Statistical analysis validates an electro-sanitation system for onboard urine treatment in buses

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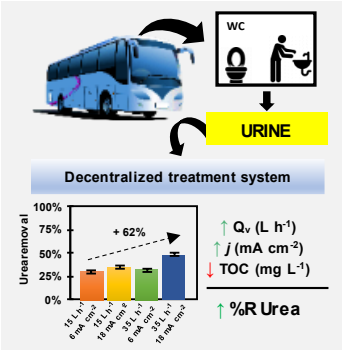

Long-distance transportation often lacks adequate sanitation solutions for managing onboard wastewater, leading to environmental concerns. This study introduces a novel decentralized electrochemically-driven treatment approach tailored for long-distance buses. By addressing specific boundary conditions, a compact electrochemical reactor was designed and tested for treating synthetic urine effluents. Results demonstrate effective reduction of urea concentration using low current densities over a realistic operational timeframe. Real-time monitoring of parametrs, showed the potential of electrochemical technology for ecologically sound sanitation solutions in portable urinary collectors, such as those utilized in bus transportation.

Introduction

Decentralized urine treatment presents a promising avenue for sustainable solutions, particularly in contexts like long-distance passenger transport, where traditional infrastructure may be lacking.

Electrochemically-driven technologies, particularly electrochemical oxidation (EO), show promise in addressing these challenges [1,2]

This study aimed to develop a compact electrochemical treatment system for urine generated during long-distance passenger transport, addressing the need for decentralized sanitation solutions in areas with limited or no sewage infrastructure. The main objective was to evaluate the impact of urine dilution on treatment efficiency, aiming for a 50% reduction in the concentration of urea in urinary solutions, the applied current density and the volumetric flow of the system. For this, a factorial design was used in the central compound design model (CCD) to statistically determine the ideal working condition. By optimizing an automated treatment system modeled after a bus's sanitary system, we aim to meet or exceed regulatory quality standards while considering energy requirements and travel time constraints. The results of this study establish the basis for the implementation of decentralized electrochemical sanitation systems adapted to urinary collectors such as those used on buses.

Material and Methods

In this study, synthetic urine was used to simulate real-world scenarios of urine concentrations The composition of the synthetic urine was based on literature reported values. Three scenarios were considered, corresponding to different levels of urination frequency per passenger during a trip. Each scenario was represented by specific dilution factors, taking into account the initial volume of clean water in the reservoirs and additional water used for flushing and hand washing.

The reactor used was a continuous flow filter-press type, operating within a closed system with upward recirculation. It consisted of four acrylic plates, with two holding the filter-press cell system and the other two accommodating three-dimensional electrodes. The Nafion® N117 membrane separated the cathodic and anodic compartments. The cathode was a carbon felt electrode, while the anode consisted of 5 DSA meshed plates ($Ti/Ru_{0.36}Ti_{0.64}O_2$). Viton® gaskets ensured proper sealing between plates. The reactor was connected to a reservoir with a mechanical stirrer and equipped with sensors for real-time monitoring of various parameters, including pH, dissolved oxygen, temperature, and conductivity. Automation was achieved using an Arduino prototyping platform integrated with the sensors. A 2^3 factorial design within the CCD model was implemented, considering three independent variables at two levels each, using PROTIMIZA EXPERIMENTAL DESIGN® software. Key parameters such as initial urine dilution (TOC_i = 402, 617 and 832 mg L^{-1}), flow rate (15, 25 and 35 L h^{-1}), and current density (6, 12 and 18 mA cm^{-2}) were chosen to reflect real bus collection conditions in the urea removal rates after 300 minutes of electrolysis. Multiple regression analysis was conducted to assess the statistical significance of the variables and the generated model.Graphical representation in response surfaces provided insights into the relationships between variables. Urea concentration was determined colorimetrically by adding p-dimethylaminobenzaldehyde to samples, forming a yellow-green solution, with absorbance measured at

420 nm using a UV-Vis spectrophotometer (HACH DR 5000).

