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An Anaerobic Digestion System Inspired by Intestinal Peristalsis - Development of a Peristaltic Bioreactor with Mixing via Rotational Flow and Negative Pressure Inflow

G. Ueki, T. Tanno, *Student Member, IEEE*, F. Ito, *Member, IEEE*, A. Ohnishi, K. Okuda,
H, Yamamura, R. Kina, T. Nakamura, *Member, IEEE*

***Abstract*— To enhance the energy-intensive mixing of highly viscous biomass in solid-state anaerobic digestion (SS-AD), a novel peristaltic bioreactor inspired by intestinal peristalsis was developed. The reactor uses rotational flow and negative pressure inflow to enhance the mixing efficiency. A prototype's performance was evaluated using a simulated biomass (total solids = 40%), and the mixing progress was quantified using a mixing index. The experimental results showed that the proposed rotational flow achieved complete mixing, unlike conventional axial flow. Furthermore, the application of negative pressure accelerated the mixing time from 5.2 min to 3.1 min. These findings validate our intestine-inspired approach, demonstrating its potential for developing compact and energy-efficient SS-AD systems.**

I. INTRODUCTION

To achieve sustainability, the circular utilization of organic waste (hereinafter, biomass) is required to generate biogas for energy use via anaerobic digestion (AD) [1-2]. However, the widespread adoption of conventional methods has been hindered by limitations such as large facility footprints and low energy yields [3-4].

AD is a biochemical reaction in which specific groups of microorganisms, capable of growing in an anaerobic environment with a low oxygen concentration, biodegrade the nutrients in biomass to synthesize methane and carbon dioxide via intermediate products such as acetic acid and lactic acid [5]. As an example of the AD process, Fig. 1 shows a schematic of the Kompogas system. This system consists of three stages: pretreatment, fermentation, and digestate disposal. First, the total solid (TS) content is adjusted via dilution in the pretreatment stage, and the resulting biomass slurry is fed into the reactor by a pump. Subsequently, during fermentation, the biomass is reacted while being mixed with microorganisms in an anaerobic bioreactor, and biogas is generated and recovered while process monitoring using sensors and sampling. Finally, in the digestate disposal stage, the biomass after fermentation (hereinafter, digestate) is discharged by an external pump. Thus, the transport for pre- and post-treatments and the mixing for fermentation are separate steps in the batch process [6-7].

AD methods are categorized by the TS content of the biomass after pretreatment. Liquid-state AD (LS-AD) is used on the biomass with a TS content of approximately 10%, while solid-state AD (SS-AD) is applied to biomass with a TS content ranging from 15% to 40%. The biomass becomes more viscous, reduces in volume, and behaves as a non-Newtonian fluid with an increasing TS content. This property allows LS-AD to be energy-efficient during mixing and transport but requires larger reactors and leaves a greater facility footprint. Conversely, SS-AD offers the advantage of smaller, space-saving reactors but suffers from a high energy consumption during mixing and conveyance [3-4]. Therefore, the lack of a system that is both space- and energy-efficient remains a barrier to the broader implementation of AD. Existing reports indicate that 60% of the total energy consumed in an AD plant is owing to mixing during digestion, and 15% is owing to transport for pre-/post-treatment [8-9]. Because these are treated as separate operations in conventional systems, the overall energy consumption is higher. These findings suggest that integrating the mixing and transport processes in SS-AD can provide a solution to this challenge. Nevertheless, a bioreactor system capable of concurrently mixing and conveying high-solids biomass in the AD process has not been developed.

This study aims to establish a space-saving and energy-efficient AD system by developing an SS-AD reactor that imitates intestinal movement when mixing and transporting high-solids biomass. The intestine is composed of a flexible muscle layer, which generates flow through volume changes

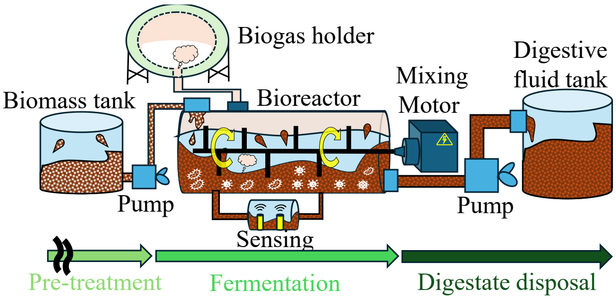

Figure 1. Flow in the Kompogas system [6]

