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Characterization of Mixing by CFD Simulation and Optimization of Mixing Frequency to Break Scum and Enhance Methane Yield in Chinese Dome Digester

Mfor E. Agborambang[1] · Masaaki Fujiwara[1] · Pranshu Bhatia[1] · Masatoshi Kishi[2,3] · Mutsumi Sekine[1] · Maria Cecilia D. Salangsang[1,4] · Tatsushi Matsuyama[1] · Tatsuki Toda[1]

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Abstract

The Chinese dome digester (CDD) is a low-cost and the most popular anaerobic digester that is used for the treatment of organic waste such as food waste and cow dung. However, the main challenge of CDD is scum formation due to inadequate mixing intensity. This study explores computational fluid dynamics (CFD) to characterize mixing in CDD and the effects of mixing frequency (0, 4, 6, and 8 times per day) on the performance of semicontinuous anaerobic digestion to break scum and enhance methane yield. The flow field simulation on a lab-scale CDD by Ansys Fluent (v.19.2), a finite volume solver, estimated that 45% of CDD working volume was occupied by dead zones which could nurture scum. The simulation results elicited the optimization of mixing frequency. Four CDDs were operated to investigate the optimum mixing frequency. The average scum thickness for the non-mixed digester was 2 ± 0.1 cm compared to 0.2 ± 0.1, 0.8 ± 0.1, and 1.3 ± 0.2 cm for the mixed digesters (4, 6, and 8 times per day, respectively). The average methane yields for 0, 4, 6, and 8 times per day were 206 ± 191, 602 ± 87, 555 ± 59, and 492 ± 109 mL g-VS^{-1}, respectively. Four times per day was the optimum mixing frequency and the energy required to break scum was 6.1 ± 0.3 Joules per mixing cycle. This study proves that by optimizing the mixing frequency in CDD, scum formation can be controlled without additional investment cost.

Keywords Chinese dome digester (CDD) · Self-mixing process · Gas release · Slurry displacement · Mixing intensity · Dead zones

Highlights

• CFD simulation showed that 45% of Chinese dome digester working volume was dead zone.
• Scum was formed in anaerobic digestion of food waste in Chinese dome digester.
• Scum formation has decreased the working volume and methane yield.
• Mixing frequency of 4-times per day was the optimum for scum control.
• The calculated energy required to break scum was 6.1 ± 0.3 Joules per mixing cycle.

Introduction

Energy is a vital component required for improving the human quality of life, abating poverty, and promoting socioeconomic activities [1]. However, millions of communities and households, particularly in developing countries, still lack access to basic energy services such as electricity, liquid fuels, and natural gas [2]. For example, ~1.5 billion people (>20% of the global population) have no access to electrical power, while ~3 billion people (~45% of the global population) still rely on traditional biomass sources such as firewood, dry food waste, and coal for their cooking needs [3, 4]. Moreover, large quantities

✉ Mfor E. Agborambang
mforebotagbor@soka.gr.jp

1 Graduate School of Science and Engineering, Soka University, 1-236 Tangi-machi, Hachioji, Tokyo 192-8577, Japan

2 Institute of Plankton Eco-Engineering, Soka University, 1-236 Tangi-machi, Hachioji, Tokyo 192-8577, Japan

3 Research Institute for Global Change, Japan Agency for Marine-Earth Science and 7 Technology, 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan

4 College of Arts and Sciences, University of the East-Caloocan, 105 Samson Rd, Caloocan City 1400, Philippines

of municipal solid waste (MSW) from numerous urban areas in developing countries are being dumped in unregulated landfills, and these pose severe threats to both the environment and human health [5]. Anaerobic digestion (AD) is a cost-effective, clean, and—arguably—the most popular renewable energy source that can utilize MSW such as food waste to produce biogas [6].

The Chinese dome digester (CDD) is a low-cost and the most widely applied household digester in rural areas of developing countries, given its energy-efficient self-mixing process, reliability, low maintenance, and long lifespan, making it suitable to meet the energy requirement for cooking applications at the domestic and community levels [7, 8]. CDD is usually constructed underground with a hemispherical dome top (headspace), which serves as gas storage and gas pressure is maintained through the height of the expansion tank [9]. When the biogas produced accumulates and is stored in the headspace above the slurry, the stored gas results in a pressure build-up and pushes part of the slurry into the expansion tank. During gas release through a valve, the slurry flows back into the main digester, thus, creating a mixing regime [10]. Figure 1 illustrates the self-mixing process in a CDD.

The major hindrance to achieving sufficient biogas production in a CDD is the formation of scum at the surface of the slurry. Scum is a mixture of undigested substrate, microbes, and virtually any material that can float [11, 12]. Scum represents a severe technological challenge because it hampers the release of biogas and seriously affects the stability and efficiency of the digestion system [13]. Consequently, excessive scum causes financial losses due to decreased biogas production and increased costs for extra labor and maintenance [12, 13]. The main reason of scum formation in CDD is insufficient mixing [14]. Various techniques have been employed to improve scum control and biogas production. These techniques include reducing the substrate particle size, improving disintegration of feedstock, mechanical mixing, and use of scum warning systems [13, 15, 16]. Though these techniques can reduce scum to some extent, the methods generate high cost due to high energy consumption, which is not acceptable in rural areas [13]. In addition, previous studies about scum control primarily focused on mechanical mixed reactors [13, 15]. While there is limited information about the strategies to prevent scum formation in CDD. Mixing intensity in Chinese dome digester is controlled by a gas valve operation (mixing frequency) during gas production and gas usage [9, 17, 18]. For instance, if a large volume of gas is released at once, it would make the mixing intensity stronger. Thus, by optimizing the mixing frequency in CDD, scum formation can be controlled for long-term operation without additional investment cost. The reason why scum is formed at the surface of slurry is attributed to dead zones created due to insufficient mixing [14]. Since the presence of the dead zones in CDD leads to the formation of scum, advanced modeling and simulation techniques could be employed.

