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Evaluation of Treatment Characteristics and Sludge Properties in a UASB Reactor Treating Municipal Sewage at Ambient Temperature

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ABSTRACT: The evaluation of treatment characteristics and sludge properties of an upflow anaerobic sludge blanket (UASB) process was investigated using a pilot-scale 1.15 m^3reactor. The UASB, inoculated with digester sludge, was operated at a hydraulic retention time of 8 h at sewage temperatures ranging from 10.6 to 27.7 °C for more than 1100 days. The stable removal efficiencies for total COD_{Cr} and SS were 63 ± 13% and 66 ± 20%, respectively. The average concentration of the retained sludge increased to more than 24.5 gSS/L of the column volume after two years of operation. In summer, the water temperature increased above 20 °C, and biodegradation of solid organic matter was enhanced. The solid retention time was evaluated to be as long as 293 ± 114 days; this is sufficient for mineralisation of solid organic matter, as indicted by a low sludge conversion of 0.029 gVSS/$gCOD_{removed}$ and a growth yield of 0.132 gVSS/gCOD, determined by seasonal sludge profiling. The bacterial communities, based on bacterial 16S rRNA genes in the retained sludge, were significantly diverse. Bacteroidetes and Firmicutes were the dominant phyla of the decomposers of solid organic matter in the library. A *Ruminococcus*-related clone detected in the Firmicutes phylum acted as a cellulose decomposer.

Key word: Anaerobic, UASB, Municipal sewage, Ambient temperature,Sludge

INTRODUCTION

Anaerobic biological waste treatment technology offers energy savings and low sludge production. This technology has been widely adopted for high-strength industrial wastewater treatment (Frankin, 2001). Upflow anaerobic sludge blanket (UASB) have also been applied to municipal sewage treatment in tropical and subtropical regions (Yoochatchaval *et al*., 2008 a, b; Monroy *et al*., 2002). However, for application in cooler regions such as Japan, particularly districts at mid and high latitudes, complete quantitative knowledge of UASB performance and the properties of retained sludge under seasonal temperature changes is not yet available (Miron *et al*., 2000; Lettinga *et al*., 2001; O'Flaherty *et al*., 2006). In this study, a UASB reactor was operated while being fed with actual municipal sewage at ambient temperature for more than 1100 days. The treatment characteristics of the reactor and the properties of the retained sludge are evaluated.

MATERIALS & METHODS

Fig. 1 shows a schematic diagram of the pilot-scale UASB reactor (total volume including the gas–solid separator (GSS), 1.15 m^3) used for the experiment. It was installed at a municipal sewage treatment plant, the Nagaoka-Chuo Wastewater Treatment Centre, Nagaoka, Japan. The upper part of the UASB consists of the GSS and gas metre, and the column part includes sampling ports. The seeding sludge was fed with 0.50 m^3 of mesophilic digester sludge from the same treatment centre. The UASB was fed with raw sewage after sieve screening of household garbage. The hydraulic retention time (HRT) was set to 8 h, and the operating temperature was allowed to vary with the ambient conditions.

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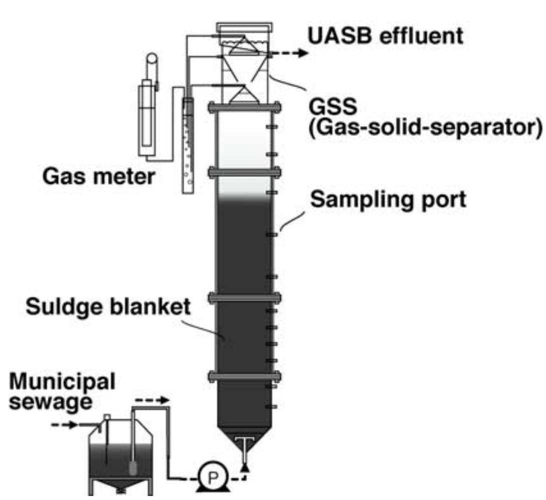

Fig. 1. Schematic diagram of the pilot-scale UASB reactor used for the experiment

The growth yield under stable UASB operation was evaluated using seasonal sludge profiling from days 730 to 1095 and daily water quality analyses, such as chemical oxygen demand (COD_{Cr}) and volatile suspended solids (VSS) measurements. (Hereafter, COD_{Cr} is denoted as COD). The amount of sludge in the UASB was examined by the curve fitting law with which the error was minimized. The death rate constant, Kd, was determined by a batch test that measured the methane production rate of the filled UASB sludge without an organic substrate in completely anaerobic serum vial bottles under several fixed-temperature conditions. In estimating the growth yield, a death constant of 0.0026/day was used, which corresponds to the average water temperature, 19.1 °C, over a one-year period. Sludge samples were harvested from the lower port of the reactor, 0.5 m above its base. DNA was extracted and the bacterial 16S rRNA gene clone library was constructed as described in a previous report, with some modifications (Narihiro *et al*., 2009). Phylogenetic analysis used the ribosomal database project (RDP) program and ARB software according to the previously described procedure. Methane-producing activity was determined using the serum vial batch activity test described by Yamaguchi *et al*. (1999).