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G. Ueki, T. Tanno, F. Ito, and T. Nakamura are with the Department of Precision Mechanics, Faculty of Science and Engineering, Chuo University, 1-13-27 Kasuga, Bunkyo-Ku, Tokyo, 112-8551, Japan (corresponding author to provide phone: 03-3817-1882; e-mail: a20.ycsh@g.chuo-u.ac.jp). A. Ohnishi and R. Kana are with the Department of Fermentation Science, Faculty of Applied Bioscience, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku, Tokyo, 156-8502, Japan (e-mail: a1ohnish@nodai.ac.jp). K. Okuda and H. Yamamura are with the Department of Integrated Science and Engineering for Sustainable Society, the Faculty of Science and Engineering, Chuo University, 1-13-27 Kasuga, Bunkyo-ku, Tokyo, 112-8551, Japan (e-mail: yamamura.10x@g.chuo-u.ac.jp).

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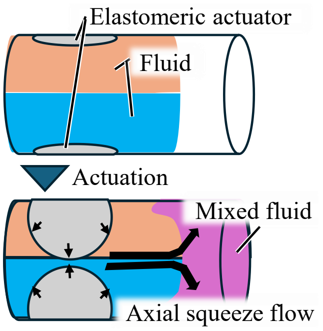


Figure 2. Axial squeeze flow via internal extrusion

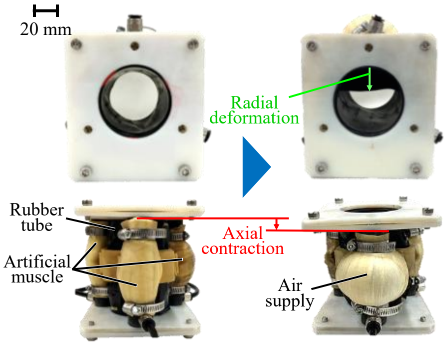


Figure 3. Peristaltic mixing conveyor with rubber tube independent deformation mechanism[20]

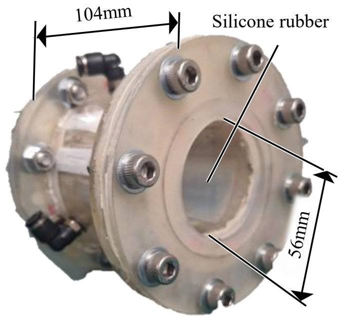


Figure 4. Prototype of the peristaltic bioreactor

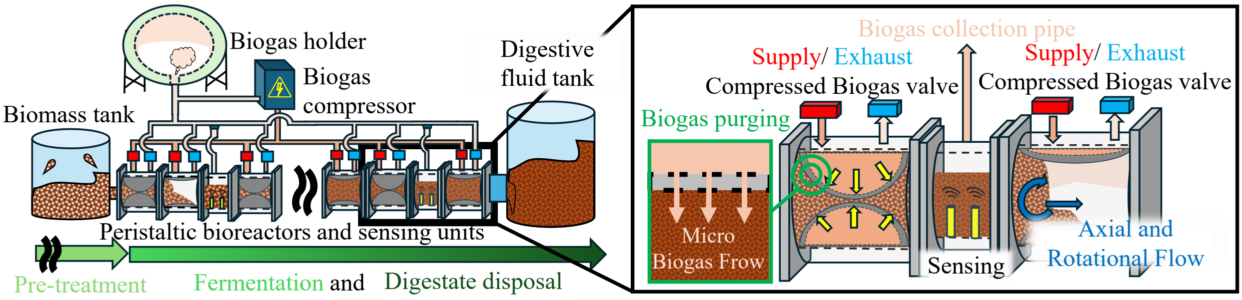


Figure 5. Image of the AD plant model employing a peristaltic bioreactor

owing to the contraction and relaxation of muscles when mixing and transporting the food bolus, which enhances microbial reactivity [10]. Based on this biological mechanism, several intestinal reactors wherein mixing is done by generating axial squeeze flow through in-tube extrusion, as shown in Fig. 2, have been proposed [11-17]. However, mixing via axial flow generation depends on the fluidity of the target fluid, and the mixing time increases for the high-solids biomass targeted by SS-AD. In fact, based on the relationship between gas production and energy consumption, 15 mins of mixing per hour is recommended in AD [18-19], whereas an existing model of the intestinal reactor required 40 mins of mixing for biomass with a TS of 35% [17].