Computational fluid dynamics (CFD) is a major tool for evaluating velocity profiles, particle trajectory, and dead zones in anaerobic digesters, reducing both expense and time [19]. CFD predictions show good qualitative comparison with the experimental data in terms of flow pattern, location of dead zones, and trends in velocity profiles [20, 21]. Notably, computer simulations have suggested that insufficient mixing can lead to lower methane yield and treatment efficiency [19].

Therefore, the objective of the present study was to perform CFD simulation to characterize mixing in CDD and the effect of mixing frequency on the performance of semi-continuous AD to identify dead zones, the optimum mixing frequency to break scum and enhance methane yield.

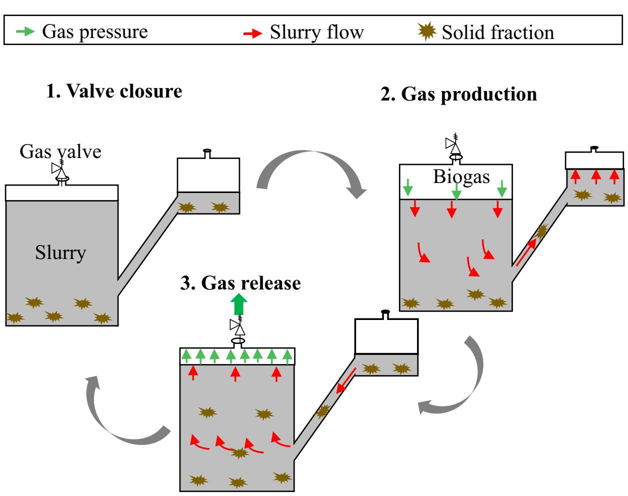

Fig. 1 The self-mixing process in Chinese dome digester. (1) feeding (2) gas production and (3) gas release

Materials and Methods

CFD Modeling and Simulation

Geometry and Operating Principle

The modeling and simulations of CDD were performed in ANSYS Workbench (v. 19.2). The CDD was constructed from PVC materials, with a digester volume of 15 L and an expansion tank of 2 L for slurry displacement and outlet [9]. The 3D geometry was developed in ANSYS SpaceClaim (v.19.2) as shown in Fig. 2a.

Model Development

Slurry flow inside an anaerobic digester is complex and it is governed by the conservation of mass and momentum [9, 19, 20].

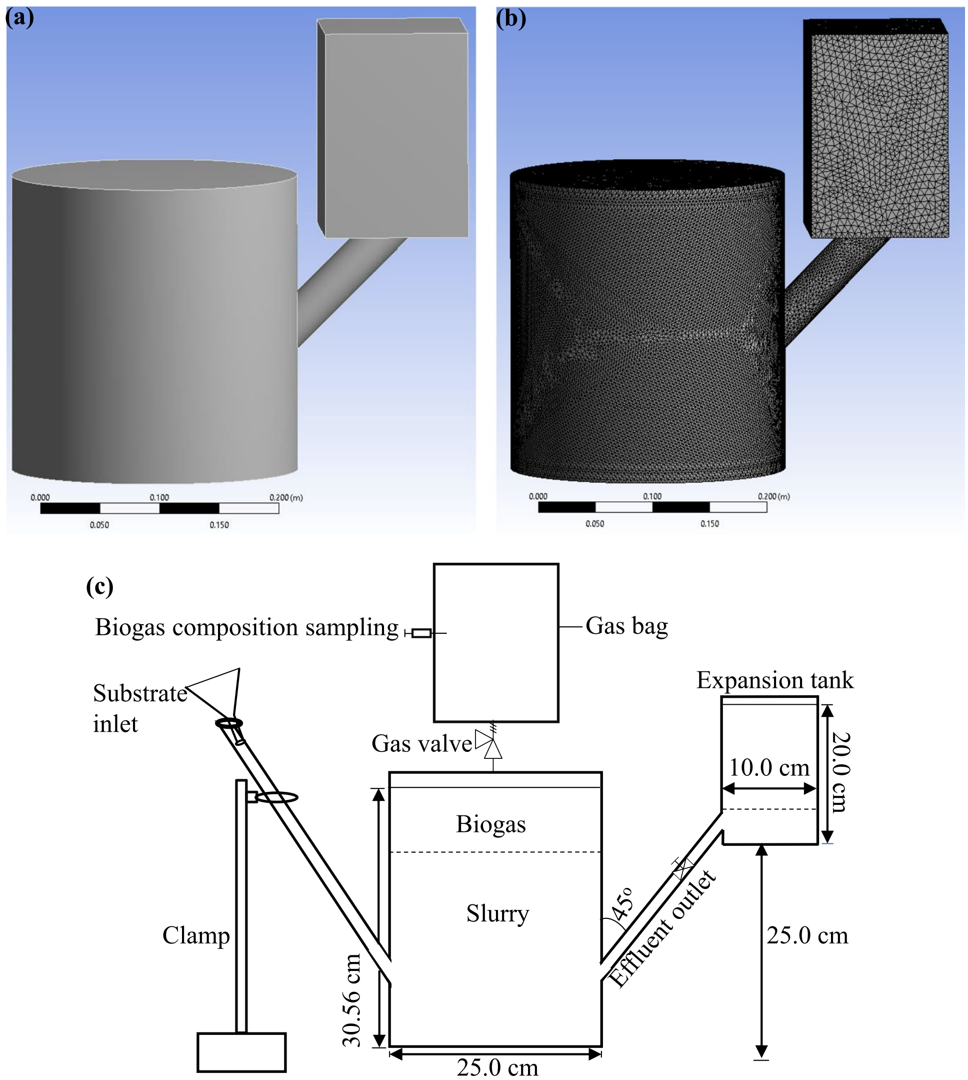

Fig. 2 CFD model of Chinese dome digester. Geometry (**a**) Meshed geometry (**b**) and schematic diagram of CDD setup in semicontinuous anaerobic digestion (**c**)

Therefore, the following assumptions were made in developing a theoretical model describing the mixing process in CDD:

(1) Fluid flow in the digester is laminar [9].
(2) Fluid is Newtonian with 12% TS concentration [9].
(3) The model is limited to the flow model without considering the heat transfer, as the slurry temperature is constant at 35 °C [19].
(4) The model is a single phase (liquid), in which gas–liquid and solid–liquid phase interactions are negligible [19, 20].

