Fermentation Biogas Production and its Combination with Hydrogen Production Using a Mixture of Livestock Manure and Straw: A Review

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This review article considers publications dealing with biogas production from mixtures of livestock manure and corn straw. Emphasis is placed on factors affecting hydrogen production rate from the residual liquid after methane production. Simulations were carried out as a means to better understand published findings related to the production of hydrogen from biomass, cow manure, and corn stalks. This review focuses on the impact of different manure-to-stalk ratios on the yield and gas production efficiency during the process of biogas fermentation. Photosynthetic-anaerobic processing of biomass with combined hydrogen production technology and its process flow were considered, aiming to achieve the reuse of waste liquid. At the same time, research progress of the fermentation degradation mechanism of modified straw is reviewed, summarizing the key factors affecting the difference in biogas yield from livestock manure and straw mixed materials. In addition, this study also considers the synergistic mechanism of operating parameters such as fermentation temperature, inoculation concentration, inoculation amount, composting time, and the optimal ratio of raw materials. This study aims to open up new avenues for the efficient utilization of biomass energy and will delve deeper into this in subsequent research.

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INTRODUCTION

With the sustainable development of social economy, energy and environment issues have become hot topics in today's society. It is of great significance to carry out research on integrated technology and resource integration utilization of collaborative gas production of livestock and poultry manure and straw mixed raw materials. Such studies have potential to improve the overall utilization efficiency of biomass, accelerating the transformation and upgrading of biomass energy development and utilization, and realizing the industrial linkage of renewable green energy. Based on the adsorption characteristics of hydrothermal carbon with porous structures, Wang *et al.* (2023b) studied the effects of cellulose hydrothermal carbonization liquid on the co-fermentation characteristics of corn stover. Penghui Chen and colleagues (2022) took cellulose after hydrothermal treatment as the research subject and found that while it increased the potential for methane production, it also required a significant amount of energy, as was shown by analyzing the changes in the content of plant cellulose after hydrothermal treatment. Ma *et al.* (2016) described the microbial community structure and diversity in fermentation substrates, analyzed the main functional microbial communities in anaerobic fermentation, and revealed the correlation between anaerobic fermentation tanks and community structures. Hua *et al.* (2023) constructed a biochar complex and studied the anaerobic fermentation process. The results indicated that the biochar complex could increase biogas production during anaerobic fermentation and shorten the production time. Based on the strengthening effect of iron-magnesium modified biochar on lignin, Liu (2023) analyzed the types of microbial communities during anaerobic fermentation and found that it could promote the enrichment of dominant microbial communities and enhance the effect of anaerobic fermentation. Li *et al.* (2023) used EBSILON to simulate the coupling scheme of anaerobic fermentation and waste incineration processes and optimized the coupling scheme. Based on the acid production mechanism of sludge fermentation, Qin *et al.* (2023) studied the effects of the ultrasonic-alkaline pretreatment process of sludge on biogas production. Asquer *et al.* (2022) analyzed the energy changes during anaerobic fermentation by changing the composition of hemp stalks and found that methane production was directly proportional to the changes in total solids content and organic loading rate. Ao *et al.* (2023) analyzed the electrochemical stimulation and metagenomic changes during anaerobic fermentation based on Na^+ and found that adding an appropriate amount of NaCl could overcome thermodynamic barriers and improve biogas production efficiency. Białobrzewski and others (2024) compared the differences in performance of methane production potential in high-temperature anaerobic fermentation for various pretreatment methods such as ultrasound, biochar, and enzymes. Kanellos *et al.* (2024) studied the effects of microbial electrolytic cell loading on sludge anaerobic fermentation. The study found that a certain load could enhance sludge activity and increase biogas production from anaerobic fermentation. Rivera *et al.* (2023) based on the effects of pH on ammonia recovery and anaerobic fermentation, indicated that as pH increases, the removal rates of COD and VS also increase. Rahimi *et al.* (2023) proposed that using layered materials could promote anaerobic fermentation and designed a microbial community layout scheme that helps increase biogas production. During the biomass fermentation process, compounds such as sugars are produced, which can be used as raw materials for hydrogen production. By adjusting the technical process of biomass fermentation, the yield and quality of sugar compounds can be significantly improved, thereby effectively increasing the efficiency of the hydrogen production process. Liu *et al.* (2024) proposed an innovative solar-biomass hybrid hydrogen production system that combines biomass gasification with chemical looping technology, achieving low-carbon emissions and stability in the hydrogen production process. In addition, Bartolucci *et al.* (2024) successfully converted lignocellulosic biomass into hydrogen by combining pyrolysis, steam-enhanced gasification, and hydrothermal deoxygenation processes.

Based on the analysis of existing literature (Tang *et al.* 2008; Zhang *et al.* 2008; Li *et al.* 2020; Jia *et al.* 2020; Zhang *et al.* 2023), the research hotspots of scholars and technicians both domestically and internationally have mainly focused on improving biogas yield by altering the fermentation environment and optimizing the anaerobic fermentation process, which has been applied in the fermentation field of various mixed materials of livestock and poultry manure with straw. However, there are fewer reports on the coupled mechanism of straw fiber-microstructural chemical bonds-fermentation temperature during the mixed material fermentation process, the degradation model of the differential performance of biogas yield during fermentation, the synergistic mechanism standard of operating parameters under multiple stochastic effects, and the clear regulatory mechanism. Furthermore, after an in-depth analysis of previous articles, it is apparent that biogas slurry also shows considerable potential and prospects in the subsequent production of hydrogen. As a product of mixed material fermentation, the rich organic matter and microbial activity in biogas slurry provide favorable conditions for hydrogen production. By optimizing the composition of biogas slurry and fermentation conditions, hydrogen yield, and efficiency can be further improved. This not only helps to solve the problem of agricultural waste disposal but also achieves the recycling of resources, contributing to sustainable development.

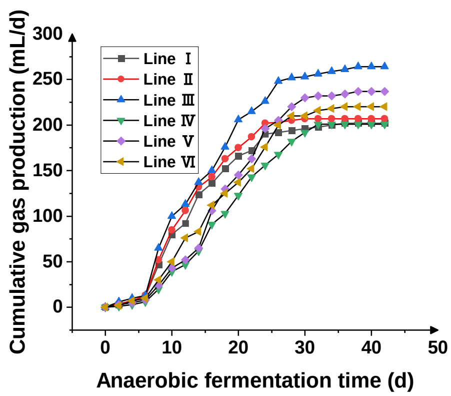
BIOMASS DEGRADATION MECHANISM IN THE FERMENTATION PROCESS OF LIVESTOCK MANURE + STRAW MIXED RAW MATERIALS

Coupling Effect of Straw Fiber-Microstructure Chemical Bond-Fermentation Temperature during Fermentation Process

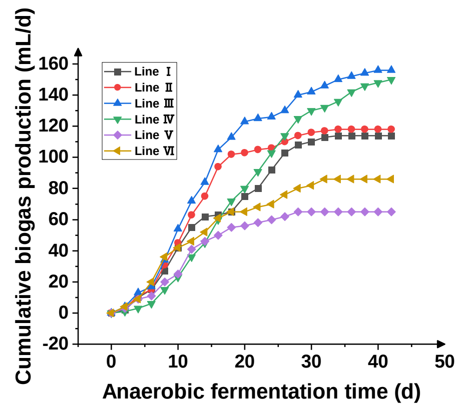
Multi-scale physical-chemical behavior of straw fiber microstructure and its interaction during fermentation process

The straw fermentation process is essentially a process of microbial material metabolism and energy conversion, which can be divided into four stages: hydrolysis, acidification, acetic acid production, and methane production. The factors affecting the yield and rate of biogas production from mixed raw materials of livestock manure + straw were analyzed. The optimal ratio of mixed raw materials in anaerobic fermentation process was studied, and the multi-scale physical-chemical behavior of straw fiber microstructure in anaerobic fermentation process and its interaction were explained. It is helpful to explore the changes of molecular micro-functional groups of cellulose, hemicellulose and lignin, and to analyze and reveal the degradation mechanism of cellulose, hemicellulose and lignin in the fermentation stage of mixed raw materials.

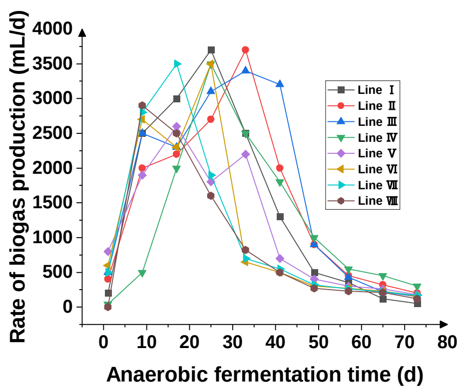
The research shows that (Tang *et al.* 2008; Zhang *et al.* 2008; Jia *et al.* 2020; Li *et al.* 2020), regarding livestock manure + straw mixed raw material anaerobic fermentation biogas production process, under the action of the chemical behavior of anaerobic bacteria, the carbon chain structure of biological macromolecules such as cellulose in the straw breaks down and releases energy at the same time. In the microenvironment, fermentation strains, chemical bonds of microstructure, and fermentation temperature had dynamic changes and interactive effects. The change curve of anaerobic fermentation biogas production of livestock manure + straw mixed raw materials (with different mixed raw materials selected and the ratio test carried out according to different proportions) is shown in Fig. 1.