In a previous study, a model wherein the inner rubber tube for extrusion is independently driven in the axial and rotational directions through the expansion of externally placed artificial muscles was proposed (Fig. 3). The addition of a rotational degree of freedom was found to contribute to an increase in the degree of mixing [20]. Therefore, the generation of rotational flow is expected to achieve the mixing of high-solids biomass, the target of SS-AD, within 15 mins. However, in this model, the stiffness of the rubber tube hindered the extrusion by the artificial muscles, causing a reduction in the flow volume. Furthermore, although occlusion is performed using an active force owing to pneumatic pressure, the opening depends on the passive, elastic recovery force of the rubber tube. However, this force is small compared to that used for occlusion; thus, the shape of the deformed tube is sometimes not restored when the contents are highly viscous.

This study proposes an SS-AD system that utilizes intestinal movement and represents a prototype of the lab-scale intestinal-motility SS-AD reactor used in this system, which is capable of generating rotational flow (Fig. 4). This prototype has a structure where the elastic expanding section is in direct contact with the contents, and its opening and closing motions can be actively controlled by applying positive and negative pressure. This design resolves the issues found in the previous study of expansion inhibition and an insufficient opening force and aims to achieve the mixing of high-solids biomass within 15 mins. Therefore, as an initial investigation, mixing experiments were conducted using a simulated biomass, and the applicability of this prototype to SS-AD was discussed based on the results.

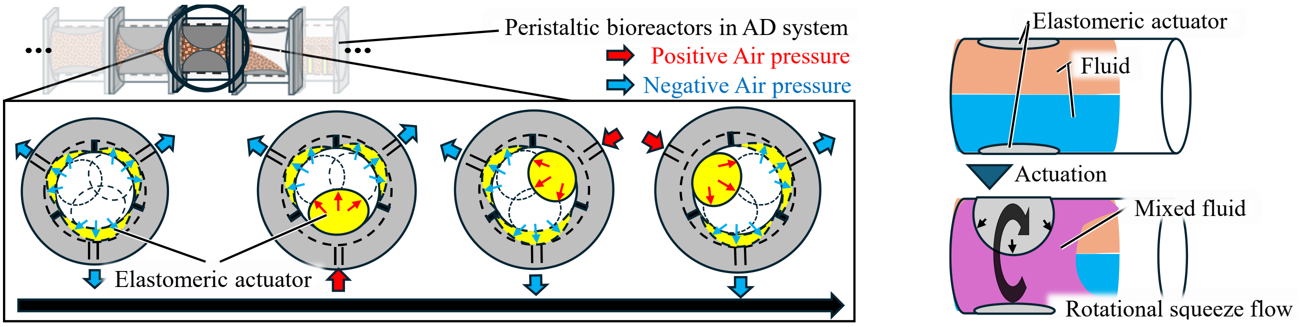
This paper is organized as follows. Section 2 describes the concept for an SS-AD system that utilizes intestinal motion. Section 3 presents the concept and configuration of the prototyped peristaltic SS-AD bioreactor. Section 4 details the mixing experiments using a simulated biomass, and Section 5 outlines the conclusions.

The contributions of this paper are as follows:

- The proposal of an SS-AD system that utilizes intestinal motion.
- Verification of the effect of rotational flow generation as an application of intestinal motion on mixing.
- Investigation of the influence of volume changes caused by the application of negative pressure on the degree of mixing.

II. CONCEPTUAL DESIGN OF THE SS-AD SYSTEM DRIVEN BY INTESTINAL PERISTALSIS

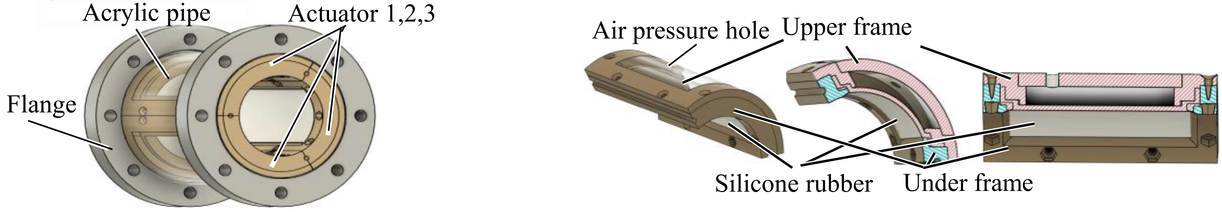
A conceptual diagram of the AD system that utilizes intestinal movement is shown in Fig. 5. This AD system model is composed of a biomass tank, a biogas holder, and a digestive fluid tank as the storage equipment; a biogas compressor as the power equipment; an intestinal-motility reactor as the reactor and transport equipment; and a sensing unit and solenoid



