज्यिक उत्पादन और अपशिष्ट जल उपचार एवं कम बायोमास उत्पादकता और जैव ईंधन में रूपान्तरण के लिए एक जटिल प्रक्रिया है। बहुसंख्यक प्राकृतिकीय उत्पन्न शैवाल के बायोमास पर ध्यान केन्द्रित करके कम ऊर्जा गहन रूपान्तरण मार्गों के चयन से प्रमुख अवरोध को दूर किया जा सकता है। यह अनुमान लगाया गया है कि शैवाल के जैव मेथेनेशन प्रक्रिया की औचित्य और ऊर्जा संतुलन प्राकृतिक रूप से विकसित शैवालवीय बायोमास के अवायवीय पाचन पर व्यवस्थित और महत्वपूर्ण प्रयासों के माध्यम से उचित कार्बन युक्त सह सब्सट्रेट (Co-substrate) सहपाचन (Codigestion) और शैवाल पाचन के लिए उपयुक्त इनोकुलम (Inoculum) की पहचान और वाष्पील ठोस (Volatile solid) का भारण (loading) / पाचन समय (Digestion time) के प्रगतिशील मध्यवर्ती के माध्यम से आगे की प्रक्रिया में सुधार किया जा सकता है।

उपरोक्त के मद्देनजर, वर्तमान कार्य का उद्देश्य अपशिष्ट जल उपचार और प्राकृतिक रूप से उत्पन्न होने वाला शैवाल संकाय को जैव मेथेनेशन की सामर्थ्य को तलाशने के उद्देश्य से किया था जिसे हौज खास यूट्रोफाइड बायोमास के रूप में नामित को छोटे स्तर के अध्ययन और उच्चतर स्तर के शैवाल उत्पादन के लिए लिया गया था इसके अलावा, अपशिष्ट शैवाल बायोमास से जैव मेथेनेशन को बढ़ाने के लिए इनोकुलम, सह सब्सट्रेट और वी एस भारण दर का क्रमबद्ध अनुकूलन का प्रयास किया गया है। इसके पश्चात, हौज खास झील में बायोमास उत्पादकता और जैव मेथेनेशन मौसमी परिवर्तन के प्रभाव (चयनित इनोकुलम और सह सब्सट्रेट का प्रयोग करके) का एक वर्ष की अवधि तक इस तरह के एकीकरण के व्यावहारिक सम्भाव्यता का मूल्यांकन एवं अध्ययन किया गया।

प्रारम्भ में, अपशिष्ट जल उपचारण के लिए पास के हौज खास झील पर प्रभुत्व रखने वाली स्वभाविक उत्पादित शैवालीय संकाय का प्रयोग किया गया एकत्र शैवालीय संकाय में प्रभुत्व रखने वाली प्रजातियां क्लोरेला जाति, मेरिस्मोपिडिया जाति, क्लोस्टेरियोप्सिस जाति और स्केन्डेसमस जाति हैं। मानक मीडिया (Standard media) और विभिन्न अपशिष्ट जल में शैवालीय संकाय का उत्पादन अच्छा रहा। उच्चतम बायोमास उत्पादकता ($1.25 \pm 0.28 \text{ g L}^{-1}$) और पोषक तत्व निष्कासन अपशिष्ट जल में प्राप्त हुई। तत्पश्चात, इस प्रक्रिया को खुले तालाब (open ponds raceway, 800 L) में बढ़ाया गया शैवालीय संकाय बायोमास उत्पादन ($0.68 \pm 0.05 \text{ g L}^{-1}$) के साथ-2 जल निकासी चैनल अपशिष्ट जल (Drainage channel wastewater, DCWW) के निरंतर उपचार के लिए कुशल था। अपशिष्ट जल उपचारण के दौरान उत्पादित शैवाल बायोमास में अधिक वसा युक्त ($45.87\% \text{ TS}$) और अनुमानित सैद्धान्तिक मीथेन क्षमता $741 \text{ mL CH}_4 \text{ g}^{-1} \text{ VS}$ थी। हालांकि, 30 दिन के अवायवीय पाचन के द्वारा प्रायोगिक संचयित उत्पन्न मीथेन $277.30 \text{ mL CH}_4 \text{ g}^{-1} \text{ VS}$ देखा गया जो कि शैवालीय बायोमास के कम पाचन शक्ति (38%) और केवल 44% वाष्पील ठोस में कमी के कारण प्राप्त हुई। सामान्यतः, परीक्षण किये गये शैवालीय संकाय बायोमास

में पर्याप्त बायोमास उत्पादन के साथ अपशिष्ट जल उपचारण के लिए अच्छी संभावना थी। हालांकि, परीक्षण किये गये शैवाल के बायोमास से मीथेन उत्पादन और पाचन क्षमता में सुधार के लिए आगे प्रयास किए जाने चाहिए।

