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**Advances in biology through
agronomy, aquaculture, coastal and
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Advances in Biology through Agronomy, Aquaculture, Coastal and Environmental Sciences, Volume II, is an e-book that continues the work of the first version (<https://editorapantanal.com.br/ebooks/2023/advances-in-biology-through-agronomy-aquaculture-coastal-and-environmental-sciences/ebook.pdf>), published in 2023 by Leandris Argente-Martínez and Ofelda Peñuelas-Rubio.

Our e-book compiles 25 manuscripts that present scientific results and reviews based on biological aspects. All of them contribute to explaining the responses of living organisms to agricultural, aquaculture, and coastal ecosystems, as well as those facing fragility or threat of climate change. This e-book was edited by Leandris Argente-Martínez, Ofelda Peñuelas-Rubio, and Joe Luis Arias-Moscato, members of the Consolidated Academic Group ITVAYA-CA-3.

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Simplified dynamic modeling for scenario analysis of the anaerobic digestion of fruit and vegetable waste

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ABSTRACT

Particle size and the substrate-to-inoculum (S/I) ratio are key factors influencing methane production during the anaerobic digestion (AD) of fruit and vegetable waste (FVW). In this study, a simplified dynamic model was used to analyze process behavior under batch conditions through two-dimensional parametric analysis, with varying particle sizes (0.01–5 mm) and S/I ratios (2–4). The model successfully captured key dynamic behaviors, including volatile fatty acid (VFA) accumulation and substrate limitation, and enabled the identification of favorable operating regions. The results showed that methane production reached its highest values at intermediate particle sizes (0.75–2 mm), where a balance between substrate availability and microbial conversion rates was achieved. Smaller particle sizes promoted rapid hydrolysis and VFA accumulation, leading to process imbalance, whereas larger particles limited methane production because of slower substrate release. Similarly, increasing the S/I ratio reduced the methane yield because of insufficient microbial capacity to assimilate intermediate products. Although quantitative predictions depend on parameter calibration, the proposed approach provides a useful framework for analyzing process dynamics and supporting the assessment of AD operating conditions for this type of waste.

Keywords: anaerobic digestion, fruit and vegetable waste, dynamic simulation.

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INTRODUCTION

Fruit and vegetable waste (FVW) is particularly important because of its high generation volume, as it is estimated that approximately 44% of fruits and vegetables produced are lost along the supply chain (Ambuko et al., 2025). When these residues are disposed of in landfills or other final disposal sites, they present environmental and public health problems because of the release of greenhouse gases and the generation of leachates, which may infiltrate soil and water bodies, in addition to creating favorable conditions for the proliferation of sanitary vectors and pathogens (Sagar et al., 2018).

Nevertheless, a technology that promotes the valorization of these residues within the circular economy framework is anaerobic digestion (AD), which enables the production of biogas rich in methane, suitable for energy generation, and a stabilized digestate rich in nutrients, with potential use as an organic fertilizer (Ganesh et al., 2022).

During the AD process, FVW is disintegrated and hydrolyzed through extracellular enzymes, releasing soluble compounds such as amino acids, sugars, and long-chain fatty acids. These compounds are subsequently converted into volatile fatty acids (VFAs), which are further transformed into acetate and ultimately into methane (Mata-Alvarez, 2002). These stages are carried out by different microbial groups; therefore, a proper balance among them is required to ensure the efficient production and consumption of intermediates, thereby maintaining process stability and efficiency (Xu et al., 2018).

In general, in the AD of solid waste, the rate-limiting step is disintegration–hydrolysis (Vavilin et al., 2008). However, since FVW is rich in readily biodegradable carbohydrates, it can be rapidly converted into VFAs. In this context, reducing the particle size (< 0.5 mm) in this type of waste may inhibit methanogenesis because of the accumulation of VFAs (Izumi et al., 2010; Vígueras-Carmona et al., 2025).