(a) Front view

(b) Side view

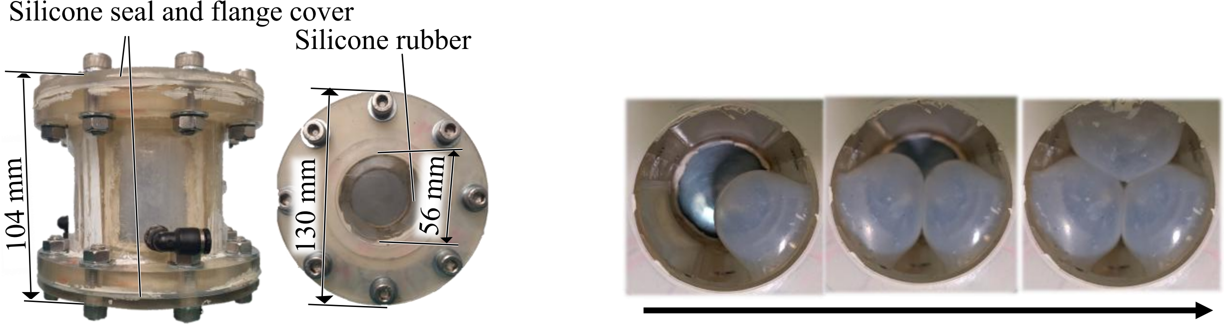
Figure 6. Concept of the peristaltic bioreactor



(a) Assembly model of Peristaltic bio-reactor

(b) Assembly model of the actuator

Figure 7. 3D models of the peristaltic bioreactor and actuator



(a) Front and side view

(b) Driving view

Figure 8. Views of the peristaltic bioreactor

valves as the measurement and control equipment, respectively.

In this system, the biomass is continuously mixed and transported by the driving motion of the peristaltic bioreactor. High-pressure biogas, pressurized by a compressor and supplied through a solenoid valve, is used to drive the device, and the biogas used for driving is stored again in the biogas holder. In addition, the gas permeability of the expanding silicone rubber is used to replace the gas inside the reactor with biogas, thereby creating anaerobic conditions. A sensing unit placed between the units analyzes the contents through biogas recovery and sensor and internal liquid sampling and monitors the processing status.

The next section describes the concept of the AD reactor used for mixing in the proposed system and its fabricated prototype. The following sections act as an evaluation test of the fabricated prototype, and describe a mixing test for high-solids biomass using a single unit of the prototype in a sealed environment that simulates anaerobic mixing conditions.

III. PERISTALTIC AD BIOREACTOR

A. *Concept of peristaltic AD reactor*

Fig. 6 shows the concept of the reactor used in the AD system proposed in this paper, which utilizes intestinal movement. As shown in Fig. 6(a), the application of positive and negative pressure to the chamber space between the outer wall and rubber parts, which are arranged on an inner wall divided into 120-degree sections, generates the active expansion and contraction of the rubber parts to extrude the contents. By adjusting the phase of pneumatic pressure application, rotational flow is generated via independent extrusion from three directions, as shown in Fig. 6(b).

B. *Prototype of the peristaltic AD bioreactor*

Fig. 7 shows a 3D CAD diagram of the peristaltic bioreactor based on the concept described above, along with the configuration of the actuator placed inside it. Fig. 8 shows the external appearance and operation of the fabricated reactor. As shown in Fig. 7(a), this reactor is composed of an actuator with an expanding section made of silicone rubber, a resin flange, and an outer layer made of an acrylic pipe. The structure of the actuator, as shown in Fig. 7(b), is a three-stage structure with two types of resin fixtures and a silicone rubber layer. The silicone rubber section expands when pneumatic pressure is applied through an air hole in the upper fixture. The external appearance of the fabricated reactor, sealed with a silicone gasket and a flange lid, is shown in Fig. 8(a), and its operation is shown in Fig. 8(b). Pneumatic pressure is applied to the actuator through the air holes in the outer casing to expand the silicone rubber and extrude the contents. During this process, rotational flow can be generated by adjusting the phase of the pneumatic pressure applied to each actuator.