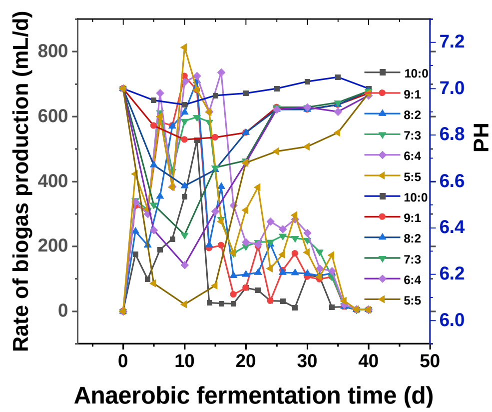
(a) Mixed raw material control group (30 °C, 45 d)



(**b**) Mixed raw material control group (35 °C, 45 d)



(c) Single raw material control group (25 °C, 30 °C, 40 °C)



(d) mixed raw material control group (pH value of feed liquid, gas production rate)

Fig. 1. Gas production curve of mixed raw materials "livestock and poultry manure + straw"

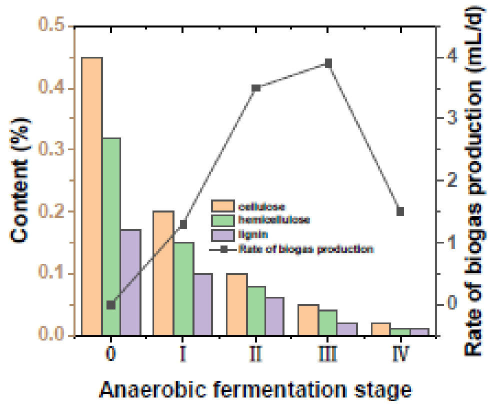
As shown in Fig. 1, part a shows the control group for cumulative gas production (using the same fermentation slurry, with a fermentation temperature of 30 °C and a composting time of 45 days). Curves I to III represent the gas production from the study by Li *et al.* (2020) on the “cattle manure + corn stalk” mixed materials (with manure to stalk ratios of 1:1, 2:1, and 3:1, respectively). When the ratio is 3:1, the cumulative gas production is higher, and the fluctuation of the gas production rate peak-valley is about 9.5%. Curves IV to VI represent the gas production from the study by Zhang *et al.* (2023a) on the pig manure + corn stalk mixed materials (with manure to stalk ratios of 2:1, 1:2, and 1:1, respectively). When the ratio is 2:1, the cumulative gas production is higher, and the fluctuation of the gas production rate peak-valley is about 7.3%. Figure b is the control group for cumulative gas production (using the same fermentation slurry, with a fermentation temperature of 35 °C and a composting time of 45 days). Curves I to VI represent the gas production from the study by Jia *et al.* (2020) on the cattle manure + wheat and rice straw mixed materials (with manure to straw ratios of 1:1, 2:1, and 3:1, respectively). For the cattle manure + wheat straw mixed materials, when the ratio is 3:1, the cumulative gas production is higher, and the fluctuation of the gas production rate peak-valley is about 12.7%. For the cattle manure + rice straw mixed materials, when the ratio is 1:1, the cumulative gas production is higher, and the fluctuation of the gas production rate peak-valley is about 28.0%. Figure c shows the control group for cumulative gas production from a single material (using the same fermentation slurry and composting time, with fermentation temperatures set at 25, 30, and 40 °C, respectively). Curves I to IV represent the gas production from the study by Zhang *et al.* (2008) on the single cattle manure material composting fermentation (with a larger gas production rate at 25 °C and a smaller gas production rate at 40 °C, the fluctuation of the cumulative gas production peak-valley is about 8.9%). Curves V to VIII represent the gas production from the single pig manure material composting fermentation (with a larger gas production rate at 35 °C and a smaller gas production rate at 40 °C, the fluctuation of the cumulative gas production peak-valley is about 9.2%). Figure d is from the study by Tang *et al.* (2008) on the chicken manure + corn stalk mixed materials anaerobic fermentation gas production process, including the changes in the material liquid pH value and gas production rate (using the same fermentation slurry and composting time). When the manure to stalk ratio is 5:5, the cumulative gas production is higher, and the fluctuation of the material liquid pH value peak-valley is larger. When the ratio is 10:0, the cumulative gas production is relatively smaller, and the fluctuation of the material liquid pH value peak-valley is relatively more stable.

Many literature studies have provided important insights into the coupling mechanism of straw fiber-microstructure chemical bond-fermentation temperature in the fermentation process of livestock manure + straw mixed raw materials, and contributed to the optimal ratio of modified mixed raw materials and the optimization design of fermentation biogas production preparation process.

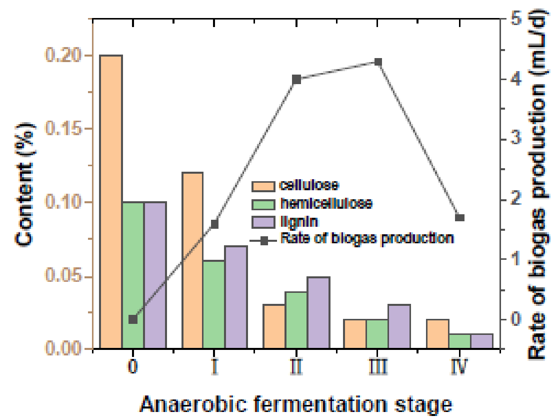
Comprehensive analysis indicates that fermentation temperature and the ratio of fermentation materials have a significant impact on gas production characteristics. For the same type of mixed materials consisting of livestock and poultry manure + straw, the trend of cumulative gas production and gas production rate is roughly consistent. However, when fermenting mixed materials of different types of livestock and poultry manure + straw, the cumulative gas production and gas production rate vary significantly, and the fermentation effect of different mixed materials is better than that of a single material. The metabolic activity of microorganisms is relatively active, and the degree of carbon chain structure breakage is enhanced. Comprehensive previous research indicates that the dynamic evolution and interactive effects of fermentation strains, microstructural chemical bonds within the microenvironment, and fermentation temperature.

The difference of biogas production rate in fermentation process and its quantitative characterization

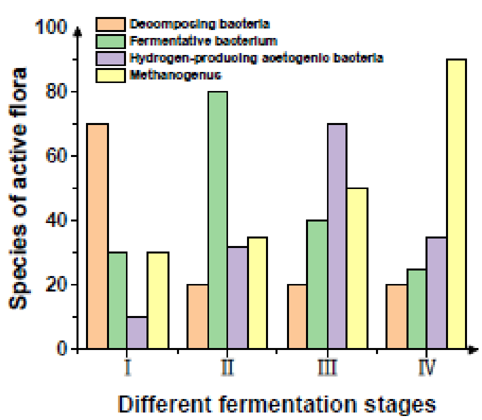
The anaerobic fermentation process was used to detect the changes of methanogenic bacteria and screen high-efficiency fermentation strains as control factors. The performance degradation model of biogas production rate differential performance was constructed, and the parameters of fermentation biogas production preparation process were optimized and adjusted. The purpose was to explore the synergistic mechanism of operating parameters such as fermentation temperature, inoculum concentration, inoculum amount, composting time and optimal ratio of raw materials. The curve of the activity of the dominant bacteria and the biogas production rate at different fermentation stages is shown in Fig. 2.



