Supplementary material

In-situ biogas upgrading with H_2 addition in an anaerobic membrane bioreactor (AnMBR) digesting waste activated sludge

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Contents

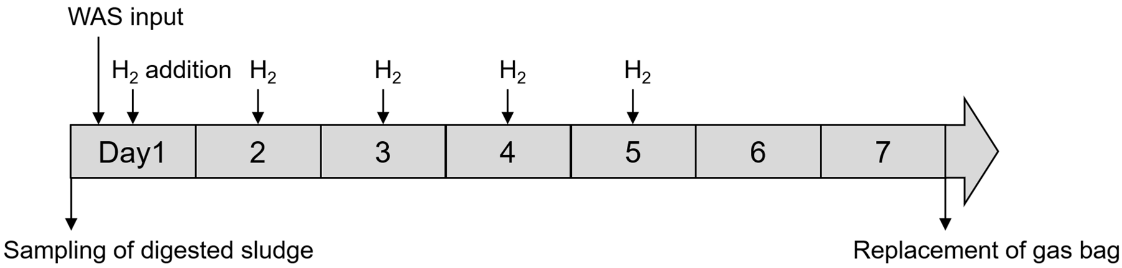

Fig. S1. Weekly procedure timeline involving the substrate input, sludge sampling, H_2 addition, and replacement of the gas bag. Filtration of the digested sludge was conducted continuously in the AnMBR mode of operation (phases 2–5). Biogas recirculation was also performed continuously during phases 3–7.

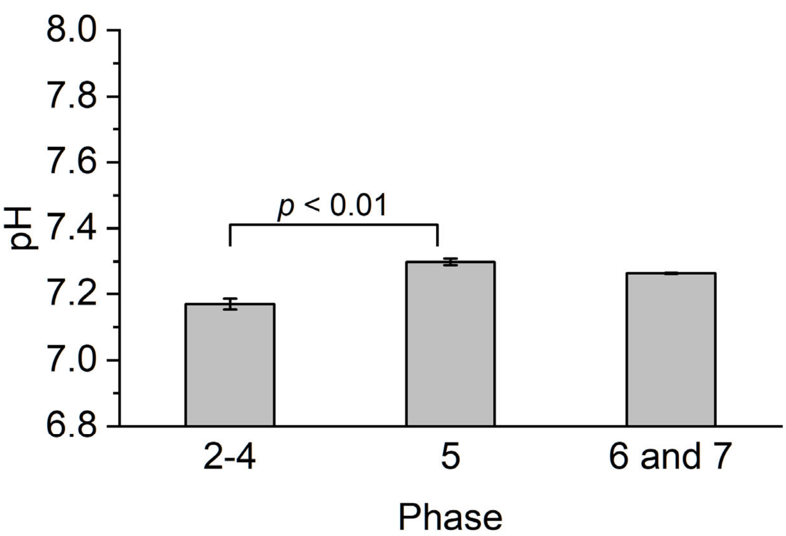

Fig. S2. Comparison in pH in biogas among operational phases.

Energy balance analysis

Energy balance analysis was conducted according to the Equations reported in previous studies (Chen et al., 2019; Cheng et al., 2021; Xiao et al., 2018). The unit of the energy is kJ/g-VS. The energy production (E_O) was determined according to Equation 1,

$$E_o = \frac{P_{CH_4} V \xi \eta_m}{Q C_{VS}} \quad (1)$$

where P_{CH4} is CH_4 yield (m^3-CH_4/m^3-reactor/d), V is reactor volume (m^3), ξ is combustion heat value of CH_4 (3.59×10^4 kJ/m^3-CH_4), η_m is energy conversion efficiency of CH_4 (0.9), Q is influent flow rate (m^3/d), C_{VS} is VS concentration of substrate (g-VS/m^3).

The energy consumption (E_C) includes energy required for heating (E_H), mixing (E_{Mixing}), sludge circulation ($E_{Sludge,\ cir.}$), biogas circulation ($E_{Biogas.\ cir.}$), and membrane filtration ($E_{Filt.}$). The energy consumption for heating was determined according to Equation 2,

$$E_H = \frac{\rho Q \kappa (T_r - T_{air})}{Q C_{VS}} \quad (2)$$

where ρ is density of substrate (1000 kg/m^3), κ is the specific heat of substrate (4.18 kJ/kg/°C), T_r is reactor temperature (37°C), and T_{air} is room temperature (23°C).

The energy consumption for mixing was determined according to Equation 3,

$$E_{Mixing} = \frac{V\omega}{Q C_{VS}} \quad (3)$$

where ω is electricity consumption for mixing (300 kJ/m^3/d).

The energy consumption for sludge and biogas circulation using two pumps were determined according to Equation 4,

$$E_{Sludge,cir.}\left(or\ E_{Biogas,cir.}\right) = \frac{Q_P \gamma h_{JF}}{1000 q_P \eta} \frac{1}{Q C_{VS}} \quad (4)$$

where Q_P is flow rate (m^3/s), γ is specific weight of fluid (N/m^3), h_{JF} is hydraulic pressure head of the jar fermenter (m), q_P is flow rate (m^3/h), and η is pump efficiency (60%).

The energy consumption for membrane filtration using a pump were determined according to Equation 5,

$$E_{Filt.} = \frac{g\left(h_{MU} - h_{JF} + h_{TMP}\right)}{\eta} \frac{1}{C_{VS}} \quad (5)$$

where g is the gravitational acceleration (9.8 m/s^2), h_{MU} is hydraulic pressure head of the membrane unit (m). The value of h_{TMP} was determined according to Equation 6,

$$h_{TMP} = \frac{TMP}{\rho g} \quad (6)$$

where TMP is the transmembrane pressure (Pa).

The net energy balance (E_{Net}) was determined according to Equation 7,

$$E_{Net} = E_O - E_C = E_O - (E_H + E_{Mixing} + E_{Sludge,cir.} + E_{Biogas,cir.} + E_{Filt.}) \quad (7)$$

The obtained values are listed in Table S1.

Table S1. Energy production and consumption in phase 5. The unit of the energy is kJ/g-VS.

E_O	E_C					E_{Net}
	E_H	E_{Mixing}	$E_{Sludge, cir.}$	$E_{Biogas, cir.}$	$E_{Filt.}$	
10.20	7.41	1.10	>0.001	>0.001	1.16	0.53

References

Chen, R., Wen, W., Jiang, H.Y., Lei, Z., Li, M.Z., Li, Y.Y., 2019. Energy recovery potential of thermophilic high-solids co-digestion of coffee processing wastewater and waste activated sludge by anaerobic membrane bioreactor. Bioresour. Technol. 274, 127–133. https://doi.org/10.1016/j.biortech.2018.11.080.

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