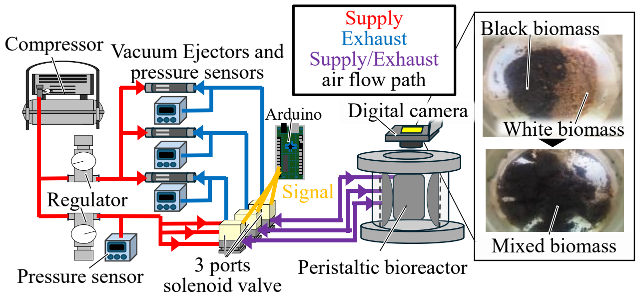


Figure 9. Experimental environment

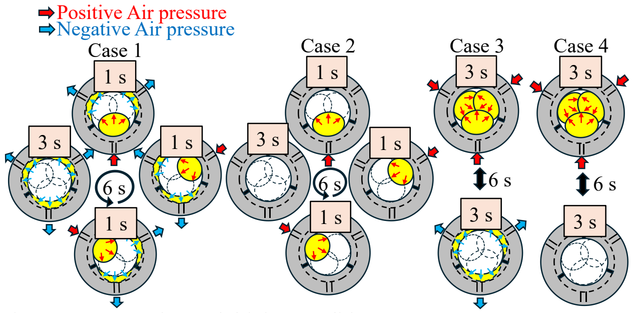


Figure 10. Experimental driving conditions

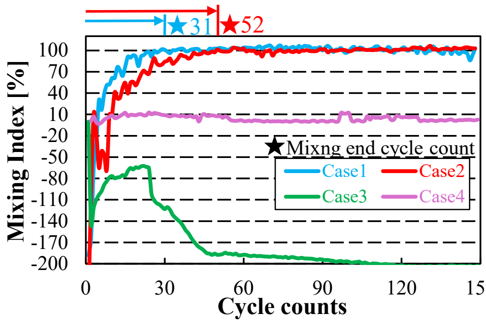


Figure 11. Mixing results under different driving conditions

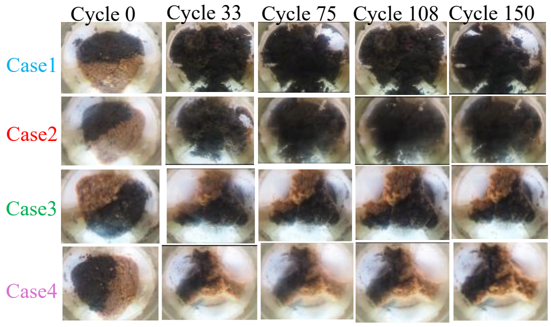


Figure 12. Changes in the experimental sample over cycles for each driving condition

IV. SOLID-STATE BIOMASS MIXING EXPERIMENT

A. Objective

This experiment was conducted using a single unit of the peristaltic bioreactor to verify the mixing enhancement effect of rotational flow and increased volumetric change owing to negative pressure application within a sealed state, simulating anaerobic conditions. A mixing degree test was performed using simulated biomass with a TS of 40%, which is the maximum TS targeted by SS-AD.

B. Materials and Methods

The experimental setup is shown in Fig. 9. Positive pressure was applied by supplying compressed air from a compressor through a regulator to a 3-port solenoid valve (SMC VT307-5G1-01-F), while negative pressure was applied to the solenoid valve by supplying compressed air through a regulator to a vacuum generator. The peristaltic bioreactor was then driven by switching between positive and negative pressure application by changing the solenoid valve's flow path. The flow path of the solenoid valve was controlled using a microcontroller (Arduino UNO R3), and a pressure sensor (CKD PPX-R01P-6M) was used to measure the positive and negative pressure values. For the experimental sample, a simulated biomass was used and was prepared by shearing 35 g of dog food with a TS of 72.3% to a particle size of less than 2 mm and then diluting it to adjust the TS to 40%. To visualize the state of mixing, the simulated biomass was divided into two equal halves, dyed white and black, and arranged in two layers.

The driving conditions comprised a 6 s cycle that consisted of a 3 s operating time and a 3 s resting time, with pressurized air at 70 kPa and negative pressure air at -40 kPa. A total of 150 cycles were performed, which corresponds to the 15 min mixing completion time required for AD. One trial experiment was conducted for each of the four driving conditions shown in Fig. 10.