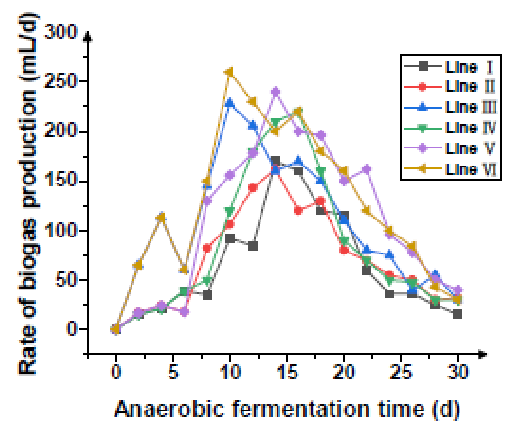
(a) Lye pretreatment and cumulative gas yield control group I



(b) Lye pretreatment and cumulative gas yield control group II



(c) Different fermentation stages, changes in the content of dominant bacteria and gas production rate



(d) changes in the mixed raw material control group and gas production characteristics

Fig. 2. Variation curves of dominant bacteria content and gas production rate at different fermentation stages

In Fig. 2, part a shows the degradation of biomass in the straw fermentation process before and after alkali pretreatment by Zhang *et al.* (2023b). In the biomass degradation conditions of straw fermentation before and after lye pretreatment, the contents of cellulose, hemicellulose, and lignin in straw of the raw materials treated without lye pretreatment were all lower than those of the lye pretreatment groups, with the range of 11.8% to 21.5%. The reason may be that after alkali pretreatment, the crystallinity of cellulose in the straw gradually decreased, the molecular bond force weakened, and the metabolic activity of the microbial strains contained in the biogas slurry was relatively active. It can promote the enzymatic hydrolysis and fermentation of cellulose, hemicellulose, and lignin in straw raw materials, and accelerate the yield and rate of biogas production in anaerobic fermentation process. Figure 2b is the control group of the yield and rate of cumulative biogas production (Qin 2023). The change of biogas production rate of straw fermentation before and after alkali pretreatment, that is, the peak biogas production rate is about 8.6%. At different fermentation stages, the types of flora are active and different (Shi *et al.* 2007). Part c of the figure shows the change of dominant flora content and biogas production rate in different stages. The active flora in the four stages of the fermentation process are decomposition bacteria, fermentation bacteria, hydrogen-producing acetic acid bacteria and methanogens, respectively. The biogas yield of straw fermentation after pretreatment with lye showed an increasing trend. Figure 2d is the curve of biogas production in the fermentation process, and the curve I ~ III in the figure (Chen *et al.* 2023). The analysis of chicken manure and primary fermentation straw, mixing, and rubbing straw and raw straw biogas production showed that the anaerobic fermentation effect of raw straw was better, and the biogas production rate of mixing and rubbing straw was smaller. Curve IV ~ VI is a simulation study on the change of biogas production in the fermentation process of curve I ~ III, that is, adding appropriate amount of fermentation bacteria, methanogens and fermentation additives respectively, to investigate the change of biogas production rate.

Research literature indicates that using a mixed feedstock of feces and straw (with the optimal ratio of feces-straw as the fermentation substrate) can effectively promote the degradation of cellulose, hemicellulose, and lignin. Adding fermentation additives appropriately during the fermentation process can significantly improve gas production efficiency, advance the peak of gas production, and shorten the fermentation cycle. This article summarizes current studies on the synergistic effects of operational parameters in the gas production process from mixed feedstock of livestock and poultry manure and straw (including fermentation temperature, inoculum concentration, inoculum addition amount, composting time, and the optimal ratio of feedstock, *etc.*), aiming to provide theoretical support for the dynamic changes and interactions of fermentation strains, microstructural chemical bonds, and fermentation temperature in the microenvironment.

Through comprehensive analysis, based on the changes in the dominant bacterial activity and gas production rate of straw at different fermentation stages, combined with the dynamic evolution and interactions of fermentation strains, microstructural chemical bonds, and fermentation temperature in the microenvironment, it helps to reveal the regularity of gas production rate differences and their quantitative characterization during the anaerobic fermentation process. At the same time, studying the coupling effects among fermentation strains, microchemical bonds, and fermentation temperature, constructing a performance degradation model for gas production rate differences, serves as a criterion for assessing the selection and optimization of fermentation additives for modified mixed feedstock, aiming to deeply explore the optimal process conditions for gas production from mixed feedstock fermentation.

The Coupling Mechanism of Fermentation Strain-Microstructure Chemical Bond-Fermentation Temperature in Fermentation Gas Production Process

The process of producing biogas using a mixed feedstock of livestock manure and straw is an exothermic and entropy-increasing process. Previous researchers have constructed a prediction model for the difference in performance of gas production rates under anaerobic fermentation influenced by multiple factors, which takes into account the effects of adding complex bacterial agents and the breaking ability of β-O-4 linkages in the microstructure. Analyzing the synergistic effects of key operational parameters such as fermentation temperature, inoculum concentration, inoculum dosage, composting time, and feedstock ratio helps to delve into the synergistic regulation strategies of pH value, carbon-to-nitrogen ratio (C/N), and feedstock ratio in the anaerobic fermentation microenvironment. Figure 3 shows the gas production under different fermentation temperatures. Figure 4 presents the relationship curves between anaerobic fermentation microbial communities, chemical bonds, and temperature changes.

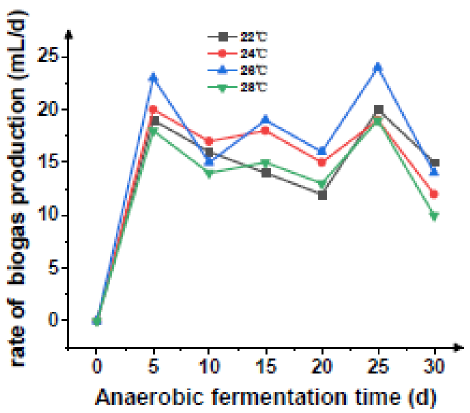


Fig. 3. Different fermentation temperatures and fermentation gas production

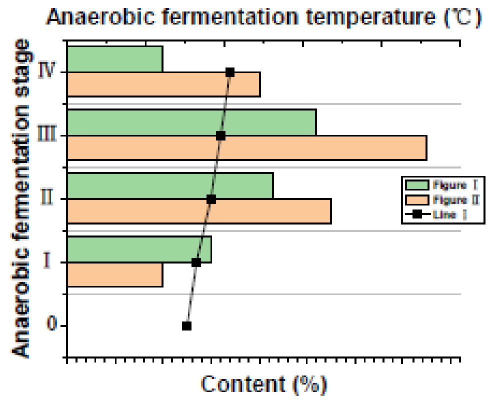


Fig. 4. Change curve of anaerobic fermentation flora chemical bond and temperature

According to the relevant literature (Pei *et al.* 2009; Zhang *et al.* 2022; Kong *et al.* 2021; Gong 2019; Jin *et al.* 2023), it can be seen from Fig. 3 (Zhang and Jiang 2022) that the trend of biogas production rate in the fermentation process is slightly different. There are some differences in the peak value of biogas production, the peak period of biogas production, and the biogas production rate in the fermentation process. The total biogas production curve first rises and then falls, and then it gradually tends to be stable and enters the fermentation recession period. The fermentation temperature was 26 ℃, the biogas production was large, and the maximum biogas production rate was about 4.52 mL/d. The fermentation temperature was 22, 24, 28 ℃, and the cumulative biogas production trend was roughly the same. According to Fig. 4 (Pei *et al.* 2009; Gong 2019; Kong *et al.* 2021; Jin *et al.* 2023), the active flora in the third stage of the fermentation process is rich in species. The connection bond force of straw particles was weakened and the degree of fracture was enhanced. The cumulative biogas production increased with the increase of fermentation temperature, and the biogas production rate changed rapidly. In the middle and late stages, it gradually decreased and tended to be stable.

Comprehensive analysis indicates that constructing the coupling mechanism of fermentative strains-microstructural chemical bonds-fermentation temperature is particularly important. Moreover, factors such as the substrate pH, carbon-to-nitrogen (C/N) ratio, and the proportion of raw materials significantly affect the growth of anaerobic fermentative bacteria. This is beneficial for an in-depth analysis of the synergistic mechanism of operational parameters such as fermentation temperature, inoculum concentration, inoculum dosage, composting time, and the optimal proportion of raw materials. It also aids in exploring the synergistic regulation of substrate pH, carbon-to-nitrogen (C/N) ratio, and raw material proportion in the anaerobic fermentation microenvironment. In summary, examining the coupling mechanism of straw fiber-microstructural chemical bonds-fermentation temperature during the anaerobic fermentation process aims to rationally regulate the optimal proportion of fermentation raw materials to study the gas production characteristics of these materials.

Analysis of PH Value and C/N Ratio of Liquid in Microenvironment at Micro / Meso Scale

The variation of organic acid concentration and carbon-nitrogen ratio in straw fermentation process has been summarized on the micro / meso scale. The appropriate addition of microenvironment feed solution was helpful to realize the degradation performance of lignin benzene ring functional group, aiming to broaden the way of different addition amount and anaerobic fermentation reaction temperature window. The changes of acid production and biogas production under different C/N conditions were shown in Fig. 5 and 6, respectively. The changes of anaerobic fermentation biogas production and biogas production rate under different pH value are shown in Fig. 7.