Gas composition was measured by a thermal conductivity detector (TCD) gas chromatograph (Shimadzu GC-8A; Unibeads-C 60/80 mesh; col. temp.: 145 °C; carrier pressure: 120 kPa; Ar). Sulfate content was determined by an ion chromatograph (CDD-6A, Shimadzu, Shimpack IC-A1; col. temp.: 40 °C; mobile phase: 2.5 mM of potassium hydrogen phthalate). Volatile fatty acids (VFAs) were analysed by a flame ionisation detector (FID) chromatograph (Shimazu GC-1700, Thermon 3000; col. temp.: 90 °C; carrier pressure: 90 kPa; N_2). The cellulose content was analysed by the method proposed by Van Soest and McQueen (1973). The sludge retention time (SRT) was calculated using monthly retained sludge estimates and outflow SS (Elmitwalli *et al*., 2002). The other analyses were based on the standard methods published by the Japan Sewage Works Association.

RESULTS & DISCUSSION

Fig. 2 shows the time course of temperature, methane production, total COD and SS for more than 1100 days. The reactor was operated under ambient temperature with daily average influent sewage temperatures ranging 10.6–27.7 °C. In all operating periods, the process performance was stable and maintained 342 ± 135 mg/L of influent total COD and 118 ± 40 mg/L of UASB effluent. Regarding SS, 120 ± 66 mg/L of sewage SS yielded to 37 ± 23 mg/L of UASB effluent. The removal efficiencies for total COD and SS were stable at 63 ± 13% and 66 ± 20%, respectively. In contrast, the methane production was affected by temperature changes. Fig. 3 represents the relationship between operating temperature and the total COD, soluble COD and methane production. The effluent COD level was stable at temperatures of 10.6–27.7 °C. The UASB could maintain the effluent water quality level even at low temperatures of less than 15 °C for three months. Fig. 3 (c) shows a tendency for methane production to decrease with decreasing sewage temperature. In addition, methane-producing activity (gCOD/gVSS/day) in the retained sludge in summer and winter was evaluated by a batch activity test using hydrogen and acetate as the test substrate at 35 °C: winter, day 920 with a sewage temperature of 12.6 °C; hydrogen substrate, 0.34; acetic acid substrate, 0.046; summer, day 1103 with a sewage temperature of 25.3 °C; hydrogen substrate, 0.56; acetic acid substrate, 0.10. The methane-producing activities of the retained sludge for both test substrates indicated that the activity level in winter was half that of summer.

Fig. 4 (a) shows the time course of the average retained sludge concentration and VSS/SS ratio in the UASB. The UASB could maintain a high sludge concentration of more than 24.5 gSS/L. The VSS/SS ratio changed with seasonal temperature changes. In summer, when the water temperature reached higher than 20 C, biodegradation of solid organic matter proceeded. In contrast, organic matter accumulated in the bed in winter, and these results correlated with the methane production, which decreased at lower temperatures [Fig. 2 (b)]. These properties indicate that the hydrolysis reaction in solid matter was the rate-limiting step in this wastewater treatment process.

Fig. 4 (b) shows the time course of the COD-VSS loading rate, estimated using the data in Fig. 4 (a) and