On the other hand, system stability has been reported to improve when a high proportion of microorganisms relative to the substrate is present, which can be achieved by applying low substrate-to-inoculum (S/I) ratios (Assis; Gonçalves, 2022; Okoro- Shekwaga et al., 2020; Zhang et al., 2019). Therefore, analyzing the combined effect of these two factors on process performance is of interest.

A suitable approach for studying these factors is modeling and simulation. One of the most widely used models is the ADM1 (Batstone et al., 2002); however, its structural complexity, representing the process through 19 processes and 52 parameters, limits its direct application to specific cases. Consequently, systematic model reductions have been proposed (Weinrich; Nelles, 2021), or simpler earlier models have been used instead (Hill; Barth, 1977; Moletta et al., 1986).

In this context, the objective of this study was to analyze operational scenarios of the anaerobic digestion of fruit and vegetable waste through simulation, with an emphasis on identifying the effects of particle size and the S/I ratio. For this purpose, a mathematical model reported in the literature (Vian et al., 2024) was implemented and integrated in MATLAB.

MATERIALS AND METHODS

Mathematical model

A simplified anaerobic digestion model reported by Vian et al. (2024) was used in this study. The model describes the process in three stages: disintegration, acetogenesis, and methanogenesis.

Disintegration is modeled as an extracellular process in which enzymes colonize the surface of the complex substrate and degrade it uniformly, generating soluble compounds (Sanders et al., 2000). These compounds are subsequently consumed by acidogenic bacteria, which produce acetate (used as a lumped variable representing the total VFAs). Finally, acetate is consumed by methanogenic archaea for methane production. It is further assumed that decaying biomass is reincorporated into the system as a soluble substrate.

a) Disintegration

The disintegration process was described using the model proposed by Esposito et al. (2008). The particles were assumed to be spherical, allowing the change in particle size to be expressed in terms of the variation in the particle radius:

$$R(t) = R_0 - \frac{k_1}{\rho} t \quad \text{Eq. (1)}$$

where $R(t)$ is the particle radius (dm) at time t , R_0 is the initial radius (dm), k_1 is the disintegration rate constant ($\text{g} \cdot \text{dm}^{-2} \cdot \text{d}^{-1}$), and ρ is the solid density ($\text{g} \cdot \text{dm}^{-3}$). The variation in the particle radius leads to a change in the specific surface area, defined as follows:

$$a^* = \frac{3}{\rho R(t)} \quad \text{Eq. (2)}$$

where a^* is the specific surface area ($\text{dm}^2 \cdot \text{g}^{-1}$).

The disintegration rate is then expressed as follows:

$$-r_{dis} = k_1 \cdot a^* \cdot S_c \quad \text{Eq. (3)}$$

where r_{dis} is the disintegration rate and S_c is the complex substrate concentration ($\text{g} \cdot \text{L}^{-1}$), corresponding to FVW. For a batch system, the dynamic behavior of the complex substrate is described as follows:

$$\frac{dS_c}{dt} = -k_1 \cdot a^* \cdot S_c \quad \text{Eq. (4)}$$

b) Acidogenesis and methanogenesis

For the description of the acidogenesis and methanogenesis stages, it is assumed that the process rates are governed by microbial growth kinetics. Acidogenic microorganisms are described using Monod kinetics, whereas methanogenic microorganisms follow Haldane kinetics to account for substrate inhibition by volatile fatty acids (VFAs). Biomass decay is modeled using first-order kinetics.