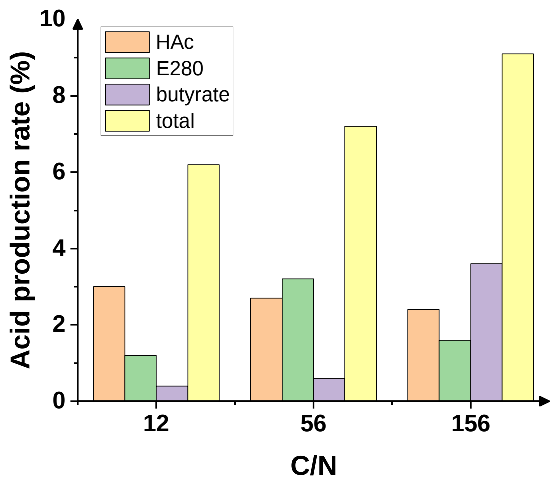


Fig. 5. Changes in fermentation acid production under different C/N conditions

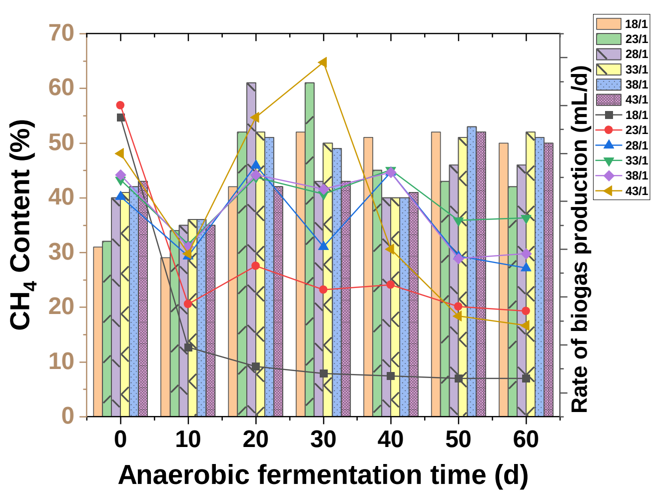


Fig. 6. Changes in fermentation gas production under different C/N conditions

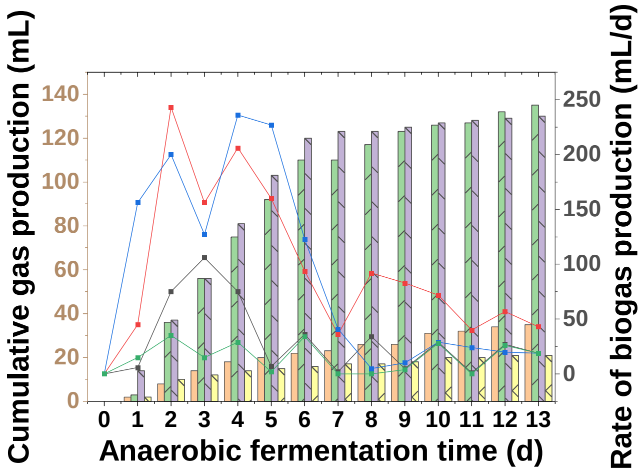


Fig. 7. Changes of gas production and gas production rate in anaerobic fermentation at different pH values

It can be seen from Fig. 5 (Liu *et al.* 2010) that the higher the C/N ratio, the higher the total acid production, and the higher the content of C element in straw particles. The enzymatic hydrolysis and activity of degrading bacteria showed an upward trend, When the C/N ratio was 56, the peak acid production amounts for propionic acid, butyric acid, and acetic acid were 68.7%, 54%, and 21.3% respectively. According to Fig. 6, Gao *et al.* (2009) analyzed the cumulative biogas production, daily biogas production rate, and methane content in the anaerobic fermentation process. The study found that the overall change of methane content in the anaerobic fermentation process was small and stable. With the increase of C/N, the biogas production increased first and then decreased. The biogas production rate increased with the increase of C/N ratio, and it gradually decreased in the middle and late stages. According to Fig. 7, Zhang *et al.* (2015) studied the biogas production and biogas production rate of anaerobic fermentation process under different PH values. When the PH value was 7 to 9, the cumulative biogas production and fermentation biogas production rate were higher. When the pH value was 7, the biogas production was large. When the pH value was 9, the cumulative biogas production and biogas production rate were small.

Previous studies (Liu *et al.* 2010; Gao *et al.* 2009; Zhang *et al.* 2015; Liu *et al.* 2020) have explored the synergistic regulation strategies for the substrate pH value, carbon-nitrogen (C/N) ratio, and feedstock composition in the microenvironment of anaerobic fermentation at micro/meso scales. By summarizing the variation patterns of organic acid concentrations and carbon-nitrogen (C/N) ratios during straw fermentation, this paper aims to reveal methods for rationally regulating the feedstock composition and analyze their impact on fermentation outcomes and gas production characteristics. Analysis of previous research results indicates that the appropriate addition of microenvironmental feedstock can facilitate the degradation performance of microstructures, adapt to Mn^{2+} (concentration of about 2 mol/L), effectively enhance MnP enzyme hydrolytic activity, strengthen the breaking ability of β-O-4 bonds in straw particle microstructures, and thus increase the gas production from mixed feedstock fermentation.

Based on the summary of previous studies, this research reveals the phenomenon of differential hydrogen production and its constraints with the hydrogen production process. To verify these findings, a series of simulation tests are planned. This article utilizes numerical simulation techniques to construct a detailed hydrogen generation model. By simulating the hydrogen production process under different conditions, this study aims to analyze the impact of various factors on hydrogen production efficiency. It is expected that through these studies, the intrinsic mechanism of differential hydrogen production can be revealed and provide a theoretical basis for optimizing the hydrogen production process.

VARIABLE PROCESS THEORY ANALYSIS OF BIOGAS PRODUCTION RATE DIFFERENTIAL PERFORMANCE IN FERMENTATION PROCESS

Discrete Modeling of Straw Fiber Microstructure in Anaerobic Fermentation Process

Based on the internal fiber microstructure of straw particles in mixed raw materials under double random effects, the dynamic evolution discrete reconstruction of fermentation strain-microstructure chemical bond-fermentation temperature in anaerobic fermentation process under the influence of multiple random effects was modeled and analyzed by means of the efficient batch embedding technology of microenvironment material liquid degradation unit in the grid model.

Model construction

ANSYS and Solidworks were used to construct the strain change model under the conditions of anaerobic fermentation, stirring, temperature control, pretreatment, suitable addition of metal ions and fermentation additives, and the richness of the flora was studied and analyzed in combination with the biogas production. The internal fiber microstructure model of straw particles in the mixed raw materials of livestock manure + straw is shown in Fig. 8. The construction of anaerobic fermentation model of livestock manure + straw mixed raw materials is shown in Fig. 9.

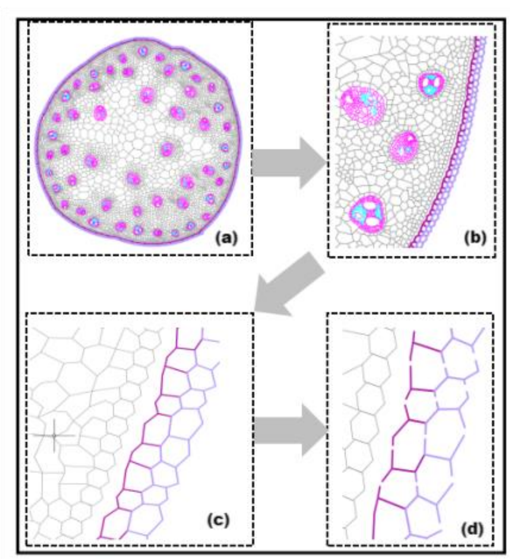


Fig. 8. Internal fiber microstructure of straw particles

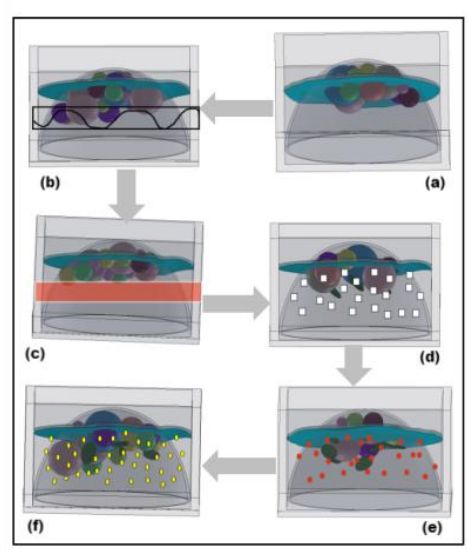


Fig. 9. Anaerobic fermentation model construction of mixed raw materials

Model prediction analysis

It can be seen from Fig. 8 (Zhang *et al.* 2009) that the Figs. a-d are straw section, local, straw epidermis without alkali pretreatment and straw epidermis model with alkali pretreatment, respectively.

