Electricity generation and winery wastewater treatment using silica modified ceramic separator integrated with yeast-based microbial fuel cell

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Abstract

The ceramic separator has been interested in low-cost alternative proton exchange membranes in a microbial fuel cell (MFC). In this study, the silica-modified ceramic separator has been integrated with the yeast-based MFC for electricity generation and phenol treatment from the winery wastewater. The 30% (w/w) silica powder was mixed with the 70% (w/w) natural clay. The modified ceramic plates (0.2, 0.5, and 1.0 cm of thickness) were prepared at 680°C and used for MFC operation. As an anolyte, synthetic winery wastewater (2,000 mg COD/L and 100 mg/L phenol) with 5% (v/v) ethanol was used. The ethanol-tolerant yeast Pichia sp. ET-KK was used as an anodic catalyst. The results showed the maximal power density of 0.212 W/m² and phenol removal of 95.05% were reached from the 0.2-thick ceramic plate integrated MFC. This study demonstrated that the silica-modified ceramic separator has a high potential for enhancing electricity generation in the yeast-based MFC.

Keywords: Microbial fuel cell; electricity generation; phenol removal; winery wastewater; ceramic membrane

1. Introduction

Winery wastewater is one of the complex wastewaters that mainly contains various organic compounds such as sugar, organic acid, glycerol, ethanol, esters, phenolic compounds, and ethanol. It contains 320–49,105 mg/L of chemical oxygen demand (COD), 10–415 mg/L of total nitrogen (TN), and 2.1–280 mg/L of total phosphorous (TP) affecting the groundwater pollution where it is discharged [1,2]. Rodriguez-Caballero et al. stated that winery wastewater contains a high ethanol concentration [3] and some previous studies showed that ethanol establishes up to 90% of the COD content in winery wastewater. In wastewater, the contaminated ethanol can inhibit the growth of various microbe and increase the water pollutant. Consequently, the ethanol tolerant yeast has been interested in being used under high ethanol-containing conditions [4].

Microbial fuel cells (MFC) convert the chemical energy in the organic materials to electrical energy throughout the microbial metabolism without combustion. It can be applied for wastewater treatment and simultaneous electricity generation. The study of Hou et al. showed that the MFC coupled with phenol degrading microbe has a high potential for phenol degradation from the wastewater as the result of the decreasing toxic pollutant from the wastewater [5]. Nevertheless, the yeast-based MFC has also generated less electrical energy than the bacterial-based MFC. Boas et al. on the other hand demonstrated that the yeast Zygosacharomyces bailii can produce flavins, an electroactive metabolite that can play an important role in ethanol degradation [6]. On the other hand, the yeast-based MFC can be applied for electricity generation and high-value-by-product production [7,8]. The performance of MFC is governed by its components and operating conditions. Proton exchange membranes, such as Nafion, play an important role in proton transport in a dual-chamber MFC. However, it has several negative outcomes, like high cost, high oxygen diffusion, and anolyte crossover [9]. The ceramic separator has been developed as a low-cost alternative separator for application in an MFC. The previous study showed a high energy conversion efficiency and constant power performance from the ceramic separator MFC [10].

Raychauhuri et al. showed that the membrane containing silica exhibits the improving performance of proton diffusion and enhances electricity generation [11]. Moreover, previous studies have shown various materials that have been used for modified ceramic plates, such as rice husk ash [12], chitosan [13], iron oxide [14], polypropylene [15], and others.

In this study, the silica-modified ceramic plates were developed for integration with MFC for winery wastewater treatment (phenol removal under ethanol-contaminant wastewater) and electricity generation with constant power performance.
2. Materials and Methods

2.1. Microbe

The ethanol-tolerant yeast *Pichia* sp. ET-KK (TSU_MFCY001) was gained from the Microbial fuel cell & Bioremediation Laboratory, Faculty of Science, Thaksin University. It was maintained on the sucrose-yeast agar (10% (w/v) sucrose, 1% (w/v) yeast extract, and 15% (w/v) agar) and kept at 4°C until being used in this experiment (figure 1).

For liquid culture preparation, the colony of yeast was inoculated into a sucrose-yeast medium (10% (w/v) sucrose, 1% (w/v) yeast extract, and 15% (w/v) agar) and incubated at a room temperature for 5 days with 150 rpm shaking.