Mesh

Mesh independence analysis was performed on the CDD. The user-defined mesh used was primarily tetrahedral (5-cell, triangular pyramid) with minimal skewness, which had surface quality independence and aligned with the user coordinate system (Fig. 2b). The total number of elements was 160,808. The maximum growth rates were constant at 1.2, while the average element quality was 0.96381.

Governing Equations

The CFD codes were solved based on the conservation laws of fluid mechanics, conservation of mass, and momentum in its calculations [19, 22].

$$\text{Continuity Equation (conservation of mass)}: \frac{\partial}{\partial \mathrm{x_i}}\left(\rho u_{\mathrm{i}}\right) = 0 \tag{1}$$

where ρ is the density of the liquid substrate and u_i is the fluid velocity in tensor form

$$\text{Momentum Equation}: \frac{\partial}{\partial \mathrm{x_j}}\left(\rho u_{\mathrm{i}}\mathrm{u_j}\right) = -\frac{\partial \mathrm{p}}{\partial \mathrm{x_i}} + \frac{\partial \tau_{\mathrm{ij}}}{\partial \mathrm{x_j}} + \rho g_{\mathrm{i}} \tag{2}$$

where p is static pressure, $\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$(stresstensor), ρg_i is the gravitational force, and μ is molecular viscosity

Physical Parameters and Boundary Conditions

The discretized (meshed) 3D model was simulated by using ANSYS Fluent (v.19.2). All simulations used a generalized coordinate, finite volume code (ANSYS Fluent, v. 19.2) with SIMPLE Pressure Velocity Coupling Scheme, First-Order Upwind for momentum and kinetic energy. The CFD simulation was performed on CDD for the gas release process. The fluid was assumed to be a Newtonian, single-phase (liquid-slurry) with a 12% TS concentration [19]. Notably, the 12% TS concentration of the slurry applied in the simulation is similar to the average TS concentration (11.6%) of slurry (sludge + food waste) obtained in the AD experiments at steady-state period (day 44 to 60). The density of the slurry was 999.66 kg m^{-3}, and the dynamic viscosity was 0.065 Pa·s [19, 20]. The flow modeling was focused on slurry flow (single phase) from the expansion tank to the main digester to find the optimal degree of mixing. An initial velocity of 0.025 m s^{-1} was applied to the top of the expansion tank [19]. The top of the expansion tank was at atmospheric pressure (101,325 Pa).

Simulation Steps

The simulation steps were as follows: (a) The solver was defined as 3D, time-dependent implicit, and pressure based. (b) A laminar flow model was selected for gas release process simulation. (c) Define the material properties of the slurry to have 12% TS concentration. (d) Configure boundary conditions for a single phase. (e) Define the operational conditions by activating the gravitational acceleration. Governing Eqs. (1) and (2) were then solved by using the semi-implicit method for the pressure-linked equation (SIMPLE) algorithm.

Semicontinuous AD Experiments

Substrate and Inoculum Collection

The food waste (FW) used in this study was freshly collected from the Ohmura Commercial Company Ltd (Saitama, Japan). Over 56.46% wet weight (wwt) of the food waste was vegetables, 21.53% wwt was rice, 14.36% wwt was eggshell, 7.39% wwt was pasta, and 0.26% wwt was fish. The food waste was milled to 3–5 mm with a milling machine (RSC-2500/MC, O-Ring Ltd, Japan) and was stored in a refrigerator at 4 °C before feeding the digesters. The carbon to nitrogen ratio (C:N) was 9.97:1 and the total solids (TS) and volatile solids (VS) of the food waste were 14.51% wwt and 13.55% wwt, respectively. In all digesters, Milli-Q water was added to the substrate during feeding to keep the working volume constant at 11 L, achieving an OLR of 1.2 g-VS L^{-1} d^{-1} and HRT of 20 days. The inoculum used for the digester start-up was mesophilic anaerobic digestion sludge, which has been acquired from the Hokubu Sludge Treatment Centre (Yokohama, Japan) with a TS concentration of 3.73% wwt and VS concentration of 1.68% wwt. The obtained sludge was preserved at 37 °C for 2 days before the startup.

Digester Design and Setup

The CDDs were constructed from polyvinyl chloride (PVC) and the effective volume of each CDD was 15 L, the working volume was 11 L and an additional 2 L for the expansion tank. The height of the expansion tank from the base was 25 cm. The schematic diagram of the CDD setup in semicontinuous AD is shown in Fig. 2c. Biogas produced in the CDD was stored in the digester headspace to create pressure for displacing some of the digester slurry to the expansion tank. Also, the effluents were removed from the digester through the expansion tank. The generated biogas was collected in aluminum gasbags.

Digester Operation

Semi-continuous anaerobic digestion was performed in four laboratory-scale CDDs to elucidate the effect of mixing frequency on the scum thickness and methane yield. All the digesters were operated at the hydraulic retention time (HRT) of 20 days, organic loading rate of 1.2 g-VS L^{-1} d^{-1}. The period of operation was 60 days to achieve the level of threefold HRT. A total of 1.2 L of effluent was removed after every 2 days from the expansion tank each digester. Then, the same quantity of freshly prepared food waste slurry was added to the digesters. The digesters were operated at the temperature of 37 °C and at different mixing frequencies, non-mixed (R1), 4 times per day (R2), 6 times per day (R3), and 8 times per day (R4) by opening of an automatic valve controlled by a timer.