In Fig. 9, parts a-e correspond to ordinary anaerobic fermentation, stirring during fermentation, temperature control (solar sub-band or simulated temperature control system to control the temperature of fermentation broth in the tank), alkali pretreatment, metal ions and suitable fermentation additives. It was predicted by the fermentation process model that in different fermentation stages, the straw was pretreated with alkali solution, and the appropriate amount of metal ions and suitable fermentation additives were added to the fermentation broth of the inoculum. The species activity and richness of the anaerobic fermentation bacteria showed an increasing trend, and the anaerobic fermentation reaction process was accelerated. The biogas yield and rate gradually increased, effectively promoting the degradation of microstructure and enhancing fermentation biogas production. The simulation results are consistent with the reported research results (Zhang *et al.* 2022; Kong *et al.* 2021; Going *et al.* 2019), and the error difference is small.

Coupling Analysis of Fermentation Strain – Microstructure Chemical Bond – Fermentation Temperature

The numerical integration method of the coupling failure mechanism of fermentation strain activation-microstructure-fermentation temperature in anaerobic fermentation process and its interaction mechanism with the evolution of fermentation biogas production (yield, rate) differential performance was studied. On the micro / meso scale, the differential performance of anaerobic fermentation biogas production under the influence of multiple factors and the velocity field, temperature field, concentration field of fermentation liquid medium flow and the phase composition of bacterial membrane and the change characteristics of fiber microstructure of gas-liquid phase interface microsystem were investigated. According to References (Yu *et al.* 2020; Ma *et al.* 2021), in the process of anaerobic fermentation, the species and quantity of flora change rapidly, and the dynamic changes of flora species at different stages are simulated (the changes of temperature field and velocity field of feed liquid). It was found that the content of anaerobic acid-producing bacteria and anaerobic ammonifying bacteria increased first and then decreased gradually during dry anaerobic fermentation, the number of anaerobic cellulose-decomposing bacteria increased first and then remained unchanged, and the content of methanogens continued to increase during fermentation. During the reaction, the cellulose content continued to decrease and remained at a certain level. The changes of bacterial species in the fermentation process of mixed raw materials are shown in Fig. 10.

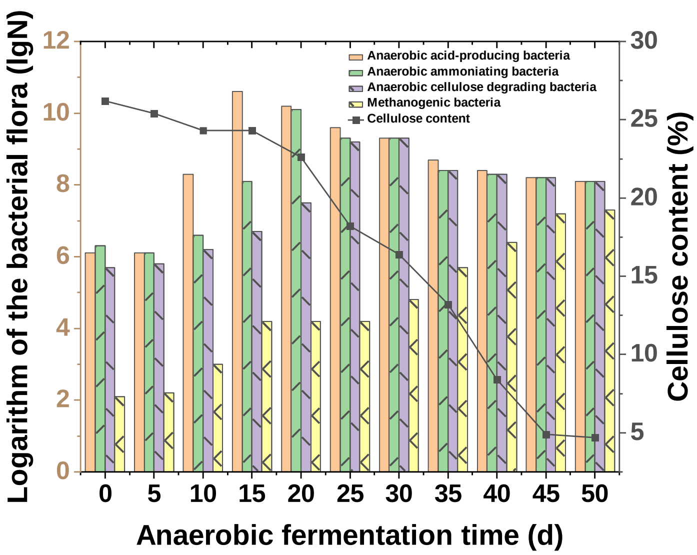


Fig. 10. Changes of flora species in fermentation process

Analysis of the Variation Process of Fermentation Biogas Production Rate Differential Performance

Aiming at the practical problems of low calculation accuracy at the macro scale and low calculation efficiency at the micro scale of the phase interface microsystem, an analytical model for the dynamic evolution of the phase composition and fiber microstructure of the gas-liquid thin-layer interface microsystem of the liquid medium under the double random effect was constructed by means of the theories of biofermentation, biochemistry, and random field.

Microsystem liquid thin layer interface stress analysis

In order to establish the thin-layer interface model of the micro-system, it is necessary to consider the combined effects of the static pressure, the surface tension, and the pressure difference between the inside and outside of the liquid surface. According to the Young-Laplace equation (Hu *et al.* 1997), the liquid surface pressure difference, the liquid surface curvature and the surface tension can be calculated according to Eqs. 1 to 4,

$$\Delta P = \gamma\left(\frac{1}{R_1}+\frac{1}{R_2}\right) \tag{1}$$

$$F = \gamma l \tag{2}$$

$$h = \frac{p - p_0}{\rho g} \tag{3}$$

$$\mathrm{p}_1 A - \mathrm{p}_2 A - \rho g A(h_1 - h_2) \tag{4}$$

where $\triangle P$ is the difference between the internal and external pressure of the thin layer liquid, γ is the surface tension coefficient of the liquid, R_1 and R_2 are the radius of curvature at a certain point on the surface of the liquid thin layer, F is the force due to the surface tension of the liquid thin layer (N), a is the thin layer interface area (m^2); h is the height of thin layer micro-liquid level (m), ρ is the density of culture medium (m^3/kg), and g is the acceleration of gravity (m/s^2).

The shear stress and shear stress of the gas-liquid thin layer of the medium were calculated according to Eqs. 5 and 6, respectively,

$$\tau = \tau_0 + \mu \frac{\mathrm{dv}}{\mathrm{dx}} \tag{5}$$

$$\sigma = \sigma_0 + \mu \frac{\mathrm{dv}}{\mathrm{dy}} \tag{6}$$

where τ is the shear stress of the gas-liquid thin layer (N), τ_0 is the initial shear stress of the gas-liquid thin layer (N), μ is the dynamic viscosity coefficient of the culture medium (Pa·s), v is the gas-liquid thin layer interface fluid velocity (m/s), σ is the shear stress on the gas-liquid thin layer (N), and σ_0 is the initial shear stress on the gas-liquid thin layer (N).

At the same time, based on the different stress of the thin layer interface of the feed liquid, the content of the bacteria in the feed liquid and the disturbance change are different. The stress analysis of the thin layer interface of the microsystem (surface protrusion) indicates that the content of the bacteria outside the liquid is more and the disturbance is enhanced, while the surface depression indicates that the content of the bacteria inside the liquid is less and the disturbance is weakened. As shown in Fig. 11 and Fig. 12.

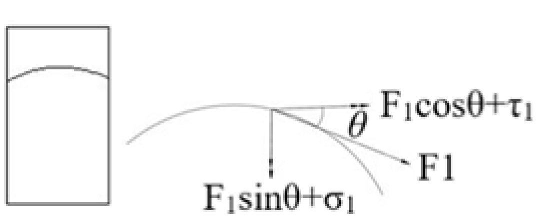


Fig. 11. Force analysis of thin layer interface (outside)

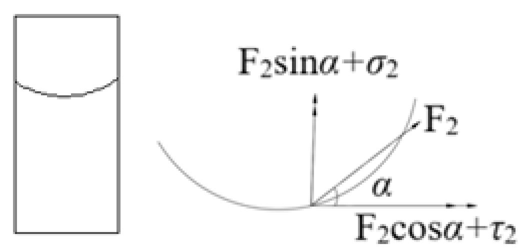


Fig. 12. Force analysis of thin layer interface (inside)

The force analysis of the material-liquid thin layer interface of the microsystem is calculated according to the Eqs. 7 and 8,

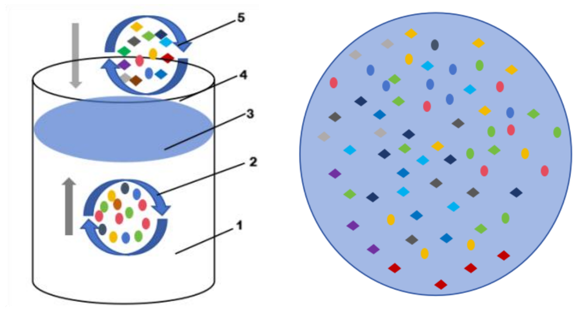
$$F_{x1} = F_1 \cos\theta + \tau_1 \; F_{y1} = F_1 \sin\theta + \sigma_1 \tag{7}$$

$$F_{x2} = F_2 \cos\alpha + \tau_2 \; F_{y2} = F_2 \sin\alpha + \sigma_2 \tag{8}$$

where F_x is the horizontal force of the phase interface (N) ; F is the surface tension of the phase interface (F_1 and F_2 are the upper and lower interface pressures of the medium, respectively), N; θ and α are the angle between the phase interface and the horizontal direction; τ is the shear stress on the liquid surface, N; F_y is the stress in the vertical direction of the phase interface, N; and F_x is the stress in the level direction of the phase interface, N. In the calculation, γ is calculated to be 0.1N / m, ρ and g are 1253m^3/kg and 9.8 kg / N, P is 101 KPa, θ and α are 3.2° and 4.0°, respectively. After calculation, F_{x1} is 0.136 N, F_{y1} is 0.0623 N, F_{x1} is 0.156 N, F_{y1} is 0.0523 N, and F is 0.0314 N, which is consistent with the force of the thin liquid layer.