![Fig. 1. The colony of *Pichia* sp. ET-KK](image)

2.2. Ceramic plate preparation

The silica-modified ceramic plate was prepared according to the modified method of Raychauhuri et al. [16]. Briefly, the 70% (w/w) of locally ceramic soil was mixed with the 30% (w/w) of silica powder. The modified ceramic plate was molded to prepare with various thicknesses of 0.2, 0.5, and 1.0 cm. The ceramic plates were dried at 80°C for 7 days and baked in a muffle furnace at 680°C for 30 minutes.

![Fig. 2. The dual-chamber MFC used in this experiment](image)

2.3. MFC operation

Figure 2 shows the construction of dual chamber in which the 7.50 cm² of graphite plated electrodes were prepared according to Kim et al. [17]. The anode and cathode chamber were made from the 50 mL cell culture flasks. The copper wire was used to connect the electrodes. The ceramic separators were inserted between the anode and cathode chamber. The 1 M KMnO₄ solution was used as a catholyte. The synthetic winery wastewater (2,000 mg/L of total COD and 100 mg/L of phenol) with 5% (v/v) ethanol was prepared according to Welz and Rose-Hill [18].

![Fig. 3. The polarization curve of the dual-chamber MFC](image)

The 10% (v/v) ethanol tolerant yeast *Pichia* sp. ET-KK (1 x 10⁶ cell/mL) and 90% (v/v) of the synthetic winery wastewater were added to the anode chamber. Here, a 1,000-Ω resistor was connected and incubated for 5 days to immobilize a yeast on the electrode surface.

For operation, the anolyte was fed-out and replaced with 40 mL of synthetic winery wastewater. The opened-circuit voltage (OCV) was collected every 6 hours for 5 days. The closed-circuit voltage (CCV) was monitored between 1 – 5,000 Ω external resistances and the electrochemical properties were calculated according to Ohm’s law [19].

The CCV was determined at the stationary phase of the bioelectrical cycle. The current, power, current density and power density were calculated as follows:

\[ I = \frac{V}{R} \]  
\[ P = IV \]  
\[ CD = \frac{I}{A} \]  
\[ PD = \frac{P}{A} \]

where I is the current (A), V is the CCV (V), R is the external resistance (Ω), P is the power (W), CD is the current density (A/m² or A/m³), PD is the power density (W/m² or W/m³), and A is the working volume (m³) or electrode area (m²).

2.4. Phenol removal

The winery wastewater (influent and effluent) was collected from the anodic chamber of the dual-chamber MFC. The wastewater was filtered through the filter paper (Whatman no.1) using a vacuum pump. The filtrate was measured the phenol content using a colorimetric method according to Chaijak et al. The Folin-Ciocalteu reagent was used, and the absorbance of the reaction was monitored at 760 nm. The phenol removal was calculated.

3. Results and Discussion

The maximal OCV of 790.0±5 mV was gained from the yeast-based MFC with the 0.2 cm of thickness silica modified ceramic separator, followed by the 0.5 cm and 1.0 cm of the thickness of 730.0±5 mV and 480.0±10.0 respectively. The thinnness membrane can produce the highest voltage owing to it providing the shortest distance for proton transportation. The results are displayed in figure 3.

According to Ohm’s law, the MFC with high voltage potential can generate high current and power. The highest CD of 29.500±1.000 A/m³ (1.573±0.000 A/m³) and the highest PD of 3.980±0.150 W/m³ (0.212±0.000 W/m³) were generated from the 0.2 cm thick modified ceramic plate. While, the internal resistance of the yeast-based MFC of 500 Ω was presented in the polarization curve (figure 4).

However, the 0.5 cm thick modified ceramic plate produced the highest CD of 1.33±0.10 A/m³ and the highest PD of 0.03±0.00 W/m³ (figure 5). Figure 6 shows the polarization curve of the dual-chamber MFC with a 1.0 cm thick ceramic plate. The maximum CD of 0.50±0.00 A/m³ and the maximum PD of 0.0005±0.0000 W/m³ were generated. Similar with the study by Khalili et al., the result indicated that the thinnest...
A ceramic separator could provide the highest electricity generation by the MFC [21].