- Case 1: Rotational flow with negative pressure suction
- Case 2: Rotational flow without negative pressure suction
- Case 3: Axial flow with negative pressure suction
- Case 4: Axial flow without negative pressure suction

To evaluate the mixing progress, still images were chronologically extracted from video data acquired by a camera placed above the device during the 3 s rest period of each cycle and quantified using image analysis. As the colored biomass, which is arranged in two layers, transitioned to a single color during mixing, the variance in the brightness values was obtained, and the degree of mixing was evaluated based on the uniformity of the color. As a preprocessing step, brightness values derived by adding an offset of 10 gradations to the maximum and minimum brightness of each initial image were used as a threshold and removed as noise. This threshold was determined to effectively mask the actuator regions, which have brighter surfaces than the simulated biomass, thereby isolating the biomass area for accurate mixing evaluation. The mixing index (MI), shown in Equation (1), was used as the evaluation index [21-22].

$$MI = \frac{\sigma_0^2 - \sigma_t^2}{\sigma_0^2 - \sigma_f^2} \times 100\ [\%] \qquad (1)$$

Here, σ_0^2, σ_t^2, and σ_f^2 are the variances in the brightness of the evaluation image before mixing (t = 0), at an arbitrary time t, and in the completely mixed state, respectively. The unmixed state is represented by an MI = 0% ($\sigma_0^2 = \sigma_t^2$), and the uniformly mixed state is represented by an MI = 100% ($\sigma_f^2 = \sigma_t^2$). In this experiment, the variance in the brightness of a sample image representing thorough mixing with a spoon ($\sigma_f^2 = 10.78$) was defined as the completely mixed state, and mixing was considered complete when the MI reaches 100%. Additionally, the MI can become a negative value if a

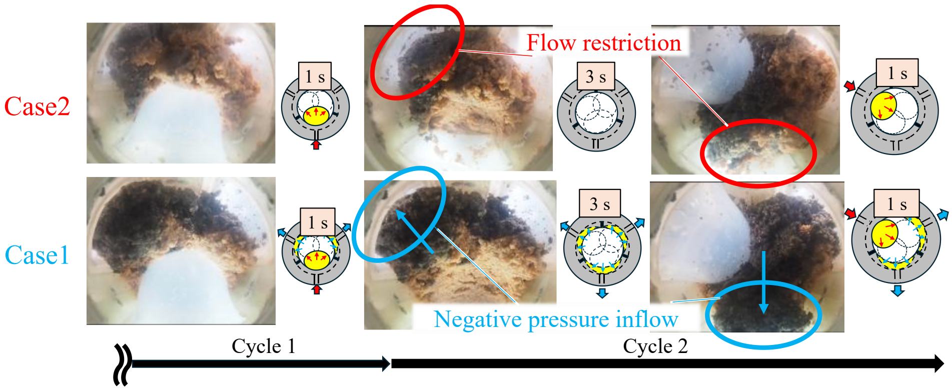


Figure 13. Effect of negative pressure application on flow behavior

brightness variance exceeding that of the initial state is calculated owing to noise from segregation or reflected light. In this experiment, if the MI < 0, no mixing progress was considered to have occurred. Additionally, all image processing and numerical calculations were performed using MATLAB (ver. 2024b, MathWorks).

C. *Experimental Results and Discussion*

Fig. 11 shows a graph of the relationship between the number of cycles and MI for each driving condition, and Fig. 12 shows the mixing process of the sample images under each driving condition. The MI in Cases 1 and 2, which generated rotational flow, is a negative value in the initial cycles but then immediately increases monotonically, reaching 100% and completing mixing at 31 cycles (equivalent to 3.1 min) in Case 1 and at 52 cycles (5.2 min) in Case 2 (Fig. 11). In contrast, Cases 3 and 4, which generated axial flow, exhibit a negative MI value from the initial stage of mixing, and the MI does not increase, failing to reach 100% within 150 cycles, which resulted in incomplete mixing. Furthermore, the sample images in Fig. 12 show that in Cases 1 and 2, the dual-colored simulated biomass can be observed transitioning to a single color as the number of cycles increases. In contrast, in Cases 3 and 4, although some flow of the simulated biomass to the center occurred, the sample accumulated in the central position and between the expanding sections of the actuator, which maintained the two separate colors.

The difference in the mixing progress between rotational and axial flow is caused by the inhibition of actuator expansion, which is caused by a rise in the internal pressure within the sealed peristaltic bioreactor. In axial flow, wherein all actuators are simultaneously expanded, the internal pressure, coupled with the viscous resistances of the high-solids biomass, acts as a reaction force that physically inhibits the expansion of the silicone rubber, thereby reducing the extrusion volume required for flow generation. In contrast, in rotational flow, wherein single actuators are sequentially driven, complete mixing was achieved because the increase in the internal pressure was smaller compared to that of axial flow, making it possible to maintain the extrusion volume.

