DEVELOPMENT OF A NOVEL RECIRCULATION PHOTOBIOREACTOR FOR ON-SITE TREATMENT OF MUNICIPAL WASTEWATER, AND INVESTIGATIONS ON VALORIZATION OF BIOMASS INTO HIGH-VALUE PRODUCT STREAMS

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by

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CERTIFICATE

This is to certify that the thesis entitled "**Development of a novel recirculation photobioreactor for on-site treatment of municipal wastewater, and investigations on valorization of biomass into high-value product streams**" being submitted by **Mr. Vivek Suresh Dalvi** 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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Vivek Suresh Dalvi

Abstract

The present work strongly sheds light on one of the basic principles of reactor design, i.e., mode of operation (agitation regime), the right choice of which can significantly enhance the microalgal photobioreactor (PBR) process performance and environmental footprints. The agitation regime is responsible for microalgal domination within the photobioreactor was identified via. comprehensive evaluation of phase transformative nutrients, biomass growth and microalgal-bacterial population dynamics. The experiments initiated with dominant M:B inoculation ratio (60:40), demonstrated higher M:B ratio (78:21) with mixing regime, as essential nutrients (dissolved inorganic carbon and ammoniacal nitrogen) were conserved within the wastewater. On the other hand, lower M:B ratio (36:63) was obtained during aeration regime, as these nutrients were transformed into CO_2 and NH_3 and emitted to the environment. The nutrient conservation mechanism within mixing regime enhanced microalgal growth by 30 %, metal removal by 14-59 %, and exhibited carbon negative global warming potential (-0.0451 kgCO_2 eqm^{-3}), along with overall non-negative environmental impact.

The agitation regime (nutrient loss or conservation) has shown direct impact on microalgal pathogen disinfection potential. The aeration system negatively affects pathogen inactivation under laboratory conditions, due to nutrient deficiency for microalgal growth. On the other hand, mixing regime showed enhanced removal of total coliforms (TC), faecal coliforms (FC), klebsiella pneumoniae carbapenemase (KPC) producing bacteria, and extended-spectrum β-lactamase (ESBL) producing bacteria. It can also be concluded that synergistic effect of process [nutrients, elevated pH (>9), and high DO (>10 mg L^{-1})] and environmental variables (light, temperature) play key role in pathogen inactivation.

The outcome of microalgae screening experiment showed that, native microalgal cultures perform better compared to other native cultures isolated from different wastewaters for both wastewater treatment ability and biomass growth potential. Further, both 10 L PBRs (aeration

PBR and mechanical mixing PBR) perform well under outdoor conditions. However, the mechanical mixing PBR showed 10.7% higher biomass yield and wastewater treatment potential, when HRT was reduced to 1d. The seasonal variation impacts the photobioreactor performance. The long-term study carried out on 100 L pilot bubble column PBR concludes that HRT as low as 2d is achievable for the wastewater treatment throughout the year, making the MWTT process a comprehensive and sustainably scalable technology with low areal footprint to 1.42 m^2 KLD^{-1}. However, winter adversely affected the wastewater treatment performance, elucidating the dominance of microalgae or bacterial community is also a function of environmental conditions. The challenge of low temperature could be mitigated through the design of novel recirculation photobioreactor exhibiting heat sink and nutrient conservation mechanism, that shows 25-35% higher biomass and nutrient removal rate along with reduced HRT of 1d, which further brings down the areal footprint to 0.71 m^2 KLD^{-1}. The suitability of ash rich biomass for bioenergy application through one step production of upgraded bio-oil highlights the importance of valorization study.

Overall, the efforts signify the applicability of the developed process of recirculation photobioreactor for wastewater resource conservation and recovery integration with subcritical hydrothermal liquefaction. The process creates a novel approach for creating high-value product streams from water reclamation sources that can significantly impact taxpayer money, generating employability in green chemistry for profit in a traditionally regulated water industry with contributing to biofuels and green catalysis. These findings provide the basis for new frontiers in microalgae-based wastewater treatment and simultaneous valorization of biomass into fuels, chemicals, and bioproducts at both the fundamental and macro commercialization levels.

सारांश

वर्तमान कार्य रिएक्टर डिजाइन के बुनियादी सिद्धांतों में से एक अर्थात्, संचालन का तरीका (मिश्रण रणनीति) पर दृढ़ता से प्रकाश डालता है। जिसका सही विकल्प माइक्रोएल्गल फोटोबायोरिएक्टर (पीबीआर) प्रदर्शन बढ़ा और पर्यावरण पदचिह्न काफी कम कर सकता है। मिश्रण रणनीति फोटोबायोरिएक्टर के भीतर माइक्रोएल्गल प्रभुत्व के लिए जिम्मेदार, चरण परिवर्तनकारी पोषक तत्वों, बायोमास विकास का व्यापक मूल्यांकन और माइक्रोएल्गल-बैक्टीरियल जनसंख्या गतिशीलता के माध्यम से पहचाना गया है। प्रमुख M: B अनुपात के साथ शुरू किए गए प्रयोग (60:40), यांत्रिक मिश्रण व्यवस्था के साथ उच्च M: B अनुपात (78: 21) का प्रदर्शन किया। यांत्रिक मिश्रण व्यवस्था ने अपशिष्ट जल के भीतर आवश्यक पोषक तत्वों (विघटित अकार्बनिक कार्बन और अमोनियाकल नाइट्रोजन) को संरक्षित किया गया था। यांत्रिक मिश्रण व्यवस्था के भीतर पोषक तत्व संरक्षण तंत्र में वृद्धि हुई जिससे माइक्रोएल्गल वृद्धि 30%, धातु हटाने में वृद्धि 14-59% और नकारात्मक कार्बन वैश्विक वार्मिंग क्षमता (-0.0451 $kgCO_2\ eqm^{-3}$) प्रदर्शित किया, समग्र गैर-नकारात्मक पर्यावरणीय प्रभाव के साथ।