Monitoring and Analytical Methods

The temperature was monitored using a digital temperature logger. The pH of feed and effluents was measured using a tabletop pH meter with a probe (B-212, HORIBA, Japan). The effluent samples were analyzed for TS, VS, nutrients ($NH4^+$) and volatile fatty acids (VFAs: acetate, propionate, and butyrate). The biogas generated was collected in aluminum gas bags every 2 days, and the volume was measured using the water displacement method. Biogas composition was determined in terms of methane (CH_4) and carbon dioxide (CO_2) content. The CH_4 content was measured indirectly by passing the biogas through 3 mol L^{-1} NaOH to absorb the CO_2 present. TS and VS were analyzed using standard procedures (APHA, 2006). VFAs were measured using high-performance liquid chromatography with a Shim-pack Fast-OA high-speed organic acids analytical column (LC-2030C Shimadzu) in combination with the Shimadzu post-column pH-buffered electrical conductivity detection method. The following organic acids were used at an analytical grade: acetic, propionate, butyrate, and valeric acids. Specific biogas and methane yields were expressed as methane produced daily. They were divided by the amount of VS daily fed to the digester and applied to monitor the digestion efficiency of the CDDs. The scum thickness was measured with a transparent ruler. The biogas pressure was monitored with a pressure gauge (TOKO Micro-Pressure Gauge 75 Diameter BL-B-AT G3/8 Diameter 75 × 5 kPa) and the slurry displacement was monitored with a camera (Apexcam Action Camera, 4 K 20 Million Pixels, Sony Sensor, WiFi Equipped, 40 M Waterproof). The digesters were mixed by hydraulic variation (slurry displacement), while the energy created and utilized during mixing to break scum was derived in the form of potential energy by using Eq. (1):

$$PE = mgh \tag{3}$$

where PE is the potential energy in joule (J), m is the mass (kg) of the maximum volume of slurry displaced during biogas production (because of pressure build-up due to gas production) each day, g is 9.8 m/s^2, and h (m) is the height of the expansion tank. The volumes of the displaced slurry in the expansion tank were found to be 0.0000 m^3, 0.0025 m^3, 0.002 m^3, and 0.0017 m^3 for the digesters R1, R2, R3, and R4 respectively. The mass of the displaced slurry was derived from its volume and density [18].

Results and Discussion

Characterization of Mixing in CDD by CFD Simulation

The velocity data of the model are captured from the simulation results. The results show the values of the slurry hydrodynamic inside CDD, as velocity profiles. Figure 3a shows the variation in velocity magnitude in the range of 0–4.2 m s^{-1} during the self-mixing process (gas release process). The self-mixing process in CDD is due to hydraulic displacement between the main digester and the expansion tank, which is to distribute organic materials in all parts of the CDD. The velocity vectors in Fig. 3b shows that the fluid rotates in a circular shape at the bottom of CDD, implying that the bottom part was well mixed. The range of velocity magnitude at the bottom was 1.5–3.0 m s^{-1} and at the top of CDD was 0.0 to 0.3 m s^{-1}. Notably, the range of velocity magnitude at the wall opposite to the flow inlet was 0.5–1.3 m s^{-1}, across the vertical length of the CDD. The reason why velocity magnitude increased only on one side of the wall was because of the slurry flow direction and the shape of CDD. The trend of mixing in the present study is similar to Jegede et al. [9] who performed 2D, three-phase simulation and evaluated the hydraulic characteristics of a CDD and an optimized CDD. 3D simulations are usually efficient and represents the actual mixing process in CDD. However, Jegede et al. [9] did not focus on the relationships between scum formation and fluid characteristics which vary in the different parts of the CDD.

The percentage of volume with mixing zones and dead zones was evaluated. The mixing zones are parts of the CDD with medium and high slurry velocities and the dead zones are parts of the CDD with no slurry flow or very low velocities [23]. The definition of mixing and dead zones in the present study was in accordance with Wu and Chen. [24], where zones with slurry velocities > 1 m s^{-1} are denoted as high mixing zones, slurry velocities in the range of 0.1 to 1 m s^{-1} are denoted as medium mixing zones, and slurry velocities < 0.001 m s^{-1} are denoted as dead zones. The mixing zones and dead zones are shown in Fig. 3a. The mixing zones are represented by multicolor areas and dead zones are represented in blue spaces, from the front view. The percentage volume of CDD that was found in the high mixing zone (> 1 m s^{-1}) was 25% (at the bottom of CDD) and the percentage volume of CDD that was found in the medium mixing zone (0.1–1 m s^{-1}) was 30% (at the wall opposite to the slurry inlet). The slurry flows from the expansion tank to the bottom of CDD with high velocity magnitude (> 1 m s^{-1}) and the wall opposite the slurry inlet with low-velocity magnitude (0.1–1 m s^{-1}). The percentage volume of CDD that was found in the dead zones (< 0.001 m s^{-1}) was 45% (in the middle and at the top, above 15 cm height of CDD). This huge volume of dead zones in CDD could nurture a massive quantity of scum at the top of CDD, leading to a decrease in biogas production. Identifying the high mixing zones and the dead zones in CDD was an important step to explore the optimum mixing frequency that can improve mixing intensity at the top of CDD to break scum.