Fig. 13 shows the difference in the flow state owing to the application of negative pressure. In Case 2, flow resistance occurred owing to the elastic restoring force of the silicone rubber. However, in Case 1, the flow resistance was reduced by the deformation of the silicone rubber owing to the application of negative pressure. In addition, the simulated biomass flowed into the deformed volume of the silicone rubber, amplifying the flow volume during the application of positive pressure. The difference in the mixing time of approximately 2 mins between Cases 1 and 2 is considered to be due to the reduction in the flow resistance and the increase in the flow volume owing to the application of negative pressure.

Therefore, the effectiveness of generating rotational flow and increasing the flow volume by applying negative pressure under sealed conditions was demonstrated.

V. CONCLUSION

In this study, an SS-AD system that uses peristaltic movement was proposed with the aim of establishing a space-saving and energy-efficient AD system. A prototype SS-AD reactor capable of generating rotational flow was modeled based on intestinal movement, and its effectiveness was verified. Simulating anaerobic conditions, a mixing test was conducted under a sealed environment using a simulated biomass with a TS of 40%, the maximum for SS-AD. Consequently, compared to the required mixing time of 15 min, mixing was achieved in 5.2 min through rotational flow and in 3.1 min with the increased flow volume owing to negative pressure application. These results demonstrate the applicability of the fabricated peristaltic bioreactor for SS-AD.

Although mixing is possible using a single unit, the feasibility of mixing when connected units are used has not yet been verified. In this study, only one trial was conducted per condition, which limits the statistical validation of the results. Therefore, future work should include multiple trials (n≥3) to establish the statistical significance of the mixing time reduction by negative pressure application. Furthermore, because there are various driving patterns when multiple units are connected, a pattern that is particularly suitable for SS-AD could exist. Therefore, in the future, three connected units should be used to conduct mixing tests using a driving pattern that combines rotational and axial flow. This should be done to verify the feasibility of mixing using multiple connected units and to validate a mixing motion pattern suitable for SS-AD.

REFERENCES

[1] E. R. Abraham, S. Ramachandran, and V. Ramalingam, “Biogas: Can It Be an Important Source of Energy?,” *Env Sci Poll Res Int*, vol. 14, no. 1, pp. 67–71, Jan. 2007, doi: 10.1065/espr2006.12.370.

[2] S. Wainaina, J. A. Nyoni, J. B. M. Nyirenda, and M, S. Karanja, "Bioengineering of anaerobic digestion for volatile fatty acids, hydrogen or methane production: a critical review," Bioengineered, vol. 10, no. 1, pp. 437-458, 2019, doi: 10.1080/21655979.2019.1644294.

[3] Q. Gao, L. Li, K. Wang, and Q. Zhao, "Mass Transfer Enhancement in High-Solids Anaerobic Digestion of Organic Fraction of Municipal Solid Wastes: A Review," *Bioengineering*, vol. 10, no. 9, p. 1084, Sept. 2023, doi: 10.3390/bioengineering10091084.

[4] R. Kothari, A. K. Pandey, S. Kumar, V. V. Tyagi, and S. K. Tyagi, "Different aspects of dry anaerobic digestion for bio-energy: An overview," *Renewable and Sustainable Energy Reviews*, vol. 39, pp. 174–195, Nov. 2014, doi: 10.1016/j.rser.2014.07.011.

[5] M. Czatzkowska, M. Harnisz, E. Korzeniewska, and I. Koniuszewska, "Inhibitors of the methane fermentation process with particular emphasis on the microbiological aspect: A review," *Energy Science & Engineering*, vol. 8, no. 5, pp. 1880–1897, 2020, doi: 10.1002/ese3.609.

[6] J. G. Akinbomi, R. J. Patinvoh, and M. J. Taherzadeh, "Current challenges of high-solid anaerobic digestion and possible measures for its effective applications: a review," *Biotechnology for Biofuels and Bioproducts*, vol. 15, no. 1, p. 52, May 2022, doi: 10.1186/s13068-022-02151-9.

[7] M. M. Uddin and M. M. Wright, "Anaerobic digestion fundamentals, challenges, and technological advances," *Physical Sciences Reviews*, vol. 8, no. 9, pp. 2819–2837, Sept. 2023, doi: 10.1515/psr-2021-0068.

[8] A. Lemmer, H.-J. Naegele, and J. Sondermann, "How Efficient are Agitators in Biogas Digesters? Determination of the Efficiency of Submersible Motor Mixers and Incline Agitators by Measuring Nutrient Distribution in Full-Scale Agricultural Biogas Digesters," *Energies*, vol. 6, no. 12, pp. 6255–6273, Dec. 2013, doi: 10.3390/en6126255.

