Ultra-fast green hydrogen production from municipal wastewater by an integrated forward osmosis-alkaline water electrolysis system

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Highlights:

- **The $FOWS_{AWE}$ process achieves hydrogen purity of over 99% from wastewater effluent.**
- **$FOWS_{AWE}$ exhibits a specific energy consumption of 4.4 kWh Nm^{-3}, comparable to commercial AWE using deionised water.**
- **$FOWS_{AWE}$ has the potential to improve aerobic wastewater treatment by providing pure oxygen, enhancing performance, and reducing residence times.**

Keywords: forward osmosis; hydrogen; water electrolysis

INTRODUCTION

The utilisation of renewable energy in water electrolysis for green hydrogen production holds significant promise for decarbonisation across various sectors. By 2050, around 86% of global power generation, equivalent to 55,000 TWh, are projected to be derived from renewables (IRENA, 2019). However, up to 40% of renewable electricity can be wasted due to the intermittent production (Chi & Yu, 2018). The power-to-hydrogen (P2H) systems provides a flexible solution to use renewable energy to produce green hydrogen (H_2), minimising renewable energy wastage. Yet, around 30% of green hydrogen projects are located in regions facing high to extremely-high water scarcity, posing challenges on P2H wide-application (Cassol et al., 2024). In this study, we propose a system that combines FO with the alkaline water electrolysis (AWE) to produce hydrogen from wastewater effluent (Figure 1). This approach involves extracting water from wastewater by an osmotic gradient and sequentially hydrolysing it to sustain a continuous steady-state operation. Using wastewater effluent is more practical than seawater, especially for inland communities where water resources are scarce, and seawater is unavailable but wind and solar farms can provide green electricity to drive P2H systems (Ge et al., 2013). Besides H_2 production and energy storage, $FOWS_{AWE}$ may also benefit wastewater treatment plants and industries by

enabling water reuse, reducing treatment load and wastewater discharge while simultaneously generating onsite energy (Hao et al., 2019). FOWS$_{AWE}$ is a sustainable and economical approach for producing hydrogen directly from wastewater respecting water-energy nexus.

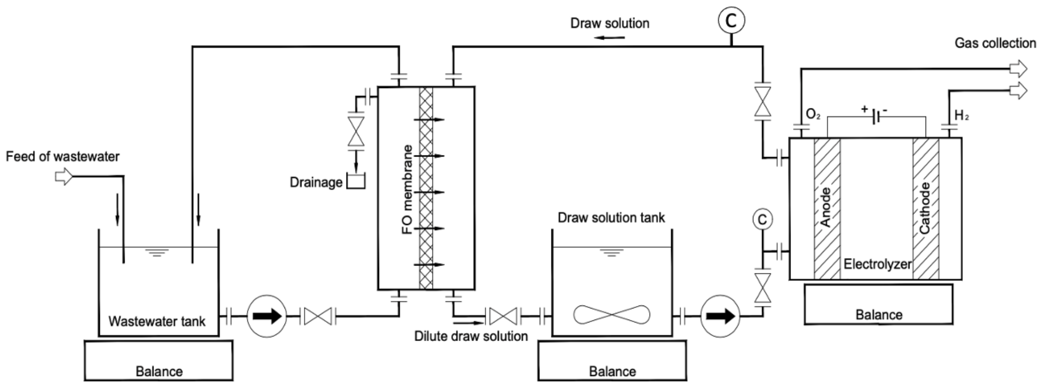

Figure 1. The schematic representation of the integration of the modules of FO and AWE.