Semicontinuous AD Experiments

Methane Yield

The performances of mixing frequency on methane yield were analyzed. Figure 4 shows the results of methane yield for the four digesters. R1 produced the lowest methane yield, which persisted throughout the experiment with an average of 206 ± 191 mL g-VS^{-1}. The methane yield in R2 was the

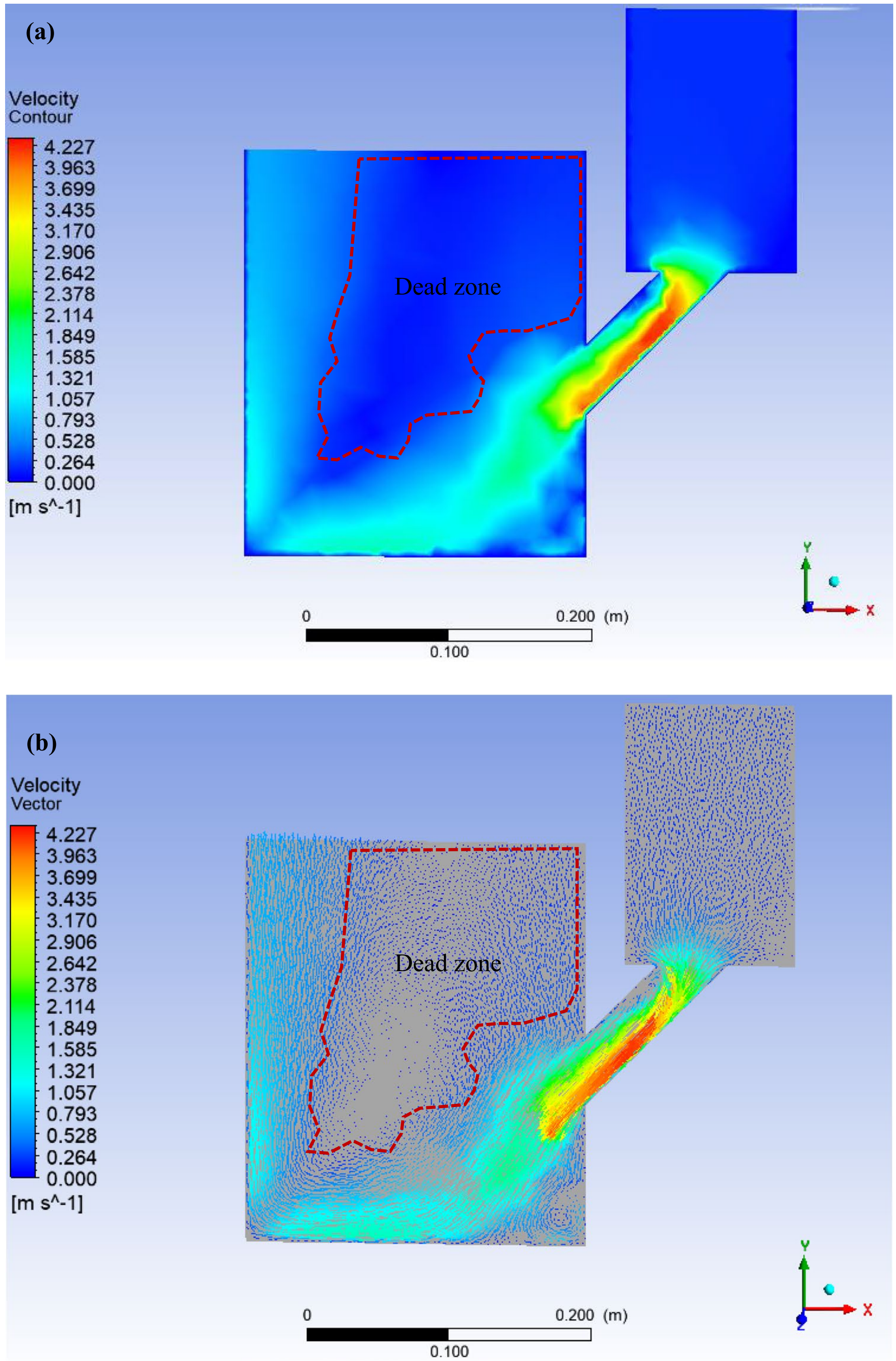

Fig. 3 Velocity contours (**a**) vectors (**b**) in CDD during gas release operation simulation

highest, with an average of 602 ± 87 mL g-VS^{-1}, while R3 and R4 had average methane yields of 555 ± 59 mL g-VS^{-1} and 492 ± 109 mL g-VS^{-1}, respectively. The methane yields in R2, R3, and R4 were nearly constant throughout the experiment, while that of R1 decreased sharply from day 32. Furthermore, R1 was a non-mixed digester, while R2, R3, and R4 were intermittently mixed digesters that were mixed four, six, and eight times per day, respectively. The driver of the low methane yield in R1 and the increase in R2, R3, and R4 was likely the restricted gas release in R1 due to scum formation while the intermittent mixing in R2, R3, and R4 increased the probability of mass transfer from the liquid phase to the gas phase [25]. This inference is in line with the results of Lin & Pearce. [26] and Karim et al. [27],

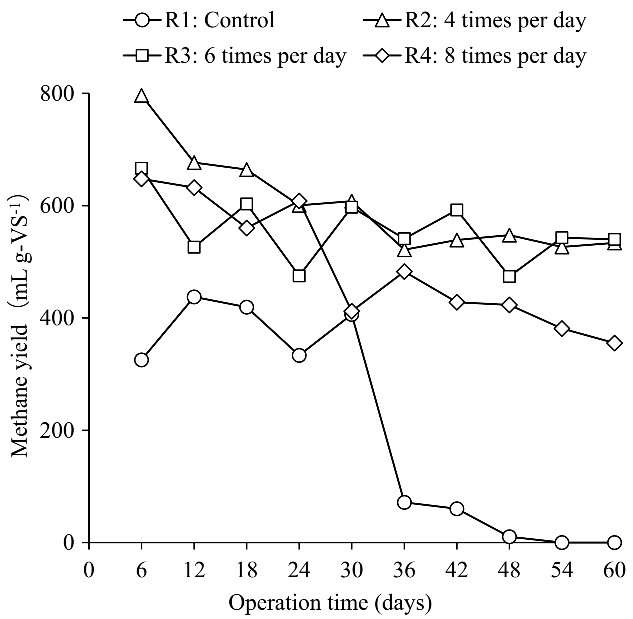

Fig. 4 Daily methane yield at different mixing conditions; no mixing (R1), 4 times per day (R2), 6 times per day (R3) and 8 times per day (R4)