The phenol removal of 95.05±0.03%, 94.02±0.10%, and 90.10±0.30% were achieved from the yeast-based MFC with 0.2, 0.5, and 1.0 cm of silica-modified ceramic separator, respectively.

The MFC technology with an ability to convert contaminants to electrical energy can be enhanced with a low-cost ceramic separator. The ceramic is porous, thus allowing the direct exchange of protons [22]. The 5% (w/w) goethite modified ceramic separator integrated with MFC produced a maximal PD of 0.112 W/m² [23]. Table 1 depicts a comparison of ceramic-separator MFC. According to the data, the modified ceramic separator has been used as a proton exchange membrane in various wastewater sources. The data suggested that the modified ceramic membrane can provide a higher electricity generation than other ceramic membranes. Moreover, the previous study by Alftessi et al. showed that the silica sand ceramic separator can be used for the high efficiency of wastewater treatment and power generation [28].

Table 1. Review of ceramic separator MFC

| MFC type       | Ceramic material                  | Wastewater/ Microbe          | PD (W/m²) | Reference |
|----------------|----------------------------------|------------------------------|-----------|-----------|
| Dual-chamber   | Silica modified ceramic          | Winery wastewater            | 3.980     | This study|
|                | Montmorillonite modified ceramic | Pichia sp. ET-KK             |           |           |
| Dual-chamber   | Montmorillonite modified ceramic | Synthetic wastewater         | 0.084     | [23]      |
|                |                                  | Anaerobic mixed sludge       |           |           |
| Dual-chamber   | Fire clay ceramic                 | Urine wastewater             |           | [24]      |
|                |                                  | Exoelectrogens               |           |           |
| Dual-chamber   | Nafion coated ceramic             | Synthetic wastewater         | 0.084     | [25]      |
|                |                                  | Sewage sludge                |           |           |
| Dual-chamber   | Native clay ceramic               | Domestic wastewater          | 0.48-20.18| [26]      |
|                | Chitosan/ Montmorillonite modified ceramic | Domestic wastewater |           |           |
|                |                                  | Sewage sludge                |           |           |
| Dual-chamber   |                                  | 0.229                        |           | [27]      |

Moreover, the MFC has been used for the brewery wastewater. In Liu et al., the winery wastewater was treated by the MFC integrated with Betaproteobacteria, which played an important role in electricity generation. The maximal voltage of 0.63 V was generated [29]. On the other hand, the maximal power density of 0.29 W/m² was caused when the initial COD concentration was 1-10 gCOD/L [30]. Vilas Boas et al. confirmed that the yeast *Zygosaccharomyces bailii* can be used for ethanol-contaminated winery wastewater treatment using an H-type dual-chamber MFC system. However, the power density of yeast-based MFC has not been analyzed [31]. Table 2 showed the comparison of winery wastewater treatment using the MFC.

Various processes have been applied for phenol removal from industrial and agricultural wastewater. The results of Luo et al. indicated that the MFC can enhance phenol degradation and electricity generation [37]. On the other hand, the cube-type dual-chamber MFC has been used for phenol removal and electricity generation from phenol-acetone wastewater. The maximal output voltage and phenol removal of 250 mV and
95.12% were gained [38]. Moreno et al. showed the batch-operated MFC with graphite-granule electrode can produce the maximum power output of 0.78 W/m³ when the phenol removal was gained [39]. Table 3 presents the comparison in the use of MFC for phenol removal and electricity generation from the wastewater.

| MFC type          | Initial COD (g/L) | Power output (W/m³) | Power output (W/m²) | Reference       |
|-------------------|-------------------|---------------------|---------------------|-----------------|
| Dual-chamber MFC  | 2.00              | 3.980               | 0.212               | This study      |
| Dual-chamber MFC  | -                 | -                   | 0.275               | [32]            |
| Dual-chamber MFC  | 6.85              | -                   | 0.420               | [33]            |
| Single-chamber MFC| 1.00              | -                   | 0.105-0.465         | [34]            |
| Dual-chamber MFC  | 140-230           | -                   | 0.111-0.262         | [35]            |
| Dual-chamber MFC  | -                 | 0.014               | -                   | [36]            |

**Table 2. Reviews of winery wastewater treatment using MFC**

The results indicated that the dual-chamber MFC with the silica-modified ceramic separator can be successfully used for wastewater treatment in terms of phenol removal under microbial inhibitor (ethanol) contaminated conditions and electrical power generation.