Accordingly, the dynamic behavior of the concentration of soluble substrate (S_s), acidogenic microorganisms (X_1), VFA (S_{agv}), methanogenic microorganisms (X_2), and methane production (P_{ch4}) are described by the following set of equations:

$$\frac{dS_s}{dt} = k_1 \cdot a^* \cdot S_c - \frac{1}{Y_1} \frac{\mu_{max1} S_s}{K_{s1} + S_s} X_1 + k_{d1} X_1 + k_{d2} X_2 \quad \text{Eq. (5)}$$

$$\frac{dX_1}{dt} = \frac{\mu_{max1} S_s}{K_{s1} + S_s} X_1 - k_{d1} X_1 \quad \text{Eq. (6)}$$

$$\frac{dS_{agv}}{dt} = \frac{\mu_{max1} S_s}{K_{s1} + S_s} X_1 Y_2 - \frac{1}{Y_3} \frac{\mu_{max2} S_{agv}}{K_{s2} + S_{agv} + \frac{S_{agv}^2}{K_i}} X_2 \quad \text{Eq. (7)}$$

$$\frac{dX_2}{dt} = \frac{\mu_{max2} S_{agv}}{K_{s2} + S_{agv} + \frac{S_{agv}^2}{K_i}} X_2 - k_{d1} X_1 \quad \text{Eq. (8)}$$

$$\frac{dP_{ch4}}{dt} = \frac{\mu_{max2} S_{agv}}{K_{s2} + S_{agv} + \frac{S_{agv}^2}{K_i}} X_2 Y_4 \quad \text{Eq. (9)}$$

where $\mu_{max,1}$ and $\mu_{max,2}$ are the maximum specific growth rates (d^{-1}), $K_{s,1}$ and $K_{s,2}$ are the half-saturation constants ($g \cdot L^{-1}$), Y_1 and Y_3 are the biomass yield coefficients, and Y_2 and Y_4 are the product yield coefficients for acidogenic and methanogenic microorganisms, respectively.

Dynamic analysis

To analyze the temporal evolution of the model variables over a 15-day period, the system was solved numerically in MATLAB R2025b using the *ode15s* solver, which is suitable for stiff systems. The parameter values used in the simulations are presented in Table 1.

Table 1. Model parameters and their values.

Parameter	Value	Parameter	Value
μ_{max1}	$1.5 d^{-1}$ ^a	Y_1	$0.2 (-)$ ^d
μ_{max2}	$0.138 d^{-1}$ ^a	Y_2	$2.45 (-)$ ^d
K_{s1}	$0.26 g \cdot L^{-1}$ ^a	Y_3	$0.06 (-)$ ^d
K_{s2}	$0.003 g \cdot L^{-1}$ ^a	Y_4	$18.26 g \cdot L^{-1}$ ^d
K_i	$0.064 g \cdot L^{-1}$ ^b	k_{d1}	$0.01 \mu_{max1}$ ^b
k_1	$0.4 g \cdot dm^{-2} \cdot d^{-1}$ ^c	k_{d2}	$0.05 \mu_{max2}$ ^b

^a Parameter taken from Moletta et al. (1986).

^b Values from Vian et al. (2024).

^c Value reported by Vigueras-Carmona et al. (2025).

^d Yield coefficients from Hill & Barth. (1977).

The analysis was conducted from two perspectives. First, the effect of particle size on the performance of the AD of FVW was evaluated. Simulations were performed using an initial total inoculum concentration of $2.5 g VS \cdot L^{-1}$, consisting of 66% acidogenic and 34% methanogenic microorganisms (Razaviarani; Buchanan, 2015; Vian et al., 2024), and an initial substrate concentration of $7.5 g VS \cdot L^{-1}$, resulting in an S/I ratio of 3. The particle size was varied by considering diameters of

0.5, 1, and 2 mm. The evaluated variables were cumulative methane production, soluble substrate concentration, and VFA concentration.

Second, the effect of the S/I ratio was evaluated. In this case, the particle diameter was fixed at 0.5 mm, and the total inoculum concentration was maintained at $2.5 \text{ g VS} \cdot \text{L}^{-1}$ (with the previously defined microbial distribution). The initial substrate concentration was varied (5, 7.5, and $10 \text{ g VS} \cdot \text{L}^{-1}$), corresponding to S/I ratios of 2, 3, and 4, respectively. The same response variables as in the previous analysis were considered.