मिश्रण व्यवस्था (पोषक तत्वों की हानि या संरक्षण) ने सूक्ष्म शैवाल के रोगज़नक़ कीटाणुशोधन क्षमता पर सीधा प्रभाव दिखाया है। प्रयोगशाला स्थितियों के तहत, वायु मिश्रण व्यवस्था सूक्ष्म शैवाल विकास के लिए पोषक तत्वों की कमी के कारण, सूक्ष्म शैवाल के रोगज़नक़ कीटाणुशोधन क्षमता को नकारात्मक रूप से प्रभावित करती है। दूसरी ओर, मिश्रण व्यवस्था ने कुल कोलीफॉर्म (TC), मल कोलीफॉर्म (FC), क्लेबसिएला निमोनिया कार्बापेनेमास (KPC) उत्पादक बैक्टीरिया, और विस्तारित स्पेक्ट्रम लैक्टामेज (ESBL) उत्पादक बैक्टीरिया को हटाने में वृद्धि दिखाई। यह भी निष्कर्ष निकाला जा सकता है कि सहक्रियात्मक प्रभाव प्रक्रिया [पोषक तत्व, उच्च pH (>9), और उच्च DO (>10 $mg\ L^{-1}$)] और पर्यावरणीय चर (प्रकाश, तापमान) रोगज़नक़ निष्क्रियता में महत्वपूर्ण भूमिका निभाते हैं।

सूक्ष्म शैवाल स्क्रीनिंग प्रयोग के परिणाम से पता चला है कि, देशी सूक्ष्म शैवाल संस्कृतियां अपशिष्ट जल उपचार क्षमता और बायोमास विकास क्षमता इन दोनों के लिए विभिन्न अपशिष्ट जल से अलग अन्य देशी संस्कृतियों की तुलना में बेहतर प्रदर्शन करती हैं। 100L पायलट बबल कॉलम पीबीआर पर किए गए दीर्घकालिक अध्ययन का यह निष्कर्ष निकलता है कि, एचआरटी 2d, पूरे वर्ष अपशिष्ट जल उपचार के लिए प्राप्त करने योग्य है, जिससे सूक्ष्म शैवाल अपशिष्ट जल उपचार पद्धति कम पदचिह्न (1.42 m^2 KLD^{-1}) के साथ एक व्यापक और स्थायी विस्तार योग्य तकनीक है। हालांकि, सर्दियों ने अपशिष्ट जल उपचार के प्रदर्शन पर प्रतिकूल प्रभाव डाला, सूक्ष्म शैवाल या जीवाणु समुदाय के प्रभुत्व को नष्ठ करना भी एक पर्यावरणीय परिस्थितियों का परिणाम है। गर्मी अवशोषण और पोषक तत्वों का संरक्षण करने वाले उपन्यास पुनर्चक्रण फोटोबायोरिएक्टर के डिजाइन के तंत्र से कम तापमान की चुनौती को कम किया जा सकता है, जो 25-35% अधिक बायोमास और पोषक तत्व हटाने की दर दिखाता है। यह तंत्र 1d के कम एचआरटी के साथ, जो पीबीआर के पदचिह्न को 0.71 m^2 KLD^{-1} तक नीचे लाता है। वही एक चरण के उत्पादन के माध्यम से जैव ऊर्जा अनुप्रयोग के लिए राख समृद्ध बायोमास की उपयुक्तता उन्नत जैव-तेल मूल्यीकरण अध्ययन के महत्व पर प्रकाश डालता है।

कुल मिलाकर, प्रयास अपशिष्ट जल संसाधन संरक्षण और उप-महत्वपूर्ण के साथ वसूली एकीकरण के लिए विकसित पुनर्चक्रण फोटोबायोरेक्टर और हाइड्रोथर्मल द्रवीकरण की प्रक्रिया की प्रयोज्यता को दर्शाते हैं। विकसित प्रक्रिया उच्च-मूल्य बनाने के लिए एक नया दृष्टिकोण बनाती है जल सुधार स्रोतों से उत्पाद धाराएं जो करदाताओं के पैसे को काफी प्रभावित कर सकती हैं। पारंपरिक रूप से विनियमित पानी उद्योग में लाभ के लिए विकसित प्रक्रिया जैव ईंधन और हरित उत्प्रेरण में योगदान के साथ हरे रसायन विज्ञान में रोजगार पैदा करती हैं। ये निष्कर्ष, सूक्ष्म शैवाल आधारित अपशिष्ट जल उपचार और एक साथ मूल्यीकरण बायोमास सूक्ष्म और मैक्रो दोनों स्तर पर ईंधन, रसायन, और जैव उत्पादों में व्यावसायीकरण के लिए आधार प्रदान करते हैं।

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