Results and Discussion

The experimental findings indicate that employing low current densities of 18 mA cm^{-2} in ECO treatment achieves approximately 50% urea removal, aligning with road service time. This approach not only facilitates decentralized system implementation but also promotes sustainable effluent treatment practices. A statistical regression model derived from CCD suggests a linear relationship among studied variables, with both volume flow rate and current density positively influencing urea removal. Notably, current density exerted the greatest impact, potentially due to increased production of active chlorine species by active anodes, enhancing overall oxidation processes. The positive effect of increasing volumetric flow rate can be attributed to the enhance of mass transport of reagents to the electrode surface.

The response surface plots depicting interaction between variables revealed that volumetric flow rate exerted a more pronounced influence at current densities above the central point (>12 mA cm-2). This suggests that at higher current densities, increased volumetric flow rate enhances the transport of reactants to the electrode surface. The correlation between volumetric flow rate and organic load, quantified by initial theoretical total organic carbon (TOC), showed that the overall urea removal percentage increases with higher volumetric flow rates and lower initial organic load (i.e., urine content). Specifically, the interaction between these variables exhibited the highest level of degradation at a volumetric flow rate of 35 L h^{-1} and a TOC of 402 mg L-1, indicating an interplay between mass transport and reaction kinetics. A lower initial TOC in urine signifies a reduced concentration of organic pollutants, thereby reducing the need for longer treatment durations to achieve significant degradation levels. Additionally, it was observed that increasing current densities, coupled with decreasing urea concentration in urine solutions (TOC < 617 mg L^{-1}), resulted in higher removal rates within the investigated variables. This effect can be attributed to intensified electrochemical reactions at higher current densities.

The response surface model was statistically validated using analysis of variance (ANOVA) and Fisher distribution (F test). The results showed that the regression is statistically significant and effectively represents the experimental results, since the ratio between the mean square of the regression and the residual of 24.0 exceeds the theoretical tabulated value of 3.4. Furthermore, the ratio between the mean square of the lack of fit and the pure error of 1.7 is below the theoretical tabulated value of 5.46. Furthermore, the mathematical model demonstrated statistical predictability, with the ratio FRegression/residual ≥ FTabeled > 5.

The energy estimate revealed an energy consumption of 63.36 kWh m^{-3} to remove approximately 50% of urea in 1 m^3 of effluent, meeting the objective of the study. The power required for this treatment, based on a current density of 18 mA cm^{-2} for 300 minutes, was approximately 12.17 W, easily supported by the batteries of the bus in which the decentralized system was deployed. With an electricity cost of US$0.165 per kWh, the estimated cost for wastewater treatment during a trip accommodating 48 passengers was approximately US$1.57, resulting in a cost per passenger of US$0.03.

The real-time monitoring of key parameters revealed significant insights into the electrosanitation system's efficacy. pH levels exhibited a notable decrease from 6.98 to 3.49 over 5 hours, while temperature gradually increased from 25.3°C to 32.0°C. Conductivity slightly rose from 2.62 mS cm^{-1} to 3.00 mS cm^{-1}, possibly due to the mineralization of organic compounds. Dissolved oxygen levels experienced a rise from 7.26 mg L^{-1} to 9.53 mg L^{-1}, surpassing the maximum solubility value of 8.24 mg L^{-1}. These findings suggest effective treatment and compliance with CONAMA standards, with minimal need for effluent adjustments.

Conclusions

The successful development of a compact electrochemical reactor for decentralized sanitary treatment of urine from long-distance road transport marks a significant advancement in wastewater treatment. Through a factorial design approach, emphasizing current density, volumetric flow rate, and urine concentration, a robust statistical model has been established, validating the effectiveness of the mathematical framework in comprehending and projecting treatment outcomes. The achieved reduction of approximately 50% in urea concentration during continuous flow treatment using low current densities highlights the reactor's potential for safe effluent disposal within decentralized systems. These findings underscore the promising application of electrochemical technology in addressing challenges associated with decentralized wastewater treatment, offering sustainable and efficient solutions for various sanitation practices.

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