As shown in table 2, this study provides a higher power output than other studies carried out in the dual-chamber and single chamber MFC owing to the thin modified ceramic separator membrane where the winery wastewater has been used as a substrate.

Moreover, the *Pichia* sp. ET-KK indicated that it had a high potential for phenol removal when being used for whole-cell biocatalyst in the anodic chamber (in table 3) owing to it can be tolerant to contaminated ethanol in the effluent.

**4. Conclusion**

This study has demonstrated that the 30% (w/w) silica powder modified ceramic plate has a high potential for use as an MFC proton exchange membrane. Furthermore, the modified ceramic separator MFC combined with the ethanol tolerant yeast was successfully used for phenol degradation from winery wastewater as well as electricity generation. This MFC system can be developed for the use with various wastes and scaled up owing to its low structural cost. However, the larger scale will be studied in further work.

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**References**

1. A. Brito, J. Peixoto, J. M. Oliveira, J. A. Oliveira, C. Costa, R. Nogueira and A. Rodrigues, *Brewery and winery wastewater treatment: some focal points of design and operation*. Cham, Switzerland: Springer Nature, 2007.
2. L. A. Ioannou, G. L. Puma and D. Fatta-Kassinos, *Treatment of winery wastewater by physicochemical, biological and advanced processes: a review*. *J. Hazard. Mater*. 286 (2015) 343-368.
3. A. Rodriguez-Caballero, J. B. Ramond, P. J. Welz, D. A. Cowan, M. Odlare and S. G. Button, *Treatment of high ethanol concentration wastewater by biological sand filters: Enhanced COD removal and bacterial community dynamics*. *J. Environ. Manag*. 109 (2012) 54-60.
4. C. Tikka, H. P. Osuri, N. Atluri, P. Chakravarthi, V. Raghavulu, N. K. Yellapu, J. S. Mannur, U. V. Prasad, S. Aluru, N. Varma and M. Bhaskar, *Isolation and characterization of ethanol tolerant yeast strains, Bioinformations*. 9 (2013) 421-425.
5. B. Hou, R. Zhang, X. Liu, Y. Li, P. Liu and J. Lu. *Study of membrane fouling mechanism during the phenol degradation in microbial fuel cell and membrane bioreator coupling system*., *Bioresour. Technol*. 338 (2021)125504.
6. J. V. Boas, L. Peixoto, V. B. Oliveira, M. Simoes and A. M. F. R. Pinto, *Cyclic voltammetry study of a yeast-based microbial fuel cell, Bioresour. Technol*. Rep. 17 (2022) 100974.
7. A. Shrivastava, M. Pal and R. K. Sharma, *Simultaneous production of bioethanol and bioelectricity in a membrane-less single-chambered yeast fuel cell by Saccharomyces cerevisiae and Pichia fermentans*. *Arabian J. Sci. Eng*. 47 (2022) 6763-6771.
8. E. T. Sayed, M. A. Abdelkareem, H. Alawadhi, E. Elsaid, T. Wilberforce and A. G. Olabi, *Graphitic carbon nitride/carbon brush composite as a novel anode for yeast-based microbial fuel cells*. *Energi*. 221 (2021) 119849.
9. M. Rahimnejad, G. Bakeri, M. Ghasemi and A. Zirepour, *A review on the role of proton exchange membrane on the performance of microbial fuel cell, Polymer. Advan. Technol*. 25 (2014) 1426-1432.
10. X. A. Walter, E. Madrid, I. Gajda, J. Greenman, I. Leropoulous, *Microbial fuel cell scale-up options: Performance evaluation of membrane (c-MFC) and membrane-less (x-MFC) systems under different feeding regimes*. *J. Power Sourc*. 520 (2022) 230875.
11. A. Raychauhuri, R. N. Sahoo and M. Behera, *Application of clayware ceramic separator modified with silica in microbial fuel cell for bioelectricity generation during rice mill wastewater treatment*, *Water Sci. Technol*. 84 (2021) 66-76.