इसके बाद, यूट्रोफाइड हौज खास झील से एकत्रित शैवाल बायोमास के जैव मेथेनेशन को बढ़ाने के लिए इनोकुलम, सह सब्सट्रेट और वाष्पील ठोस भारण दर का अनुक्रमिक अनुकूलन किया गया। उच्चतम मीथेन उत्पादन ($279 \text{ mL} \cdot \text{g}^{-1} \cdot \text{VS}_{\text{fed}}$) शैवाल और पशु गोबर आधारित बायोगैस संयंत्र से इनोकुलम उपयोग करते हुए देखा गया था जो कि अन्य प्रकार के इनोकुला (Inocula) (सीवेज गाद/जटरोफा/करंजा केक और गौबर आधारित संयंत्र) का उपयोग करके मीथेन उत्पादन $170 - 200 \text{ mL} \cdot \text{g}^{-1} \cdot \text{VS}_{\text{fed}}$ प्राप्त किया गया था जैव मीथेन उत्पादन बढ़ाने में हौज खास झील से एकत्रित शैवाल (HL) के साथ गौबर से मीथेन ($312 \text{ mL} \cdot \text{g}^{-1} \cdot \text{VS}_{\text{fed}}$) और (सक्रिय कीचड़) की तुलना में जैव मीथेन ($282 \text{ mL} \cdot \text{g}^{-1} \cdot \text{VS}_{\text{fed}}$) बढ़ा हैं। इसके अलावा, $5 \text{ g VS} \cdot \text{L}^{-1}$ भारण से उच्चतम मीथेन उत्पादन $315 \text{ mL} \cdot \text{g}^{-1} \cdot \text{VS}_{\text{fed}}$ हो गया जबकि क्रमशः 10 और $15 \text{ g VS} \cdot \text{L}^{-1}$ पर (240 and $224 \text{ mL} \cdot \text{g}^{-1} \cdot \text{VS}_{\text{fed}}$) की कमी देखी गयी हैं।

प्रस्तावित एकीकरण की व्यावहारिक व्यवहार्यता सुनिश्चित करने के लिए हौज खास झील के पानी में मापदण्डों और शैवाल बायोमास उत्पादकता का एक वर्ष (जनवरी से दिसंबर 2015) की अवधि तक अध्ययन किया गया है। जबकि अगस्त और नवंबर माह में हौज खास झील में सबसे ज्यादा पोषक तत्व भार देखा गया है और शैवाल बायोमास उत्पादकता अप्रैल और नवंबर माह में सर्वाधिक प्राप्त हुई और वार्षिक शैवाल बायोमास उत्पादकता $2.06 \pm 0.21 \text{ g L}^{-1}$ थी जुलाई 2014 से सितम्बर 2015 एक वर्ष की अवधि के लिए पायलट स्केल (Pilot scale) अवायवीय पाचक (Anaerobic digester, $\approx 0.5 \text{ m}^3$) को शैवाल बायोमास व गौबर (1:1 ratio on the VS basis) सह पाचन फीडस्टोक के प्रदर्शन के मूल्यांकन के लिए स्थापित किया गया था बैच (batch) पैमाने अनुकूलन के परिणामों के द्वारा इनोकुलम, सह सब्सट्रेट और वाष्पील ठोस भारण दर को चुना गया था गर्मियों के दौरान मीथेन की औसत उत्पादकता $0.6 - 0.8 \text{ m}^3 \text{ methane m}^{-3} \text{ digester d}^{-1}$ प्राप्त की गयी जबकि सर्दियों में $0.5 - 0.6 \text{ m}^3 \text{ methane m}^{-3} \text{ digester d}^{-1}$ पायी गयी और मीथेन अवयव $51 - 60 \%$ की सीमा में पाया गया था। विभिन्न अपशिष्ट पदार्थों के मासिक आकलन जैसे पॉवोइर हाइड्रोजीन (pH), कुल क्षारीयता (total alkalinity), कुल वाष्पील वसा अम्ल (total volatile fatty acids, TVFA) और अमोनिया नाइट्रोजन (ammonia nitrogen, $\text{NH}_4\text{-N}$) में पायलट स्केल की प्रक्रिया दीर्घकालिक स्थिति का संकेत दिया। इस अध्ययन के द्वारा वर्ष भर के बायोमास उत्पादन के लिए अपशिष्ट जल उत्पादक निकासी शैवाल संकाय का उपयोग करने की व्यवहार्यता की स्थापना की।

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ABBREVIATIONS

Accumulating volume reactor- AVR;
Anaerobic Digested Slurry- ADS;
Anaerobic granular sludge- AGS;
Biogas plant at sewage treatment plant (STP), Okhla Delhi- Ino.2;
Biomethane potential- BMP;
Brewery waste- BREW;
Cattle dung based biogas plant- Ino. 4;
Cattle dung- CD;
Chicken manure-CM;
Chlorophyll-a Chl-a;
Dry cell weight- DCW;
Differential interference contrast- DIC;
Digestate dairy manure-DM;
Digested slurry collected from algae-cattle dung based biogas plant- Ino. 1;
Dissolved oxygen- DO;
Drainage channel Wastewater- DCWW;
Electric conductivity- EC;
Energy crop waste-ENG;
Hauz Khas lake- HL;
High rate algal ponds-HRAP;
Hydraulic retention time- HRT;
Jatropha/ Karanja cake based biogas plant, CRDT, IIT Delhi- Ino. 3;
Mainly animal manure- MAN;
Municipal sludge- MS;
Organic biological waste-OBW;
Organic loading rate- OLR;

Paper mill sludge- PS;
Phosphate buffer saline- PBS;
Photobioreactor- PBR;
Relative Centrifugal Force- RCF;
Scanning electron microscopy- SEM;
Sewage Treatment Plant Effluent- STPE;
Sludge manure- SM;
Soluble Chemical Oxygen Demand- sCOD
Soluble chemical oxygen demand-sCOD;
Specific methanogenic activity- SMA;
Stoichiometric methane potential- SMP;
Theoretical chemical oxygen demand (COD_{th});
Theoretical methane potential- TMP;
Total Ammonical Nitrogen- TAN;
Total Chemical Oxygen Demand- tCOD;
Total Dissolved Phosphorus- TDP;
Total Dissolved Solids-TDS;
Total Suspended Solids- TSS;
Volatile fatty acids-VFAs;
Volatile Solid reduction- VSR;
Waste activated sludge- WAS;
Wastewater treatment plant-WWTP;