who used impeller mixed rectors to identify the effect of intermittent mixing and unmixed modes on methane yield in semicontinuous AD. However, the increase in methane yield in R2 over the other intermittently mixed digesters (R3 and R4) was due to the increase in mixing intensity. It was also found that R3 (6 times mixing per day) and R4 (8 times mixing per day), with their higher gas release, exhibited lower mixing intensities and were considered insufficiently mixed digesters. Similar results were previously reported by Jegede et al. [18], who examines the effect of mixing on the performance of anaerobic digestion of cow manure in Chinese dome digesters (CDDs) in comparison with impeller mixed digesters (STRs) and unmixed digesters (UMDs). They reported that the low methane yield in the CDDs (mixed once per day) compared to the STRs was attributed to insufficient mixing intensity. Overall, these results indicate that different mixing frequencies induced the variation in methane yield. The results of methane yield are summarized in Supplementary Table 1.

VFA Accumulation

The concentrations of VFAs were analyzed for all digesters (R1, R2, R3, and R4). Acetate, propionate, and i-butyrate were the main VFAs analyzed, and i-butyrate had the highest concentration. i-butyrate is produced mainly from the degradation of the branched amino acid valine, implying that the substrate was rich in proteins [28]. The high concentration of i-butyrate was due to its slower degradation rate [29]. VFAs concentrations were high in R1with acetate: 40 ± 35 mg L^{-1}, propionate: 86 ± 78 mg L^{-1}, and i-butyrate: 302 ± 80 mg L^{-1} compared to the mixed digesters (R2, R3, and R4). The VFAs concentration in R2 was the lowest with only acetate (0.5 ± 2.0 mg L^{-1}) and i-butyrate (148 ± 92 mg L^{-1}) detected. Acetate, propionate, i-butyrate, n-butyrate, and i-valeric were detected in R3. However, the VFA concentrations in R3 were relatively low with acetate: 39 ± 35 mg L^{-1}, propionate: 31 ± 18 mg L^{-1}, i-butyrate: 167 ± 77 mg L^{-1}, n-butyrate: 5 ± 3 mg L^{-1}, and i-valeric: 4.3 ± 0.3 mg L^{-1}. i-butyrate was the main VFA in R4 with acetate and propionate at lower concentrations. The VFA concentration in R4 was as follows: acetate: 21 ± 31 mg L^{-1}, propionate: 11 ± 16 mg L^{-1}, and i-butyrate: 103 ± 96 mg L^{-1}. The high VFA concentrations in R1, compared with R2, R3, and R4, could potentially have been driven by the inhibition of methanogenesis, given the instability of the system in the absence of mixing [18]. Meanwhile, mixing in the mixed digesters could stabilize the digester and prevent overloading. The pH range throughout the experiments was 6.89–8.15, signifying the stability of the AD process [11, 30]. The stability of the VFA concentration could also be due to the pH range. The growth rate of methanogens appeared to be strongly reduced at $pH < 6.6$ [31]. Wang et al. [32], explored the effects of VFAs on methane yield and methanogenic bacteria growth and they reported that at high concentrations of acetate and butyrate (2400 and 1800 mg L^{-1}, respectively), no significant inhibition of the activities of methanogenic bacteria was detected. However, when the concentration of propionic acid was increased to 900 mg L^{-1}, significant inhibition occurred while the concentration of bacteria decreased. In this study, the average concentration of VFAs in all the digesters was < 800 mg L^{-1}. Thus, they could be regarded as well-balanced digesters [33]. We surmise that the low concentration of VFAs in all digesters, R1, R2, R3, and R4, was unlikely to inhibit the methane yield. Moreover, the lower concentration of VFAs in R2 and R3 indicates that acid produced by the microbes during acetogenesis was consumed by the methanogenic bacteria, leaving a low inhibition level [32]. These results suggest that mixing facilitated the conversion of VFAs to methane, but the present study did not identify any cogent effects of VFA conversion in different mixing conditions (Table 1). Therefore, the decrease in methane yield in R1 might not be related to the accumulation of VFAs.

Scum Formation

Figure 5 shows the scum formation in the four digesters (R1, R2, R3, and R4). Scum formation began on day 32 (scum thickness = 0.5 cm) in R1 and progressively increased to day 44 (scum thickness = 2.2 cm) and then stabilized until day 60. Scum formation began on day 40 in R2 (scum

Table 1 Methane yield and VFAs concentration for all the digesters (R1, R2, R3, and R4). Numbers in parentheses indicate the average values

Digester	R1 (no mixing)	R2 (4 times per day)	R3 (6 times per day)	R4 (8 times per day)
Methane yield (mL g-VS^{-1})	0–435 (206 ± 191)	522–785 (602 ± 87)	474–664 (555 ± 59)	354–646 (492 ± 109)
VFAs (mg L^{-1})				
Acetate	0–94 (39 ± 34)	0–5 (1 ± 2)	0–80 (39 ± 35)	0–83 (21 ± 31)
Propionate	0–188 (85 ± 77)	- (-)	0–60 (31 ± 18)	0–22 (11 ± 16)
i-butyrate	0–358 (301 ± 79)	0–250 (148 ± 92)	50–273 (166 ± 77)	6–243 (103 ± 96)
n-butyrate	- (-)	- (-)	0–8 (5 ± 2)	- (-)
i-valeric	- (-)	- (-)	0–4 (4 ± 0)	- (-)

