Integrating wastewater treatment to groundwater remediation and energy production using microbial desalination cell

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Abstract

Groundwater (GW) supports one-third of the global population, with India leading in annual withdrawals; however, its use is increasingly constrained by contamination and depletion. Conventional treatment systems, despite high removal efficiencies, involve trade-offs in chemical use, energy demand, fouling, and waste generation, and are often limited in addressing multiple parameters in a cost-effective and scalable manner. This has driven a shift toward integrated systems that combine processes to enhance performance and energy efficiency, while coupling with renewable technologies enables self-sustained operation. Therefore, this research aims to develop an integrated and renewable system that combines wastewater treatment with GW to achieve sustainable and energy - efficient water management. Building on this objective, the microbial desalination cell (MDC) technology was adopted for its inherent sustainability and self-driven operation. MDC is a bioelectrochemical system which tackles the metabolic activities of microorganisms present in the wastewater to generate electricity from waste and subsequently deionize water. Originally developed for desalting saline streams, MDC technology is applied in the present study to treat SGW, which typically features low ion concentrations, compared to sea/brackish water. The MDC fed with GW and wastewater was successful in bringing down total hardness, fluoride, and chloride levels in GW to the permissible limits, as per BIS standards, without any energy or chemical inputs. A maximum wastewater treatment efficiency of 75% was also obtained along with a self-generated power output. However, existing MDC configurations are limited by low ion removal and energy recovery along with high cost of components.

The present study addressed three aspects to enhance the overall effectiveness of MDC. First, to enhance ion removal and energy generation, the anode was modified, as it plays a decisive role in overall MDC performance. The existing carbon-based anode was modified using dimethyl sulfoxide (DMSO), a common laboratory solvent; and titanium carbide MXene ($Ti_3C_2T_x$), a conductive 2D material. To the best of our knowledge, this is the first demonstration of DMSO- and MXene-functionalized anodes in MDCs for synthetic GW (SGW) remediation. As a result, SGW treatment performance improved by 1.27 and 2.36 times following DMSO and MXene modification, respectively, while power generation increased by approximately 2.2 - fold for both cases. The modification with $Ti_3C_2T_x$ exhibited the highest performance. Secondly, in parallel, discarded LCD screens were employed as low - cost alternative anodes in MDCs for bioelectrochemical desalination, for the first time, to our knowledge. They exhibited electrochemical behavioural patterns comparable to conventional electrodes and generated measurable bioelectricity, confirming their potential as bioanodes. However, their performance remained inferior to carbon - based electrodes due to inherent surface limitations. Upon MXene functionalization, an increase of 3.5 folds in power production, 1.1 - and 2.5 - times improvement, respectively, in both wastewater and SGW treatment efficiencies, was observed. Despite these advancements, performance remained inferior to carbon electrodes. Moreover, water jet cutting for LCD electrode fabrication did not yield significant cost benefits, underscoring the need for further refinement to enable practical application.

Notwithstanding the improvements in treatment efficiency, the final water quality obtained from the functionalized electrodes remained non-compliant with regulatory standards, thereby underscoring the imperative for system - level optimization. To address this, as the third strategy, this study introduced a novel hexagonal MDC architecture which, unlike the conventional linear three - chamber design, markedly enhanced electrokinetic activity. This configuration enabled faster attainment of regulatory standards, improving SGW treatment efficiencies by 1.3 - 1.9 folds and power output by 6.2 folds. Furthermore, integration of the best-performing MXene-coated carbon electrode within the developed architecture enabled stable and sustained current generation, underscoring its reliability and stability. Overall, the study establishes the developed MDC configuration as a promising decentralized solution for integrated GW and wastewater treatment, advancing self-reliant water management systems.

Keywords: Microbial desalination cells, Synthetic groundwater treatment, $Ti_3C_2T_x$ MXene functionalization, LCD anode, Hexagonal microbial desalination cell.