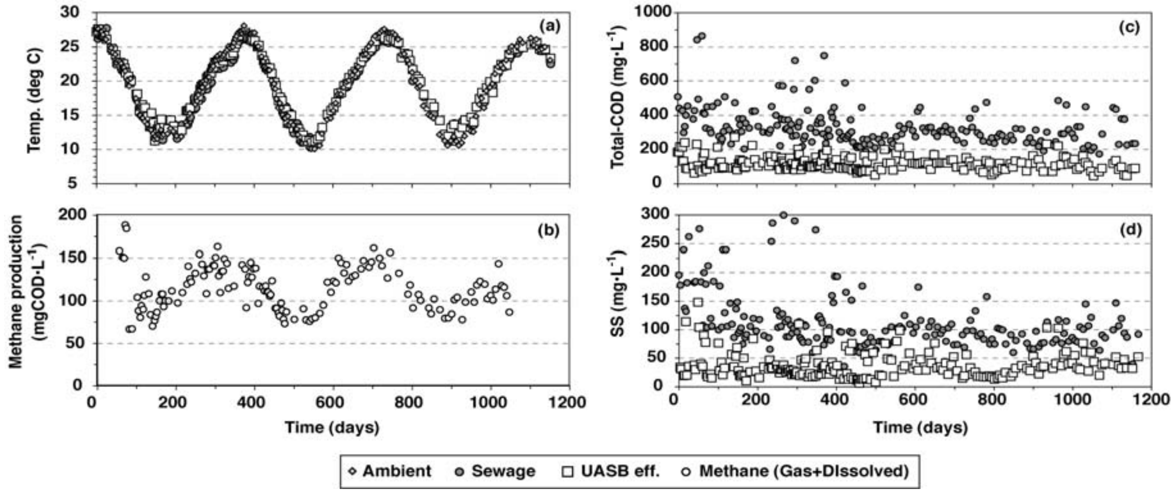

Fig. 2. Time course of temperature (a), methane production (b), total COD_{Cr} concentration (c) and SS concentration (d) during operation

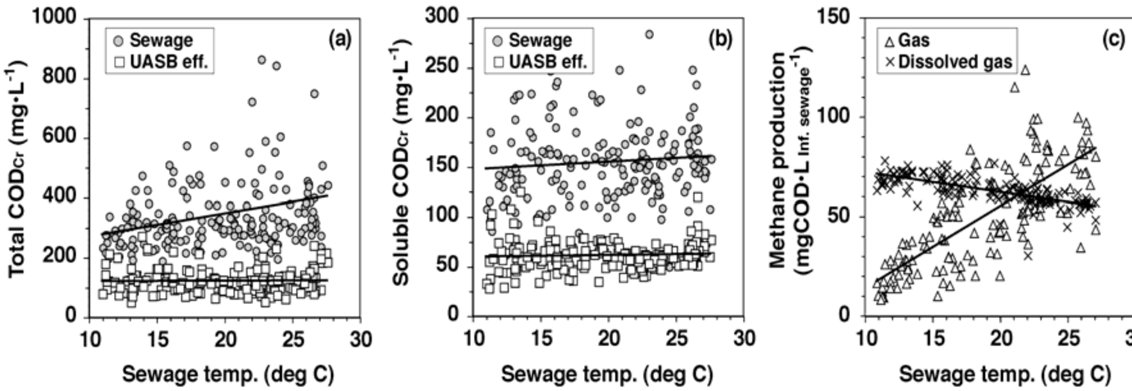

Fig. 3. Relationship between operating sewage temperature and the total COD_{Cr} (a), soluble COD_{Cr} (b) and methane production (c)