Operational scenarios

The combined effect of the particle size and S/I ratio was evaluated through two-dimensional parametric analysis. A simulation grid was defined in which the initial particle diameter ranged from 0.01 to 5 mm, while the initial S/I ratio was varied between 5 and 6.

The analysis was carried out in MATLAB by numerically solving the system of ordinary differential equations using the *ode15s* solver, which is suitable for stiff systems. For each combination of initial conditions, the system was integrated over a time interval of 0 to 10 days, using relative and absolute tolerances of 10^{-6} and 10^{-9} , respectively, to ensure numerical stability and solution accuracy.

Finally, the results were arranged into a response matrix to construct response surfaces, enabling the identification of optimal operating conditions. The response variable was the methane yield ($\text{mL} \cdot \text{g}^{-1} \text{ VS}$), defined as the ratio between the cumulative methane produced and the initial mass of substrate added.

RESULTS AND DISCUSSION

Effect of particle size on process dynamics

The effect of the initial particle size on the performance of the AD of the FVW is shown in Figure 1. The highest cumulative methane production was obtained at 1 mm (317 mL), followed by 2 mm (307 mL) and 0.5 mm (57 mL) (Figure 1a).

For larger particles, the lower methane production is attributed to a reduced substrate availability rate due to slower hydrolysis, resulting in more gradual methane accumulation. Therefore, although comparable methane yields were observed for particle sizes of 1 and 2 mm after 15 days, the 1 mm condition achieved its maximum production within the first 6 days, whereas for 2 mm particles, the maximum was reached on day 15. This finding indicates that the process proceeded at a faster rate for the 1 mm particle size. In contrast, the smallest particle size (0.5 mm) led to a sharp decrease in methane production after day 1, suggesting an imbalance between acidogenic and methanogenic activities.

This behavior is supported by the data in Figures 1b and 1c. At 0.5 mm, a rapid increase in soluble substrate is observed, followed by its rapid conversion into VFAs, reaching $3.5 \text{ g} \cdot \text{L}^{-1}$. Under these conditions, the consumption of VFAs is limited, and their accumulation suggests a potential inhibitory

effect on methanogenic activity. Conversely, at larger particle sizes, lower substrate release rates result in reduced VFA production, allowing their efficient consumption and maintaining concentrations below $0.0035 \text{ g}\cdot\text{L}^{-1}$.

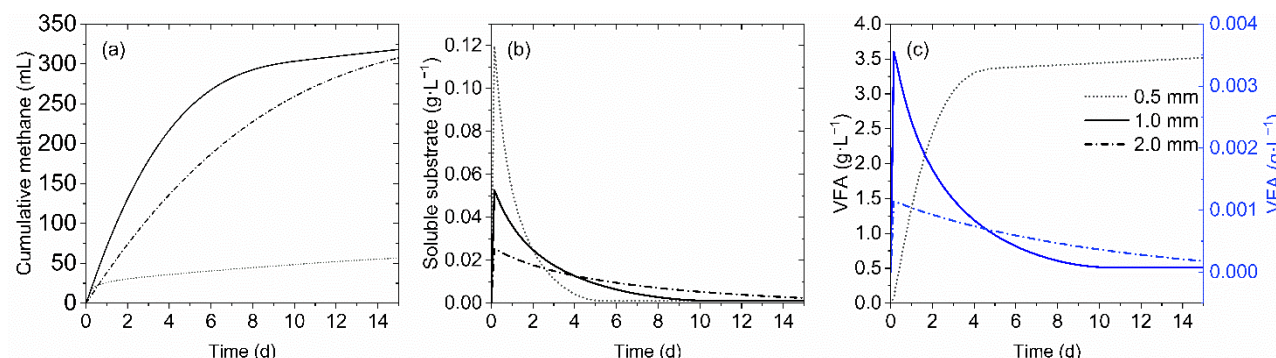


Figure 1. Effects of particle size on (a) cumulative methane production, (b) soluble substrate concentration, and (c) total VFA concentration at an S/I ratio of 3.