"-" indicates no detection in the digester

thickness = 0.1 cm), and there was no significant increase until day 60 (scum thickness = 0.2 cm). Scum formation began on day 38 (scum thickness = 0.2 cm) in R3 and increased till day 60 (scum thickness = 0.9 cm). In R4, scum formation began on day 34 (scum thickness = 0.5 cm) and increased continuously until day 60 (scum thickness = 1.5 cm). The continuous increase in the scum formation in R1 was driven by the non-mixed state of the digester because gas bubbles were trapped in the scum and could not be discharged [34, 35]. The buoyant force caused by gas bubbles was gradually strengthened as more biogas was produced. It pushed the slurry to go up and then form a scum layer at the top of the slurry [34]. As discussed above, CDD has dead zones mainly in the upper part of the digester; therefore, once the scum was formed in the dead zones, it was difficult to break. The delay in scum formation in R2, R3, and R4 occurred because they were mixed digesters, and more shear was exerted on the scum layers by the mixing [35, 36]. Supplementary Fig. 1 shows photos of scum formation for all digesters at the end of experiments. Scum was nearly completely broken in R2 (mixed 4 times per day), likely because more slurry was displaced to the expansion tank therein; it increased the mixing intensity more than the other mixed digesters (R3 and R4). The slight increase in the scum formation in R3 and R4 could potentially have been driven by the limited mixing that did not break the scum. Overall, this study reveals that scum can be reduced to a minimum by optimizing the mixing frequency (4 times per day).

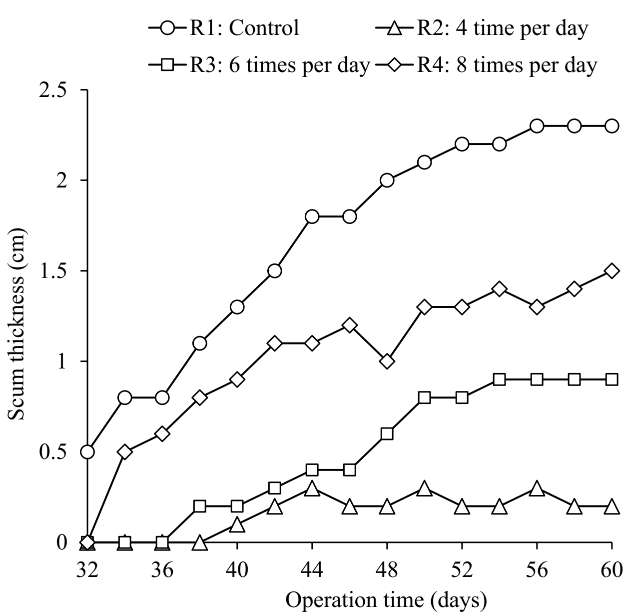

Fig. 5 Scum formation at different mixing conditions; no mixing (R1), 4 times per day (R2), 6 times per day (R3) and 8 times per day (R4)

Effects of Scum Thickness on Methane Yield

Figure 6 shows the effects of scum thickness on methane yield at a steady-state period (44–60 days). At the beginning of the experiments (0–31 days), no scum was formed, while methane yield was nearly stable in all mixing conditions. As scum formation started on day 32 in R1, a sharp decrease in methane yield emerged as well. The methane yield in R1 greatly dwindled and then maintained the low level from day 32 to 60. However, the scum formation in R2 started 6 days after that of R1 without any significant increase in scum thickness. Methane yield in R2 was higher and was nearly constant throughout the experiment. Note that these findings go in line with that of Ong et al. [37], who did findings on the anaerobic digestion

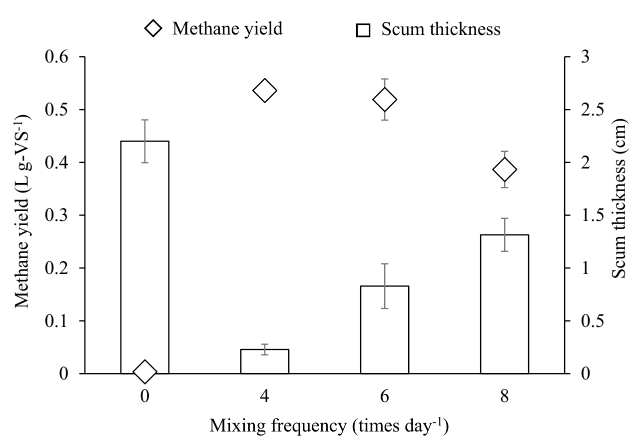

Fig. 6 The effects of scum thickness on methane yield at steady state condition (day 44–60)

of cattle manure slurry in impeller mixed digesters (160 rpm) with a mixing frequency of 4 times per day and duration of 30 min. Specifically, they have demonstrated that gas released from the liquid digestate in intermittently mixed digesters was 70% higher than that in the unmixed digester. Scum formation was started in R3 on day 38 and day 34 in R4. There was a slight increase in scum thickness and a slight decrease in methane yield in R3 and R4. These results suggest that the biogas produced in R3 and R4 could have been trapped in the scum without being able to discharge. The average scum thickness and methane yield of the digesters were determined to be 2 ± 0.1 cm and 206 ± 191 mL g-VS^{-1}, 0.2 ± 0.1 cm and 602 ± 87 g-VS^{-1}, 0.8 ± 0.1 cm and 555 ± 59 mL g-VS^{-1}, and 1.3 ± 0.2 cm and 492 ± 109 mL g-VS^{-1}, for R1, R2, R3, and R4, respectively. As seen in the results, R1 (no mixing) exhibited the highest scum thickness and lowest methane yield, while R2 (4 times per day) exhibited the lowest scum thickness and highest methane yield.

These findings agree with Tian et al. [34] results, where the effects of scum layer on biogas production at different mixing conditions have been reported. Scum layers were formed in the early stage of the no-mixing period. Notably, the daily biogas production was decreased by 81.87–87.90% in the non-mixed digesters, compared with the mixed digesters. The reduction of biogas production in the non-mixed digesters was mainly associated with scum formation, which induced the poor contact of substrate-microorganisms [34]. Overall, these results prove that optimization of mixing frequency can enhance methane yield in CDD without design modification.