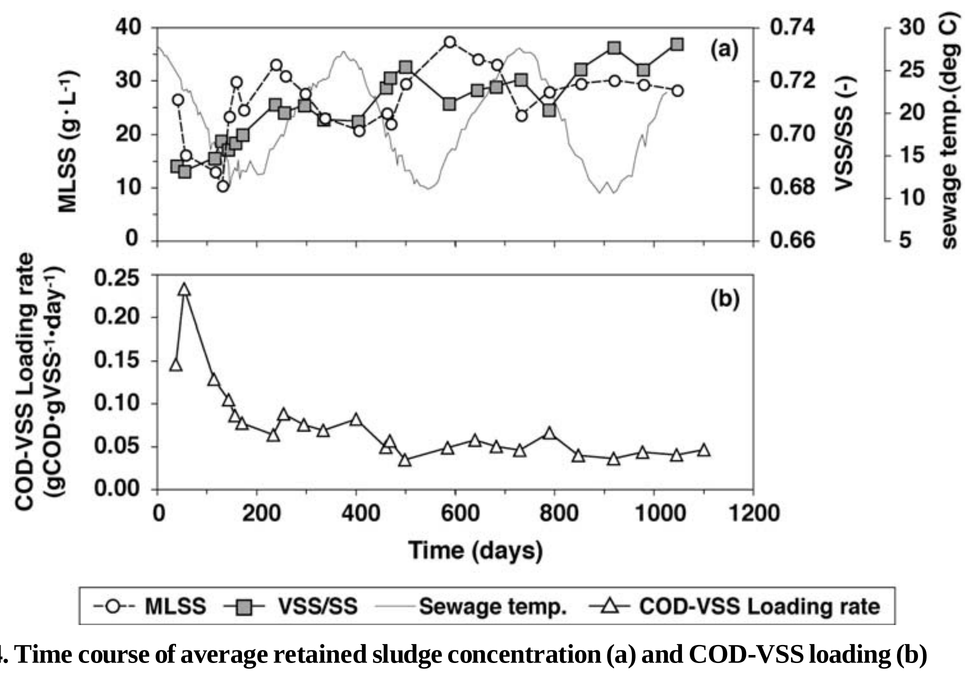

Fig. 4. Time course of average retained sludge concentration (a) and COD-VSS loading (b)

daily water quality analyses.The loading rate was as low as less than 0.05 gCOD/gVSS/day. In the yearly day 730–1095, when reactor operation was stable and the retained sludge concentration was approaching saturation, the $COD_{removal}$-VSS conversion rate and growth yield were evaluated as 0.029 gVSS/gCOD and 0.132 gVSS/gCOD, respectively, using data in Fig. 4 (a) and a death rate constant of 0.0026/day.

Fig. 5 shows the profiles of the VSS/SS ratio, sludge volume index (SVI) and cellulose concentration in the UASB. The VSS/SS ratio indicates that some inorganic substance was precipitated in the lower part of the reactor. Fig. 6 shows the particle size distribution and photographs of retained sludge in the lower, middle and upper parts of the UASB. The UASB could be gaining granular sludge in the bed, whereas the reactor was fed with dispersed mesophilic digester sludge and operated feeding with lower-concentration wastewater having high SS [SS/COD (g/g) ratio: 0.35 ± 0.11] at the ambient temperature. During operation, the particle size distribution shifted to larger particles. In particular, in the lower part of the reactor, at a height of 0.5 m, the weight percentage of granular sludge with particles larger than 0.85 mm was 55% of the retained sludge on day 520. Fig. 5 (b) shows that the retained sludge has higher sedimentation ability, with an SVI of 20–60 gSS/L. This sedimentation ability is due to precipitation of inorganic matter in the sludge (VSS/SS ratio of 0.64–0.74) and granular sludge formation.

Fig. 5 (c) shows the cellulose concentrations at different reactor heights. The cellulose concentration in the influent sewage was measured as 0.0065 g/L. As much as 2.1 g/L of cellulose (320 times more than in the influent) accumulated temporarily in the lower part of the reactor. Cellulose degradation was enhanced in the lower part of the reactor with increasing retained sludge concentration. The fed cellulose was initially retained in the reactor and could be degraded within only 6–10 days. The SRT of the UASB throughout the experimental period was estimated to be as long as 293 ± 114 days. The long residence time is considered to contribute not only to the retention of bacterial sludge in the reactor but also to the temporary accumulation and resolution of difficult-to-resolve materials such as cellulose. Fig. 7 shows the bacterial communities based on bacterial 16S rRNA gene analysis of retained sludge in the UASB. The analysis obtained 92–96 clones from each sludge sample. The number of phylotypes increased from 157 to 203 as operation proceeded. The evenness of each sample was around 0.91–0.97, and many uncultured bacterial clones were detected. These results indicated that the bacterial communities were significantly diverse. *Proteobacteria*, *Bacteroidetes* and *Firmicutes* were the dominant phyla of the solid organic matter decomposers in the library. Among the clones that belonged to the *Proteobacteria* phylum, 40–80% belonged to the *Delta-Proteobacteria* class. The *Desulfovibrionaceae* and *Desulfobacteraceae* families made up 30% of the *Delta-Proteobacteria* class. It considered that these bacteria contributed as a hydrogen-scavengers by sulfate-reduction and an organic-substance decomposer by fermentation whereas methane-production was decreased with sewage-temperature decrement in Fig. 3 (c) (Guyot and Brauman, 1986). Bacterial phyla belonging to the *Bacteroidetes* phylum made up 30–40% of the phylogenetic composition in cooler seasons. Bacteria of the *Bacteroidetes* phylum have been widely observed as acid-forming bacteria derived from ordure and as bacteria that degrade cellulose and protein (Whitehead *et al*., 2005; Bertin *et al*., 2006). This suggests that bacteria of the *Bacteroidetes* phylum contributed to resolving the accumulated solid organic matter. Fifty percent of the clones belonging to the *Firmicutes* phylum belonged to the *Clostridiales* order, and the genera *Clostridium* and *Ruminococcus* were detected. Bacteria of the *Firmicutes* phylum are known to form acid by hydrolysis, hydrogen