Overall, these results confirm that hydrolysis is the rate-limiting step (Vavilin et al., 2008). While larger particles slow down the process, smaller particles increase the risk of intermediate accumulation and process imbalance (Agyeman; Tao, 2014; Izumi et al., 2010; Viguera-Carmona et al., 2025), with an optimum observed at intermediate particle sizes.

Effect of the S/I ratio on process dynamics

In addition, the effect of the initial substrate-to-inoculum (S/I) ratio was evaluated by comparing scenarios at constant particle size. As shown in Figure 2a, the highest cumulative methane production was obtained at an S/I ratio of 2 (223 mL), whereas significantly lower values were observed at higher S/I ratios (57 and 41 mL for S/I = 3 and 4, respectively). These findings indicate that increasing the S/I ratio negatively affects methane production.

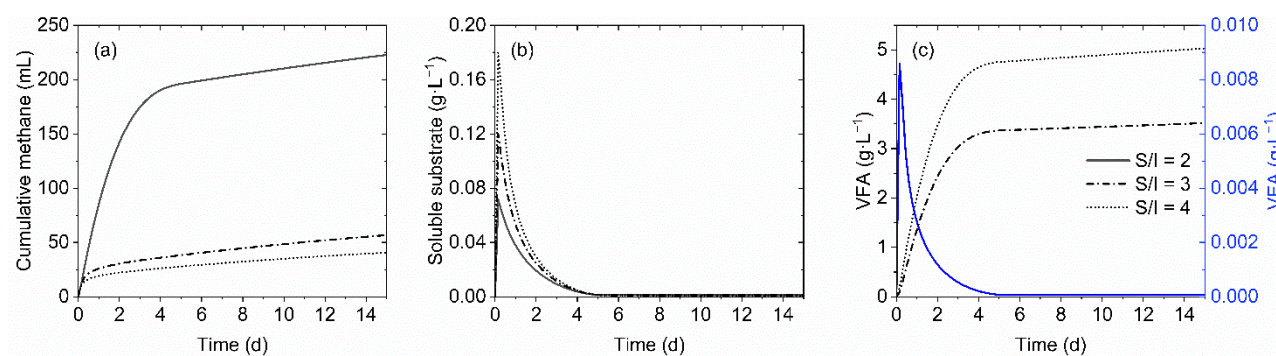


Figure 2. Effects of the S/I ratio on (a) cumulative methane production, (b) soluble substrate concentration, and (c) total VFA concentration for a particle size of 0.5 mm.

The presence of soluble substrate peaks within the first 6 days in all the cases is shown in Figure 2b, with slightly higher magnitudes at higher S/I ratios, indicating rapid substrate consumption by acidogenic microorganisms. However, as shown in Figure 2c, efficient VFA consumption is only observed at the lowest S/I ratio, where the VFA concentration remains below $0.01 \text{ g}\cdot\text{L}^{-1}$. In contrast, for higher S/I ratios, VFA accumulation reaches approximately 3.5 and $5 \text{ g}\cdot\text{L}^{-1}$ (for $S/I = 2$ and 3, respectively), suggesting an imbalance between acidogenic production and methanogenic consumption.

This behavior is consistent with previous studies on the anaerobic digestion of food waste, which reported that low S/I ratios increase methane production because of the relatively high abundance of microorganisms, providing an effective sink for metabolic intermediates (Okoro-Shekwaga et al., 2020; Zhang et al., 2019). Accordingly, S/I values less than 0.5 are often recommended for readily biodegradable substrates such as FVW, whereas values of approximately 1 are suggested for more slowly degradable materials (Assis; Gonçalves, 2022).

In this study, the simulation results suggest that stable operation may still be achieved under intermediate conditions (e.g., a particle size of 0.5 mm and $S/I = 2$), as indicated by the fact that most methane production occurs within the first 6 days (Figure 2a). This observation is consistent with previous reports indicating that up to 80% of methane production from fresh organic waste occurs during the initial days of digestion (Martínez et al., 2022).