Analysis of the interface change process of the feed liquid thin layer in the microsystem

According to the literature (Shi 2007; Tang *et al.* 2012), the biogas production stage of raw material fermentation is different, and the types of flora are active and different (Shi 2007). At the same time, the surface tension of the fermentation broth has a certain effect on the surface characteristics, structure and function of the bacterial cell membrane (Tang *et al.* 2012). In this study, Soildworks software was used to establish the composition model of the thin-layer interface microsystem change process, in order to analyze the correlation between the activity and richness of the microbial flora in the fermentation broth and the gas-liquid thin-layer interface microsystem and the microbial flora change process in the culture medium. The composition of the micro-system change process at the thin layer interface is shown in Fig. 13.



1. Internal interface of culture medium; 2. Fermentation flora;
3. Gas-liquid thin layer interface; 4. Air interface; 5. Airborne flora;

Fig. 13. Composition of thin layer interface microsystem variation process

According to Fig. 13, with the process of fermentation and biogas production, the phase composition of the bacterial film at the thin layer interface (gas-liquid phase) of the micro-system (the content of the fermentation flora accounts for about 75 to 78% of the total amount of the micro-system) and the microstructure of the straw granule fiber are dynamically evolved in a timely manner. The phase of the bacterial film at the thin layer interface of the micro-system is affected by the liquid phase tension and free diffusion of the liquid phase in the medium, and the gas phase mixed into the thin layer interface of the liquid phase. Through the prediction model of fermentation process and comprehensive literature analysis (Shi 2007; Tang *et al.* 2012), the influencing factors of the differential performance change process of anaerobic fermentation biogas production rate were studied. The purpose of this study was to study the coupling failure mechanism of fermentation strain activation-microstructure-fermentation temperature in anaerobic fermentation process and its differential performance with fermentation biogas production (yield and rate). Furthermore, exploration into hydrogen production from biogas is conducted to uncover its potential in enhancing energy conversion efficiency and environmental friendliness. By subjecting biogas to specific catalytic treatments, the goal is to unlock its latent hydrogen production capabilities and analyze the impact of this process on overall fermentation efficiency. This research aims to broaden the application scope of anaerobic fermentation technology, providing new insights for the development and utilization of sustainable energy sources.

Prediction of dynamic evolution of chemical bonds in microstructure

Based on the dynamic evolution of the microstructure of the feed liquid of the phase interface microsystem medium, a model was constructed to analyze the dynamic changes of the microstructure of the biogas production process in the fourth stage of anaerobic fermentation. The dynamic evolution of chemical bonds in the biogas production process of the microstructure of the medium is shown in Fig. 14. Taking the mixed raw material of cattle manure + corn straw (the ratio of manure and straw is 2 : 1) as the research object, the biogas production in the fermentation process was studied. The biogas digester model setting: 1 The overall size is 1.5 m in diameter and 3.0m in height. The diameter of the biogas collection outlet above is 0.5 m. The solar temperature control zone is set on both sides of the pool wall 10 cm, and the temperature control adjustment range is 298 to 338 K; 2 The mesh is divided into 5mm × 5mm, and the step size is set to 1000 s. The change of biogas production rate at different fermentation temperatures is shown in Fig. 15.

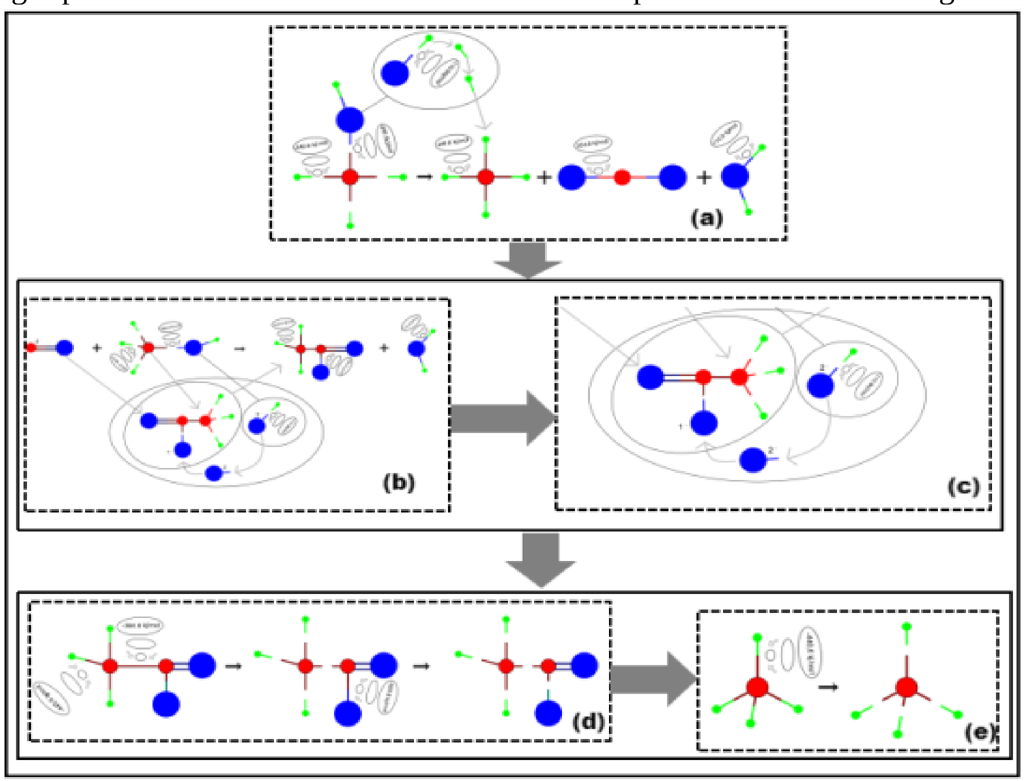


Fig. 14. Dynamic evolution of chemical bonds during gas production

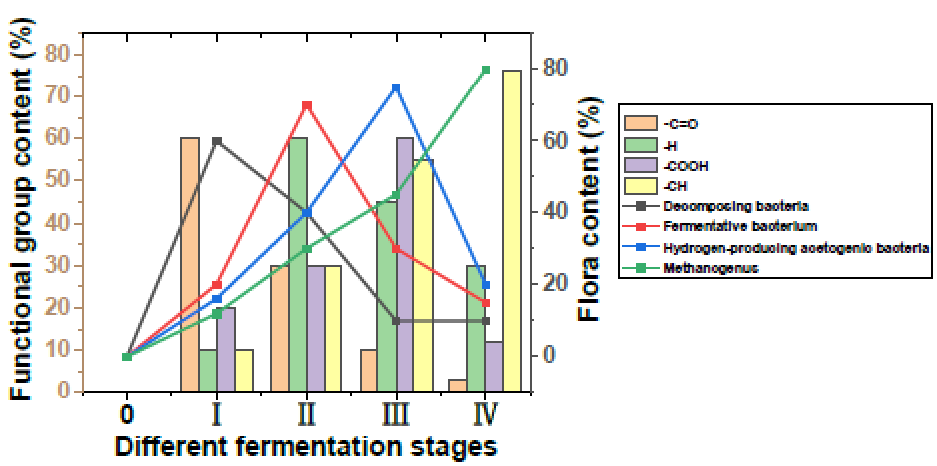


Fig. 15. Change of gas production rate during fermentation at different fermentation temperature

According to Fig. 14, part a shows the evolution process of acetic acid production stage $4CH_3OH+2CO_2 \rightarrow 3CH_3COOH+2H_2O$ in anaerobic fermentation process, Fig. 14b is the dynamic change of molecular microstructure and bond energy in anaerobic fermentation process, Fig. 14c is the evolution process $4CH_3OH \rightarrow 3CH_4+CO_2+2H_2O$

under the action of anaerobic bacteria, Fig. 14d is the fracture and energy release of acetate molecular bond in anaerobic fermentation process, and Fig. 14e is the structure diagram of methane production stage $4HCOO^{-}+2H^{+}\rightarrow CH_4+CO_2+2HCO_3^{-}$ in anaerobic fermentation processes.

According to Shi (2007) and Pei *et al*. (2009), the simulation and comparative analysis are shown in Fig. 15. In the anaerobic fermentation hydrolysis stage, the macromolecular organic matter is decomposed into small molecules in vitro by extracellular enzymes, and the C-C bond (about 1/2) and C-O bond (about 3/4) are broken and a large amount of energy is consumed. In the fermentation hydrolysis stage, the proportion of OH bond breakage was about 33%, that is, 1/3. In the acetic acid production stage, -CO and-OH are combined to convert into acetic acid and carbonic acid. The proportion of-COOH is slightly higher than that of-CH, and the proportion is about 1/3. The-CH bond in the methanogenic stage of the anaerobic fermentation process breaks (accounting for about 2/5), forming a C-H bond and forming a stable CH_4 (accounting for about 2/3).