12. A. Raychauhuri and M. Behera, *Ceramic membrane modified with rice husk ash for application in microbial fuel cells*, *Electrochem*. Acta. 363 (2020), 137261.
13. V. Yousefi, D. Mohhebs-Khalori and A. Samimi, *Start-up investigation of the self-assembled chitosan/montmorillonite nanocomposite over the ceramic support as a low-cost membrane for microbial fuel cell, Int. J. Hydrogen Ener*. 45 (2020) 4808-4820.
14. M. J. Salar-Garcia, X. A. Walter, J. Guruskis, A. de Ramon Fernandez and I. Leropoulous, *Effect of iron oxide content and microstructural porosity on the performance of ceramic membranes as microbial fuel cell separators*, *Electrochem. Acta*. 367 (2021) 137385.
15. G. Pasternak, N. Ormeno-Can and P. Rutkowski, *Recycled waste polypropylene composite ceramic membranes for extended lifetime of microbial fuel cells*, *Chem. Eng. J*. 425 (2021) 130707.
16. J. Rodriguez, L. Mais, R. Campena, L. Piroddi, M. Mascia, J. Guruskis, A. Vaccia and S. Palmas, *Comprehensive characterization of a cost-effective microbial fuel cell with Pt-free catalyst cathode and slip-casted ceramic membrane, Int. J. Hydrogen Ener*. 46 (2021) 26205-26223.
17. M. Kim, Y. E. Song, S. Li and J. R. Kim, *Microwave-treated expandable graphite granule for enhancing the bioelectricity generation of microbial fuel cells*, *Electrochem. Sci. Technol*. 12 (2021) 297-301.
18. P. J. Welz and M. L. Rose-Hill, *Biodigestion of organics and accumulation of metabolites in experimental biological sand filters used for the treatment of synthetic winery wastewater: A mesocosm, J. Water Proc. Eng*. 3 (2014) 155-163.
19. P. Chajak, C. Sukkasem, M. Lertworapreecha, P. Boonsawang, S. Wijasaka and C. Sato, *Enhancing electricity generation using a laccase-based microbial fuel cell with yeast Galactomyces reessii on the cathode,*
J. Microbiol, Biotechnol. 28 (2018) 1360-1366.
20. P. Chaijak, M. Lertworapreecha and C. Sukkasem, Phenol removal from palm oil mill effluent using Galactomyces reessitii termite-associated yeast, Pol. J. Environ. Stud. 27 (2018) 39-44.
21. H. B. Khalidi, D. Mohhebi-Khalouri, and M. S. Afarani, Microbial fuel cell (MFC) using commercially available unglazed ceramic wares: Low-cost ceramic separators suitable for scale-up, Int. J. Hydrogen Ener. 42 (2017) 8233-8241.
22. M. F. H. Me and M. H. A. Bakar, Tubular ceramic performance as separator for microbial fuel cell: A review, Int. J. Hydrogen Ener. 45 (2020) 22340-22348.
23. I. Das, S. Das, R. Dixit and M. M. Ghangrekar, Goethite supplemented natural clay ceramic as an alternative proton exchange membrane and its application in microbial fuel cell, Ionics, 26 (2020) 3061-3072.
24. I. Merino-Jimenez, F. Gonzalez-Juarez, J. Greenman and I. Ieropoulos, Effect of the ceramic membrane properties on the microbial fuel cell power output and catholyte generation, J. Power Sour. 429 (2019) 30-37.
25. J. Suransh, A. K. Tiwari and A. K. Mungray, Modification of clayware ceramic membrane for enhancing the performance of microbial fuel cell, Environ. Prog. Sust. Ener. 39 (2020) e13427.
26. M. Cheraghipoor, D. Mohhebi-Khalouri, M. Noroozifar and M. T. Maghsoodlou, Comparative study of bioelectricity generation in a microbial fuel cell using ceramic membranes made of ceramic powder, Kalporgan’s soil, and acid leached Kalporgan’s soil, Energy, 178 (2019) 368-377.
27. V. Yousefi, D. Mohebbi and A. Samimi, Start-up investigation of the self-assembled chitosan/montmorillonite nanocomposite over the ceramic support as a low-cost membrane for microbial fuel cell application, Int. J. Hydrogen Ener. 45 (2020) 4804-4820.