Overall, these results highlight the critical importance of properly balancing the S/I ratio to prevent intermediate accumulation and ensure stable and efficient methane production.

Operational scenarios

The methane yield as a function of both the particle size and the S/I ratio are shown in Figure 3. A region of high performance ($470\text{--}581 \text{ mL}\cdot\text{g}^{-1} \text{ VS}$) is observed within a particle size range of 0.75 to 2 mm across all evaluated S/I ratios. However, within this range, smaller particle sizes are associated with higher yields at lower S/I ratios, whereas larger particle sizes achieve higher yields at higher S/I ratios. This behavior can be explained by the need to avoid VFA accumulation at smaller particle sizes, whereas at larger particle sizes, higher S/I ratios help prevent limitations in soluble substrate availability and subsequent VFA production.

As observed and discussed in the previous sections, the model successfully captures both VFA accumulation effects and substrate availability limitations associated with particle size. The range of maximum methane yield predicted by the simulations lies at the upper end and is partially beyond the values reported in the literature for the anaerobic digestion of FVW ($207\text{--}523 \text{ mL}\cdot\text{g}^{-1} \text{ VS}$) (Agrawal et al., 2022; Yan et al., 2021). Such variability in reported yields is attributed mainly to differences in substrate composition (Edwiges et al., 2018, 2020).

These results suggest that a more accurate prediction of methane yield would require calibration of the yield coefficients, as these parameters directly control biomass growth and product formation.

Nevertheless, the simplified model proved adequate for capturing the system dynamics and evaluating the effects of the studied factors.

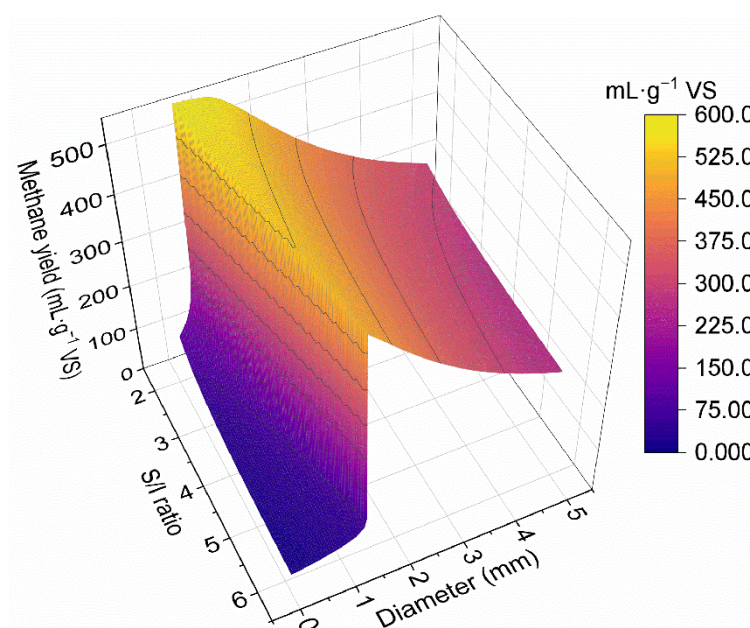


Figure 3. Effects of the S/I ratio and particle size on the methane yield during the anaerobic digestion of fruit and vegetable waste.

CONCLUSIONS

Through simulation analysis of the AD of FVW, it was determined that the methane yield is strongly influenced by the combined effect of particle size and the substrate-to-inoculum (S/I) ratio. The highest yields were obtained at intermediate particle sizes (0.75–2 mm), where a balance between substrate availability and microbial activity was achieved. Smaller particle sizes promote rapid hydrolysis and the accumulation of VFAs, which may lead to process imbalance, whereas larger particles limit methane production because of a lower substrate conversion rate.

Similarly, low S/I ratios favor stable conditions by ensuring sufficient microbial capacity to assimilate intermediate products, whereas higher ratios increase the risk of VFA accumulation. Although quantitative predictions require further parameter calibration, particularly because the model does not explicitly account for substrate composition, the simplified model proved effective at capturing key system dynamics and identifying favorable AD processes.