Effects of Mixing Frequency on Slurry Displacement

The minimum (R2, 4 times per day) and maximum (R4, 8 times per day) mixing frequencies were examined with an Apexcam action camera for 48 h to investigate the effect of mixing frequency on slurry displacement. Supplementary Fig. 2 shows the results of the effects of mixing frequency on slurry displacement. The volume of slurry displaced in the expansion tank at the first hour of gas production in R2 was 0.3 ± 0.1 L and the fifth hour before gas release was 2.0 ± 0.2 L. The gauge pressure of biogas for the first hour in R2 was 0.2 ± 0.1 kPa and the fifth hour was 2.5 ± 0.2 kPa. The volume of slurry displaced in the expansion tank at the first hour of gas production in R4 was 0.3 ± 0.1 L and the third hour before gas release was 0.9 ± 0.1 L. The gauge pressure of biogas for the first hour in R4 was 0.3 ± 0.1 kPa and the third hour was 0.9 ± 0.1 kPa. Notably, the volume of slurry displaced in R2 was more than twice the volume of slurry displaced in R4. These results show that more slurry was displaced into the expansion tank at a lower mixing frequency which increased the mixing intensity during gas release operation. This was because more gas was retained in the digester headspace over a long period (6 h) before the next mixing cycle which displaced more slurry into the expansion tank. The above result could explain the reason why scum was broken in R2.

Energy Required to Break Scum

The gravitational potential energy (P.E), created by the CDDs, was calculated from the results of the effects of mixing frequency on slurry displacement, using Eq. (1). Since scum was broken in R2, the energy required to break scum was calculated from the P.E created in each mixing cycle in R2 (4 times per day). The average P.E created during the six mixing cycles in R2 was 6.1 ± 0.3 Joules per mixing cycle. In R4 (8 times per day), the average P.E created was just 1.8 ± 0.2 Joules per mixing cycle. Notably, the gravitational potential energy (P.E) created in R2 increased threefold compared to P.E created in R4. The energy consumed for breaking scum in CDD was generally low (6.1 ± 0.3 Joules per mixing cycle) and was achieved by the slurry displacement between the main digester and expansion tank, due to gas pressure build-up in the digester [9]. Importantly, this study demonstrates that by optimizing mixing frequency, the natural P.E created in CDD can possibly break scum without the use of eternal energy.

Comparison of the Performance of Mixing Frequency on Methane Yield with Previous Studies and Future Prospect

The effects of mixing frequency on methane yield and energy consumption obtained in the present study are given in Table 2 along with the results of previous studies. The digester type differed, mainly the impeller mixed digester [38, 39] and the CDD [14, 18, 40]. In the previous studies that used impeller mixed digester [38, 39], methane yield was less than 0.45 LgVS^{-1} while the energy consumption ranged between 406 and 9746 kJ L^{-1} d^{-1}, in contrast to impeller mixed digesters, which were operated at high mixing frequency and consumed a high amount of energy throughout the operational period. The methane yield for the CDDs in the previous studies [14, 18, 40] and the present study was 0.13–0.32 L gVS^{-1} and 0.60 L gVS^{-1}, respectively, with 0 kJ L^{-1} d^{-1} energy consumption. One of the main reasons why the CDDs in the previous studies [14, 18, 40] produced low methane yield was attributed to insufficient mixing. Mixing frequency is a very important aspect to improve mixing intensity in CDD. However, there are no studies on the effects of mixing frequency on treatment performance in CDD. As stated earlier, the optimum mixing frequency of 4 times per day in the present study probably achieved sufficient mixing intensity to break scum and maintained high treatment efficiency. Hence, the results

Table 2 Comparison of the performance of mixing frequency on methane yield with previous studies and future prospect

Substrate	Digester type	Mixing frequency (times/day)	Methane yield (L/g VS)	Electricity consumption (KJ/L/d)	Reference
Food waste	Impeller mixed digester	24 (2 min/h)	0.44 ± 0.03	406	[38]
Food waste	Impeller mixed digester	Continuous	0.40 ± 0.03	9746	[38]
Cow dung	Impeller mixed digester	2	0.22 ± 0.03	-	[39]
Buffalo dung	Chinese dome	1	0.23	0	[40]
Cow dung	Chinese dome	2	0.25 ± 0.05	0	[14]
Cow dung	Chinese dome	1	0.13 ± 0.003	0	[18]
Food waste	Chinese dome	4	0.60 ± 0.08	0	Present study

Jegede et al. [14, 18]; Zhang et al. [38]; Kaparaju et al. [39]; Hamad et al. [40]

of the present study indicate the possibility of applying an optimum mixing frequency of 4 times per day in an actual AD plant. Further studies on 3D, CFD multiphase simulation, structural modification, and the volume ratio of the main digester and expansion tank of CDD are required to improve the performance of the system.

Conclusions

The simulation results identified dead zones at the upper part of CDD which nurtured scum. Identifying dead zones by CFD simulation prompted the optimization of mixing frequency. The results of AD experiments showed that the non-mixed CDD produce the highest scum thickness and lowest methane yield, compared to the mixed digesters. The optimum mixing frequency of 4 times per day yielded efficient mixing intensity for (a) breaking scum, (b) enhancing methane yield, and (c) improving the anaerobic digestion performance. The energy (P.E) required to break scum was 6.1 ± 0.3 Joules per mixing cycle. Ultimately, this finding is particularly valuable for operating anaerobic digestion in CDD efficiently without additional investment cost.

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Declarations

Conflict of Interest The authors declare the following financial interests/personal relationships which may be considered potential competing interests:
Soka University reports financial support was provided by the Japan Science and Technology Agency (JST). Mfor Ebot Agborambang reports a relationship with Soka University Faculty of Engineering Graduate School of Engineering that includes the following: funding grants and travel reimbursement.

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