METHODOLOGY

The electrochemical experiments were conducted using a 5-cell alkaline stack with nickel alloy-based electrodes separated by polymer diaphragm to avoid gas crossover. H_2 and O_2 gas streams were separated from the electrolyte with a gravity gas-liquid separator. H_2 was collected in an inverted measuring cylinder filled with water, and the production rate evaluated by measuring the volume displacement over pre-determined time intervals. The purity of the collected H_2 was analysed by gas chromatography (990 Micro GC System, Agilent) equipped with a thermal conductivity detector. The membrane tests were performed in a bench-scale FO cell utilising a thin film composite (TFC) membrane (Porifera®) with an area of 12 cm^2. The water flux was gravimetrically measured by the loss of water weight in the feed tank per unit of time using an electronic balance (FX-3000GD, A&D Instruments) divided by the membrane area. To achieve the steady-state operation, the flowrate of water crossing the FO membrane was set to be equal to the outflow of water in the form of H_2 and O_2 in the AWE process by adjusting the current applied (i_{cell}) per concentration gradient between feed and draw solution (ΔC), according to an established water-hydrogen balance model ($i_{cell}/\Delta C = IRT(K_w S/d)(2F/FE\ N_{cell}V_m)$). In this model, K_W is the membrane permeability coefficient for water, A is the membrane surface area, d is the membrane thickness, I is the van't Hoff factor, R is the ideal gas constant, T is the temperature, FE is the Faradaic efficiency, N_{cell} is the number of cells constituting the electrolyser stack, F is Faraday's constant, and V_m is the molar volume of H_2O. The KOH concentration was continuously monitored by analysing the change in the conductivity of the draw solution and the change in the pH of feed the wastewater effluent. The resulting voltage was collected using a DC power supply (DP3030, MESTEK). The concentration of total organic carbon (TOC) was measured by a TOC analyser (TOC-L, Shimadzu). The concentration of chloride was quantified using ion chromatography (IC, 940 Professional IC Vario, Metrohm).

RESULTS AND CONCLUSIONS

This study demonstrated the use of municipal wastewater effluent by an $FOWS_{AWE}$ system for fast and energy efficient green H_2 generation to address the large-scale H_2 production need associated with potential water constraints. The $FOWS_{AWE}$ system exhibited stable and continuous H_2 production at the highest yields of H_2 to date (448 $Nm^3\ day^{-1}\ m^{-2}$) using alternative water resources a low SEC of 4.4 $kWh\ m^{-3}$. In addition, the $FOWS_{AWE}$ system demonstrated long-term stability during a continuous operation of 168 hours using real wastewater effluent, maintaining a consistent water flux, ΔC, and voltage, as shown in Figure 2. Notably, the H_2 gas purity remained stably high at over 99% throughout the entire long-term operation. The system demonstrated rejection rates exceeding 90% for common impurities found in wastewater, such as chloride and organic matter. It is estimated that an onsite $FOWS_{AWE}$ station with a capacity of 5–6 MW can produce O_2 at ~20,000 kg day^{-1}, which can supply the aerobic processes of a wastewater treatment plant in treating 50,000 $m^3\ day^{-1}$ of wastewater. The $FOWS_{AWE}$ system is shown to be a sustainable and economical approach for producing hydrogen directly from wastewater, marking a significant leap in P2H practice.

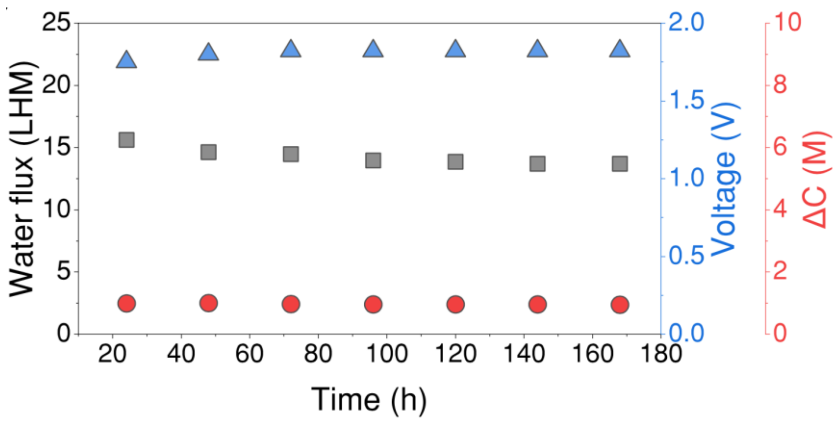

Figure 2. The water flux, voltage, and concentration gradient (ΔC) during the 168-h continuous operation of the integrated $FOWS_{AWE}$ system using real wastewater effluent. (Conditions: [KOH] = 1 M, S = 1 cm^2, and i_{cell} = 0.90 A).

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