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REFERENCES

- Agrawal, A., Chaudhari, P. K., & Ghosh, P. (2022). Anaerobic digestion of fruit and vegetable waste: a critical review of associated challenges. *Environmental Science and Pollution Research*, 30(10), 24987–25012. <https://doi.org/10.1007/s11356-022-21643-7>
- Agyeman, F. O., & Tao, W. (2014). Anaerobic co-digestion of food waste and dairy manure: Effects of food waste particle size and organic loading rate. *Journal of Environmental Management*, 133, 268–274. <https://doi.org/10.1016/j.jenvman.2013.12.016>
- Ambuko, J. L., Masakhwe, S. M., Amwoka, E., Mujuka, E., & Fabi, C. (2025). Food loss and waste data gaps in fruit and vegetable value chains: a review of the literature. *Frontiers in Horticulture*, 4. <https://doi.org/10.3389/fhort.2025.1529040>
- Assis, T. I., & Gonçalves, R. F. (2022). Valorization of food waste by anaerobic digestion: A bibliometric and systematic review focusing on optimization. *Journal of Environmental Management*, 320, 115763. <https://doi.org/10.1016/j.jenvman.2022.115763>
- Batstone, D. J., Keller, J., Angelidaki, I., Kalyuzhnyi, S. V., Pavlostathis, S. G., Rozzi, A., Sanders, W. T., Siegrist, H., & Vavilin, V. A. (2002). The IWA Anaerobic Digestion Model No 1 (ADM1). *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, 45(10), 65–73. <https://doi.org/10.2166/wst.2002.0292>
- Edwiges, T., Frare, L. M., Lima Alino, J. H., Triolo, J. M., Flotats, X., & Silva de Mendonça Costa, M. S. (2020). Methane potential of fruit and vegetable waste: an evaluation of the semicontinuous anaerobic mono-digestion. *Environmental Technology*, 41(7), 921–930. <https://doi.org/10.1080/09593330.2018.1515262>
- Edwiges, T., Frare, L., Mayer, B., Lins, L., Mi Triolo, J., Flotats, X., & de Mendonça Costa, M. S. S. (2018). Influence of chemical composition on biochemical methane potential of fruit and vegetable waste. *Waste Management*, 71, 618–625. <https://doi.org/10.1016/j.wasman.2017.05.030>
- Esposito, G., Frunzo, L., Panico, A., & d'Antonio, G. (2008). Mathematical modelling of disintegration-limited co-digestion of OFMSW and sewage sludge. *Water Science and Technology*, 58(7), 1513–1519. <https://doi.org/10.2166/wst.2008.509>
- Ganesh, K. S., Sridhar, A., & Vishali, S. (2022). Utilization of fruit and vegetable waste to produce value-added products: Conventional utilization and emerging opportunities-A review. *Chemosphere*, 287, 132221. <https://doi.org/10.1016/j.chemosphere.2021.132221>