[9] A. Amel *et al.*, "Total Solids Content Drives High Solid Anaerobic Digestion via Mass Transfer Limitation," *Bioresource technology*, vol. 111, pp. 55–61, Feb. 2012, doi: 10.1016/j.biortech.2012.01.174.

[10] J. Cremer et al., "Effect of flow and peristaltic mixing on bacterial growth in a gut-like channel," Proceedings of the National Academy of Sciences, vol. 113, no. 41, pp. 11414–11419, Oct. 2016, doi: 10.1073/pnas.1601306113.

[11] Y. Enomoto, M. Uchino, K. Nomura, R. Sawahashi and T. Nakamura, "Experimental Verification of the Effect of Peristaltic Mixing Pumps on Fermentation Acceleration: Initial Investigation of the Acceleration of Lactic Acid Fermentation by a High Viscosity Fermentation Substrate, " 2024 IEEE/SICE International Symposium on System Integration (SII), Ha Long, Vietnam, 2024, pp. 1381-1386, doi: 10. 1109/SII58957. 2024. 10417527.

[12] J. Wang, A. Xia, Z. Deng, Y. Huang, X. Zhu, X. Zhu, and Q. Liao, "Intensifying biofuel production using a novel bionic flow-induced peristaltic reactor: biodiesel production as a case study," Biofuel Research Journal, vol. 9, no. 4, pp. 1721–1735, 2022. doi: 10.18331/BRJ2022.9.4.3.

[13] D. Vorländer, G. Schultz, K. Hoffmann, D. Rasch, and K. Dohnt, "PETR: A novel peristaltic mixed tubular bioreactor simulating human colonic conditions," *Biotechnology and Bioengineering*, vol. 121, no. 3, pp. 1118–1143, 2024, doi: 10.1002/bit.28636.

[14] S. Zhang, P. Wu, C. Li, X. D. Chen, R. Deng, and B. Dai, "A soft tubular model reactor based on the bionics of a small intestine: anti particulate fouling by peristalsis," *Braz. J. Chem. Eng.*, vol. 39, no. 1, pp. 123–136, Mar. 2022, doi: 10.1007/s43153-021-00196-1.

[15] K. Lin *et al.*, "Insight into the synergistic effects of surface microstructures and wall peristalsis on glucose production in a bionic microreactor," *Chemical Engineering Journal*, vol. 490, p. 151602, June 2024, doi: 10.1016/j.cej.2024.151602.

[16] A. Hernalsteens, H. H. Cong, and X. D. Chen, "Soft elastic tubular reactor: An unconventional bioreactor for high-solids operations," Biochem. Eng. J., vol. 184, p. 108472, 2022. doi: 10.1016/j.bej.2022.108472.

[17] H. Lyu, S. Hernalsteens, H. Cong, S.-Y. Quek, and X. dong Chen, "Solid state fermentation of mung beans by Bacillus subtilis subsp. natto on static, shaking flask and soft elastic tubular reactors," *Food sci. technol. int.*, vol. 30, no. 7, pp. 623–635, Oct. 2024, doi: 10.1177/10820132231162167.

[18] L. Li *et al.*, "Effect of optimized intermittent mixing during high-solids anaerobic co-digestion of food waste and sewage sludge: Simulation, performance, and mechanisms," *Science of The Total Environment*, vol. 842, p. 156882, Oct. 2022, doi: 10.1016/j.scitotenv.2022.156882.

[19] I. D. Kariyama, X. Zhai, and B. Wu, "Influence of mixing on anaerobic digestion efficiency in stirred tank digesters: A review," *Water Research*, vol. 143, pp. 503–517, Oct. 2018, doi: 10.1016/j.watres.2018.06.065.

[20] T. Tanno, G. Ueki, K. Kikyodani, F. Ito, and T. Nakamura, "Development of a Peristaltic Mixing Conveyor with a Radial Independently Deformable Closing Mechanism," to be presented at the Joint 10th IFAC Symp. Mechatronic Syst. and 14th Symp. Robotics (MECHATRONICS & ROBOTICS 2025), Paris, France, Jul. 15-18, 2025.

[21] P. M. C. Lacey, "Developments in the theory of particle mixing," *Journal of Applied Chemistry*, vol. 4, no. 5, pp. 257–268, 1954, doi: 10.1002/jctb.5010040504.

[22] X. Jin, G. R. Chandratilleke, S. Wang, and Y. Shen, "DEM investigation of mixing indices in a ribbon mixer," *Particuology*, vol. 60, pp. 37–47, Jan. 2022, doi: 10.1016/j.partic.2021.03.005.