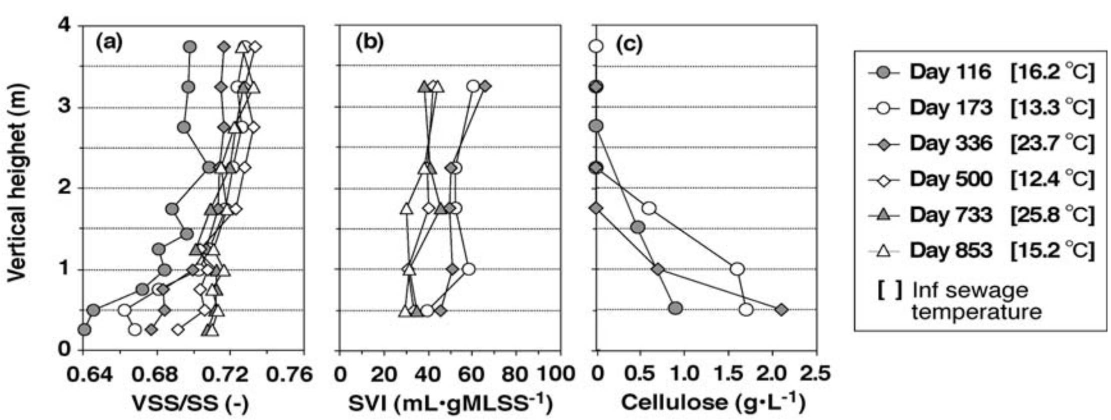

Fig. 5. Profiles of VSS/SS ratio (a), SVI (b) and cellulose concentration (c) in the UASB

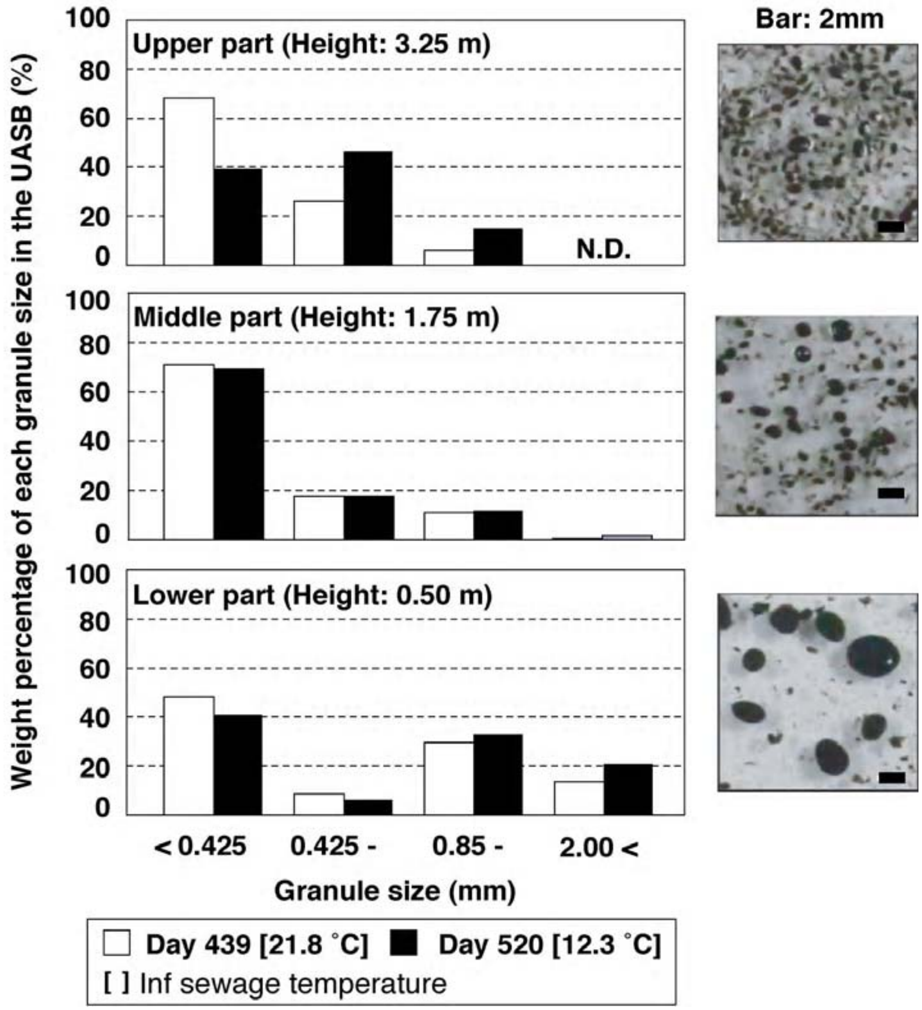

Fig. 6. Particle size distributions in summer and winter and photographs of retained sludge at each height position