Simulated Experiment Comparative Verification

Physical model

A model was established for the purpose of better understanding literature findings. Specifications for the model were as follows: The model setting of fermentation gas production tank: I. The overall size is 1.5 m in diameter and 3.0 m in height. The diameter of the upper gas collection port is 0.5 m. The solar temperature control zone is set on both sides of the tank wall, and the manure-stalk hemisphere model is set in the tank. The wall temperature T = 312 K, the initial temperature of the medium liquid 318 K, and the temperature control range 298 K to 338 K; II. The mesh is 5mm×5mm, and the step size is set to 1000 s.

Control equations

The governing equations include heat transfer equation, kinetic energy equation and energy equation. Due to the continuous chemical reaction of the substrate during the anaerobic fermentation process, it can be considered that the anaerobic fermentation process is a three-dimensional constant physical property, laminar flow, and compressible steady-state flow. The basic equations are as follows:

1) Continuity equation

$$\frac{\partial \rho \mathrm{u}}{\partial \mathrm{x}}+\frac{\partial \rho \mathrm{v}}{\partial \mathrm{y}}+\frac{\partial \rho \mathrm{w}}{\partial \mathrm{z}}=\frac{\partial \rho}{\partial \mathrm{t}} \tag{9}$$

In Eq. 9, ρ is the fluid density, kg / m^3, and u, v, and w are the velocity components of the fluid in the x, y, and z directions, m/s.

2) Momentum conservation equation (10)

where b is the flow time of fermentation broth, s; V_a is the volume of fermentation broth flow process, m^3, and f_x is the friction force between fluids, N.

3) Energy conservation equation

$$\rho\frac{De}{Dt}=\rho_a q_d+\phi(t)-\xi+B_u+B_v+B_w \tag{11}$$

Among the equations,

$$\begin{cases} \varphi(t) = \frac{\partial}{\partial x}(k\frac{\partial T_a}{\partial x}) + \frac{\partial}{\partial y}(k\frac{\partial T_a}{\partial y}) + \frac{\partial}{\partial z}(k\frac{\partial T_a}{\partial z}) \\ \xi = p(\frac{\partial u_a}{\partial x} + \frac{\partial u_a}{\partial y} + \frac{\partial u_a}{\partial z}) \\ B_u = b_{xx}\frac{\partial u_a}{\partial x} + b_{yx}\frac{\partial u_a}{\partial y} + b_{zx}\frac{\partial u_a}{\partial z} \\ B_v = b_{xy}\frac{\partial v_a}{\partial x} + b_{yy}\frac{\partial v_a}{\partial y} + b_{zy}\frac{\partial v_a}{\partial z} \\ B_w = b_{xz}\frac{\partial w_a}{\partial x} + b_{yz}\frac{\partial w_a}{\partial y} + b_{zz}\frac{\partial w_a}{\partial z} \end{cases} \tag{12}$$

where D_e / D_t is the material derivative, and q_d is the heating rate per unit mass volume. $\rho_a q_d + \Phi\ (T)$ is the total heat of fluid pellets (J), ζ is the work done by the pressure on the fermentation broth in different directions (J), B_u is the work of the surface force on the fermentation broth in the x direction (J), B_v is the work J of the surface force on the fermentation broth in the y direction, B_w is the work of the surface force on the fermentation broth in the z direction (J).

Numerical computation model

The heat transfer and average temperature difference in the fermentation process of mixed raw materials were calculated. After calculation, the mixed raw materials fermentation tank temperature is higher: the heat exchange is about 7800 W, the average temperature difference is 99.6 °C. When the temperature in the fermentation tank of mixed raw materials is low, the heat transfer is about 15600 W, and the average temperature difference is 199.3 °C.

The shear stress of the thin layer interface (gas-liquid phase) of the micro-system in the fermentation process can be calculated according to Eqs. 13 and 14,

$$\tau = WS^l \tag{13}$$

$$\tau = \tau_y + Q\alpha^N \tag{14}$$

where τ is the shear stress (N), S is the surface area of the fiber structure (m^2), τ_y is the yield stress of the fluid (N), a is the shear rate of the fluid (s^{-1}), and W, l, N are constants related to the material. In the calculation, S and τ_y are $3.14 \times 10^{-4} m^2$ and 26 Pa respectively, a is 3.2×1002 s^{-1}, and W, l, Q and $\underline{N}$ are 100, 20, 50 and 63 respectively, and the shear stress value is 0.0157 N.

According to the ANSYS software, the two-phase fluid grid particle model in the fermentation biogas production tank is established. The initial model and residual diagram of the anaerobic fermentation process are shown in Fig. 16.

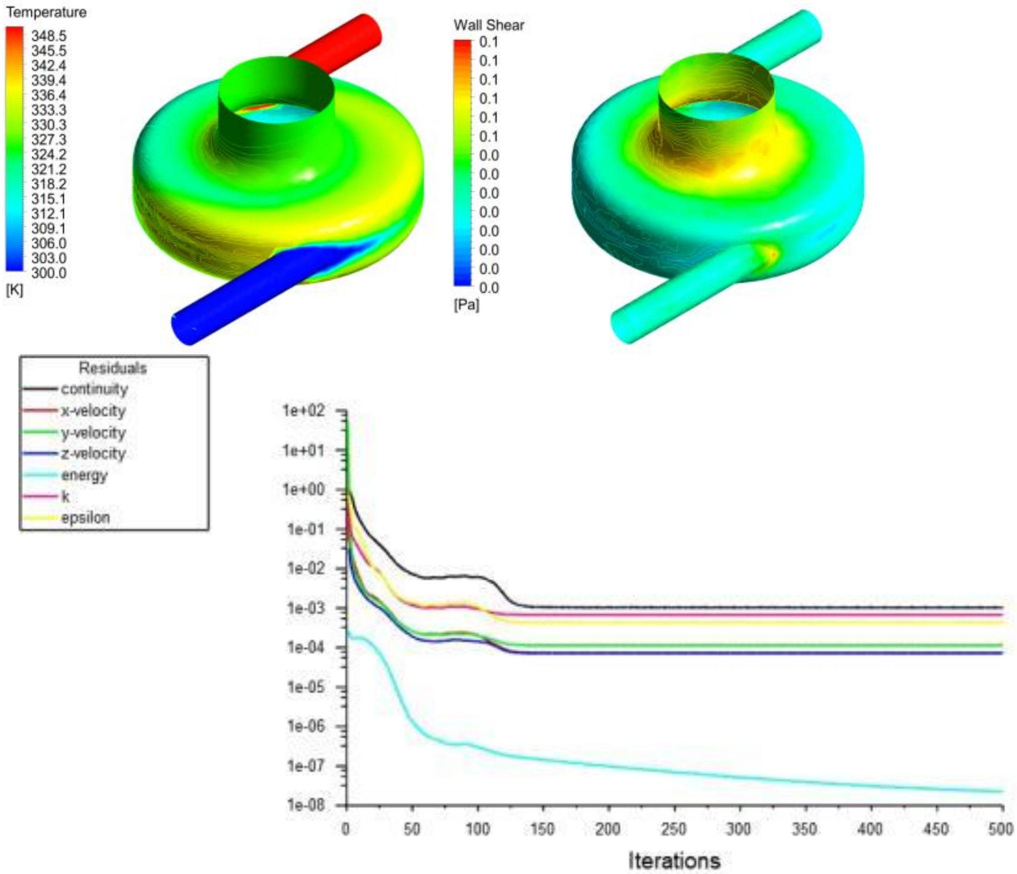


Fig. 16. Initial model and residual of anaerobic fermentation process

The mixed raw materials of cow dung + corn straw (the ratio of manure to straw was 3:1) were used as the research object. The solar temperature control zone on both sides of the pool wall was used to control the temperature of the fermentation process, and the biogas production during the fermentation process was studied. That is, through simulation and prediction, the effects of temperature, flow rate, pressure and viscosity on the microsystem changes in the fermentation process were analyzed. The changes in the fermentation process of mixed raw materials are shown in Fig. 17 (a, temperature change b, biogas viscosity change, c, pressure change, d, flow rate change I, e, flow rate change II).