- Hill, D. T., & Barth, C. L. (1977). A Dynamic Model for Simulation of Animal Waste Digestion. In Journal (Water Pollution Control Federation) (Vol. 49, pp. 2129–2143). Wiley.
<https://doi.org/10.2307/25039421>
- Izumi, K., Okishio, Y. ki, Nagao, N., Niwa, C., Yamamoto, S., & Toda, T. (2010). Effects of particle size on anaerobic digestion of food waste. International Biodeterioration and Biodegradation, 64(7), 601–608. <https://doi.org/10.1016/j.ibiod.2010.06.013>
- Martínez, E. J., González, R., Ellacuriaga, M., & Gómez, X. (2022). Valorization of Fourth-Range Wastes: Evaluating Pyrolytic Behavior of Fresh and Digested Wastes. Fermentation, 8(12), 744. <https://doi.org/10.3390/fermentation8120744>
- Mata-Alvarez, J. (2002). Biomethanization of organic fraction of municipal solid wastes. IWA Publishing.
- Moletta, R., Verrier, D., & Albagnac, G. (1986). Dynamic modelling of anaerobic digestion. Water Research, 20(4), 427–434. [https://doi.org/10.1016/0043-1354\(86\)90189-2](https://doi.org/10.1016/0043-1354(86)90189-2)
- Okoro- Shekwaga, C. K., Turnell Suruagy, M. V., Ross, A., & Camargo- Valero, M. A. (2020). Particle size, inoculum-to-substrate ratio and nutrient media effects on biomethane yield from food waste. Renewable Energy, 151, 311–321. <https://doi.org/10.1016/j.renene.2019.11.028>
- Razaviarani, V., & Buchanan, I. D. (2015). Calibration of the Anaerobic Digestion Model No. 1 (ADM1) for steady-state anaerobic co-digestion of municipal wastewater sludge with restaurant grease trap waste. Chemical Engineering Journal, 266, 91–99. <https://doi.org/10.1016/j.cej.2014.12.080>
- Sagar, N. A., Pareek, S., Sharma, S., Yahia, E. M., & Lobo, M. G. (2018). Fruit and Vegetable Waste: Bioactive Compounds, Their Extraction, and Possible Utilization. Comprehensive Reviews in Food Science and Food Safety, 17(3), 512–531. <https://doi.org/10.1111/1541-4337.12330>
- Sanders, W. T. M., Geerink, M., Zeeman, G., & Lettinga, G. (2000). Anaerobic hydrolysis kinetics of particulate substrates. Water Science and Technology, 41(3), 17–24. <https://doi.org/10.2166/wst.2000.0051>
- Vavilin, V. A., Fernandez, B., Palatsi, J., & Flotats, X. (2008). Hydrolysis kinetics in anaerobic degradation of particulate organic material: An overview. Waste Management, 28(6), 939–951. <https://doi.org/10.1016/j.wasman.2007.03.028>
- Vian, J., Velasco-Pérez, A., Solar-González, R., García-Herrera, T., Puebla, H., & Vivar-Vera, G. (2024). Particle Size Effect on Anaerobic Digestion of Fruit and Vegetable Waste. Fermentation, 10(9), 485. <https://doi.org/10.3390/fermentation10090485>
- Vigueras-Carmona, S. E., Velasco-Pérez, A., Montes-García, M. M., Puebla, H., Rodríguez-Jara, M., & Vian, J. (2025). Particle Size Effect on Biodegradability and Kinetics During Anaerobic Digestion of Fruit and Vegetable Waste. Processes, 13(4), 937. <https://doi.org/10.3390/pr13040937>
- Weinrich, S., & Nelles, M. (2021). Systematic simplification of the Anaerobic Digestion Model No. 1 (ADM1) – Model development and stoichiometric analysis. Bioresource Technology, 333, 125124. <https://doi.org/10.1016/j.biortech.2021.125124>

- Xu, F., Li, Y., Ge, X., Yang, L., & Li, Y. (2018). Anaerobic digestion of food waste – Challenges and opportunities. *Bioresource Technology*, 247(July 2017), 1047–1058. <https://doi.org/10.1016/j.biortech.2017.09.020>
- Yan, H., Cai, F., Wang, L., Chen, C., & Liu, G. (2021). Compositional components and methane production potential of typical vegetable wastes. *Environmental Science and Pollution Research*, 28(38), 54177–54186. <https://doi.org/10.1007/s11356-021-15798-y>
- Zhang, W., Li, L., Xing, W., Chen, B., Zhang, L., Li, A., Li, R., & Yang, T. (2019). Dynamic behaviors of batch anaerobic systems of food waste for methane production under different organic loads, substrate to inoculum ratios and initial pH. *Journal of Bioscience and Bioengineering*, 128(6), 733–743. <https://doi.org/10.1016/j.jbiosc.2019.05.013>

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