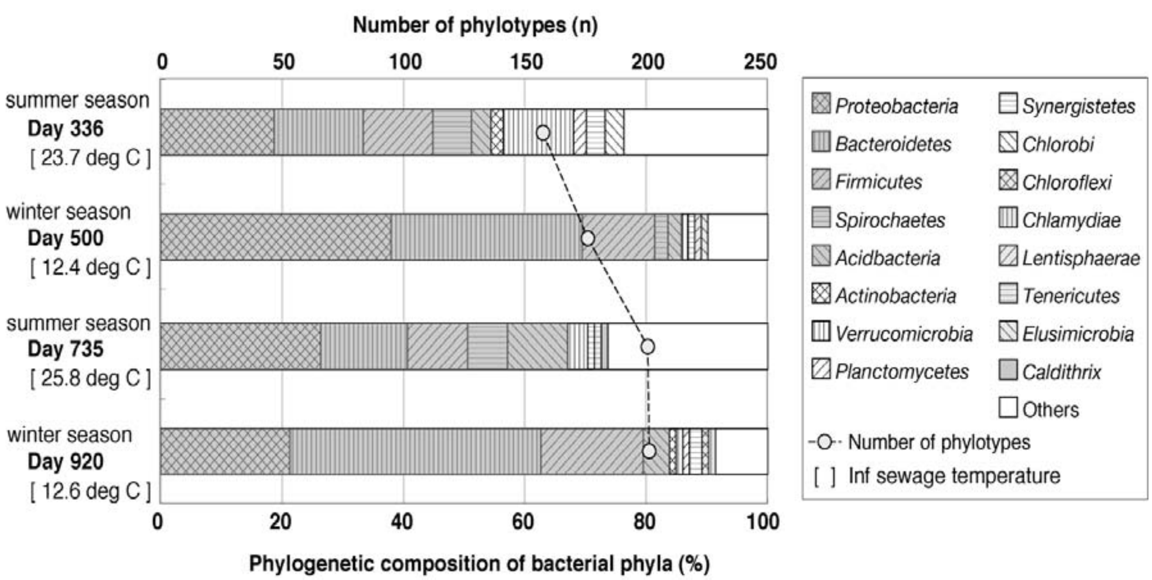

Fig. 7. Communities in the UASB retained sludge based on bacterial 16S rRNA genes

production and cellulose decomposition (Lo *et al.*, 2010; Chen *et al.*, 2005; Ntaikou *et al.*, 2009). The reactor could mineralize the accumulated solid substrate, such as the cellulose shown in Fig. 5, mainly by bacteria belonging to the *Bacteroidetes* and *Firmicutes* phyla.

CONCLUSION

The UASB reactor could maintain stable treatment with a COD removal efficiency of 63 ± 13% and a UASB effluent of 118 ± 40 mg/L in a temperature range of 10.6–27.7 °C at an HRT of 8 h. The UASB reactor could maintain a high concentration of retained sludge (24.5 g/L), with a lower COD-VSS loading rate of 0.05 gCOD/gVSS/day, at which granular sludge could form from the seeded mesophilic digester sludge. The richness of the retained sludge is understood to contribute to stable COD removal efficiency in winter, with around three months at temperatures below 15 °C. The VSS conversion rate and growth yield were clearly evaluated as 0.029 gVSS/$gCOD_{removed}$ and 0.132 gVSS/gCOD, respectively, using seasonal sludge profile estimation and daily water quality analyses. Longer SRTs, such as the 293 ± 114 days shown during operation, seemed to contribute to not only retention of bacterial sludge in the reactor but also temporary accumulation and resolution of difficult-to-resolve materials such as cellulose. *Proteobacteria*, *Bacteroidetes* and *Firmicutes* were the dominant phyla of decomposers of solid organic matter in the library. The UASB reactor accumulated low degradable solid substances such as cellulose, and it could mineralize them by bacteria belonging to the *Bacteroidetes* and *Firmicutes* phyla.

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