28. S. A. Alfatti, M. H. D. Othman, M. R. Adam, T. M. Farag, A. F. Ismail, M. A. Rahman, J. Jaafer, M. A. Habib, Y. O. Raji and S. K. Hubadilllah, Novel silica sand hollow fibre ceramic membrane for oily wastewater treatment, J. Env. Chem. Eng. 9 (2021) 104975.
29. T. Liu, A. V. Nadaraja, J. Friesen, K. Gill, M. I. Lam and D. J. Roberts, Narrow pH tolerance found for a microbial fuel cell treating winery wastewater, J. Appl. Microbiol. 131 (2021) 2280-2293.
30. T. Liu, A. V. Nadaraja, J. Shi and D. J. Roberts, Stable performance of microbial fuel cell technology treating winery wastewater irrespective of seasonal variations, J. Environ. Env. Eng. 147 (2021) 1.
31. J. Vias Boas, L. Peixoto, V. B. Oliveira, M. Simoes and A. M. F. R. Pinto, Cyclic voltammetry study of a yeast-based microbial fuel cell, Bioresour. Technol. Rep. 17 (2022) 100974.
32. B. Taskan, Investigation of electricity generation performance of grape marc in membrane-less microbial fuel cell, Environ. Res. Technol. 4 (2021) 108-115.
33. E. D. Penteado, C. M. Fernandez-Marchante, M. Zaiat, E. R. Gonzalez and M. A. Rodrigo, Optimization of the performance of a microbial fuel cell using the ratio electrode-surface anode-compartment volume, Braz. J. Chem. Eng. 35 (2018) 141-146.
34. E. D. Penteado, C. M. Fernadez-Marchante, M. Zaiat, P. Canizares, E. R. Gonzalez and M. A. R. Rodrigo, Energy recovery from winery wastewater using a dual chamber microbial fuel cell, J. Chem. Technol. Biotechnol. 91 (2016) 1802-1808.
35. T. P. Sciarria, G. Merlino, B. Scaglia, A. D’Epifanio, B. Mecheri, S. Borin, S. Licoccia and F. Adani, Electricity generation using red wine lees in air cathode microbial fuel cells, J. Power Source. 274 (2015) 393-399.
36. M. Sugnaux, M. Happe, C. P. Cachelin, O. Gloriod, G. Huguenin, M. Blatter and F. Fischer, Two stage bioethanol refining with multi litre stacked microbial fuel cell and microbial electrolysis cell, Bioresour. Technol. 221 (2016) 61-69.
37. H. Luo, G. Liu, R. Zhang and S. Lin, Phenol degradation in microbial fuel cells, Chem. Eng. J. 147 (2009) 259-264.
38. H. Wu, Y. Fu, C. Guo, Y. Li, N. Jiang and C. Yin, Electricity generation and removal performance of a microbial fuel cell using sulfonated poly (ether ether ketone) as proton exchange membrane to treat phenol/acetone wastewater, Bioresour. Technol. 260 (2018) 130-134.
39. L. Moreno, M. Nemati and B. Predicala, Biodegradation of phenol in batch and continuous flow microbial fuel cells with rod and granular graphite electrodes, Environ. Technol. 39 (2018) 144-156.
40. M. Zhang, Y. Wang, P. Liang, X. Zhao, M. Liang and B. Zhou, Combined photoelectrocatalytic microbial fuel cell (PEC-MFC) degradation of refractory organic pollutants and in-situ electricity utilization, Chemosphere. 214 (2019) 669-678.
41. H. Hassan, B. Jin, E. Donner, S. Vasileiadis, C. Saint and S. Dai, Microbial community and bioelectrochemical activities in MFC for degrading phenol and producing electricity: Microbial consortia could make differences, Chem. Eng. J. 332 (2018) 647-657.
42. J. Shen, Z. Du, J. Li and F. Cheng, Cometabolism for enhanced phenol degradation and bioelectricity generation in microbial fuel cell, Bioelectrochem. 134 (2020) 107527.
43. J. Shen, J. Li, F. Li, H. Zhao, Z. Du and F. Cheng, Effect of lignite activated coke packing on power generation and phenol degradation in microbial fuel cell treating high strength phenolic wastewater, Chem. Eng. J. 417 (2021) 128691.
44. B. Hou, R. Zhang, X. Liu, Y. Li, P. Liu and J. Lu, Study of membrane fouling mechanism during the phenol degradation in microbial fuel cell and membrane bioreactor coupling system, Bioresour. Technol. 338 (2021) 125504.