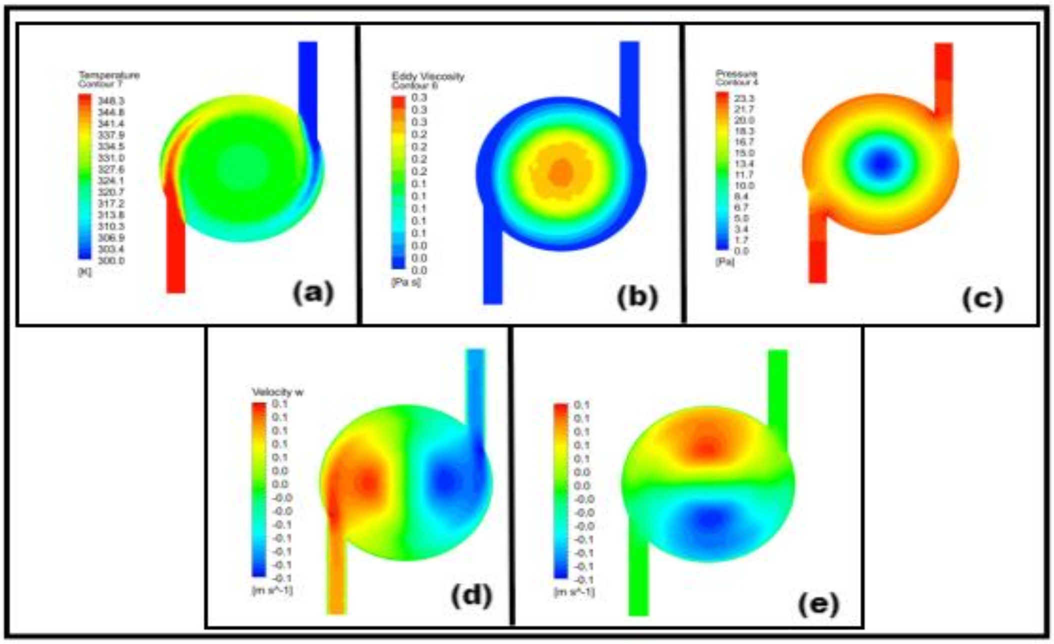


Fig. 17. Changes of gas production process of mixed raw materials fermentation

According to the simulation prediction of Fig. 17, the change is basically consistent with the change of the coupling mechanism of fermentation strain-microstructure chemical bond-fermentation temperature. The change of one of the fermentation strain, microstructure chemical bond and fermentation temperature will cause the change of the other two quantities, and the change range is maintained between 1.26 % and 1.57 %. The simulation results are consistent with the research results of Zhang *et al.* (2023) and Chen *et al.* (2023), and the error difference is small.

Comparative analysis of numerical calculation results with previous research findings

In order to verify the feasibility of the above related research and analysis, explore the difference of biogas production rate in the straw fermentation process, and the quantitative characterization of the coupling failure behavior of fermentation strain-microstructure chemical bond-fermentation temperature, this study used the Design-Expert design tool to Livestock manure + straw mixed raw materials. The change of biogas production in the fermentation process under different manure-straw ratio conditions was simulated, and Origin was used for editing and processing. The biogas production curve of mixed raw material fermentation under different manure-rod ratio conditions is shown in Fig. 18. The cumulative biogas production curve of fermented biogas slurry added with additives is shown in Fig. 19.

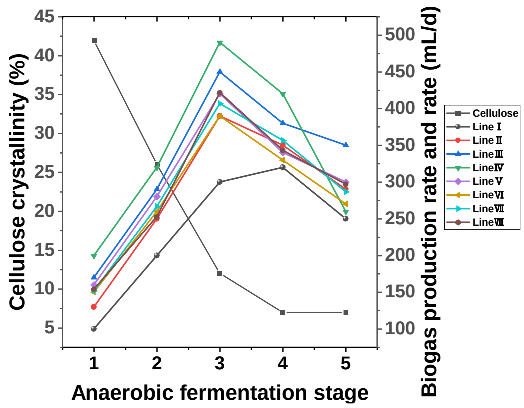


Fig. 18. Changes of gas production in fermentation of mixed raw materials (different fecal-rod ratio)

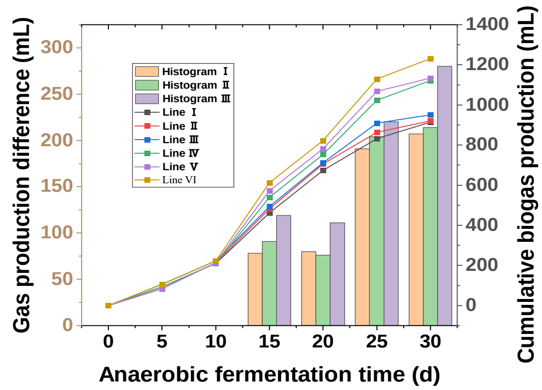


Fig. 19. Changes of gas production in fermentation biogas slurry with additives

The simulation setting of Fig. 18, curve I is pig manure-corn straw ratio 1:1, curve II is pig manure-corn straw ratio 2:1 ; curve III is pig manure-corn straw ratio of 3:1, curve IV is cow manure-corn straw ratio of 3:1 ; curve V is cow dung-corn straw ratio of 2:1, curve V is cow dung-corn straw ratio of 1:1. According to Fig. 18, when the ratio of cow manure to corn straw is 3:1, the biogas production rate is larger, and the peak biogas production is about 467 mL/d. When the ratio of pig manure to corn straw is 1:1, the biogas production rate is smaller, and the peak biogas production is about 332 mL/d. The difference between the two is 26.8 %. The cellulose crystals in the straw changed greatly in the first and second stages, and the decrease in the third and fourth stages slowed down and gradually stabilized. The reason is that there are differences in the components of cow manure and pig manure, the degree of acidification of the fermentation liquid (Hu *et al.* 1997), and the functional group transformation of the fiber microstructure, the difference in biomass degradation performance during fermentation and biogas production, *etc*., resulting in different biogas production rates. The simulation results (average biogas production curve VII) have an error of about 4.12 % during the change of biogas production rate during the research process in the literature (Li *et al.* 2020; Zhang *et al.* 2023; Jia *et al.* 2020).

DYNAMIC ANALYSIS OF THE DIFFERENTIAL PERFORMANCE CHANGE PROCESS OF ANAEROBIC FERMENTATION BIOGAS PRODUCTION RATE

Micro / meso Performance Model of Fermentation Process

Based on the multi-scale physical-chemical behavior of straw fiber microstructure in anaerobic fermentation process and its interaction, the synergistic regulation of pH value, carbon-nitrogen (C/N) ratio and raw material ratio in anaerobic fermentation microenvironment and the effect of suitable dosage of modified mixed raw material fermentation additives on the enzymatic hydrolysis characteristics of microstructure were analyzed by the dynamic evolution analysis model of phase composition and fiber microstructure of phase interface microsystem.

After a comprehensive analysis of the literature (Wang *et al.* 2023a; Wu *et al.* 2020), it has been found that pretreating straw before anaerobic fermentation can improve the biogas yield of the process. When straw is pretreated with alkaline solutions, its internal mass fraction (loss rate) gradually decreases, and the dynamic change index of the straw fiber size also gradually diminishes. By adjusting the pH value, carbon-to-nitrogen ratio (C/N), and the ratio of raw materials in the microenvironment of anaerobic fermentation, the internal microenvironment of the biogas fermenter can be altered, thereby changing the biogas yield of the anaerobic fermentation process. According to the fermentation process, adjusting the pH value, C/N ratio, and adding appropriate amounts of improved mixed raw material fermentation additives can maintain the biogas yield at a level close to the peak (Zhang *et al.* 2022; Kong *et al.* 2021; Gong *et al.* 2019; Jin *et al.* 2023; Pei *et al.* 2009).

Based on the comprehensive analysis, the appropriate dosage of fermentation additives has a certain significance for the improvement of the compounding and activation of micro-system bacteria at the phase interface and the rheological properties of the liquid. According to the literature (Shi *et al.* 2020; Bi *et al.* 2015; Zhang *et al.* 2022), the anaerobic flora are compounded and activated, and fermentation additives are suitable to be added. According to the different fermentation stages, the flora types in the fermentation process are adjusted to increase the proportion of dominant flora. At the same time, the introduction of homogeneous catalysis technology can reduce the activation energy of the reaction in the anaerobic fermentation process. Through the compounding and activation of the flora, the proportion of the dominant flora and the activity of the flora can be improved, and the efficiency of anaerobic fermentation biogas production can be greatly improved. It is helpful to explore the high efficiency and temperature adaptability of biomass degradation mechanism and quantitative characterization of micro-functional groups in the process of modified straw fermentation biogas production.

Based on the dynamic analysis model of the phase composition of the bacterial film and the microstructure of the fiber based on the gas-liquid thin-layer interface microsystem of the liquid medium under the double random effect, the ANSYS software was used to simulate, and the SoildWorks tool was used to model (micro / meso) analysis, which was basically consistent with the changes of flora and biogas production in the literature (Zhang *et al.* 2023; Qin *et al.* 2023; Shi *2*007; Chen *et al.* 2023). The types and macroscopic performance models of the fermentation process of different treatment methods (Figs. a-d are the apparent before fermentation, the apparent of the fermentation process, the apparent of the pretreatment fermentation process and the apparent of the fermentation process with the addition of fermentation additives). The fermentation process (micro/meso) performance model is shown in Fig. 20.

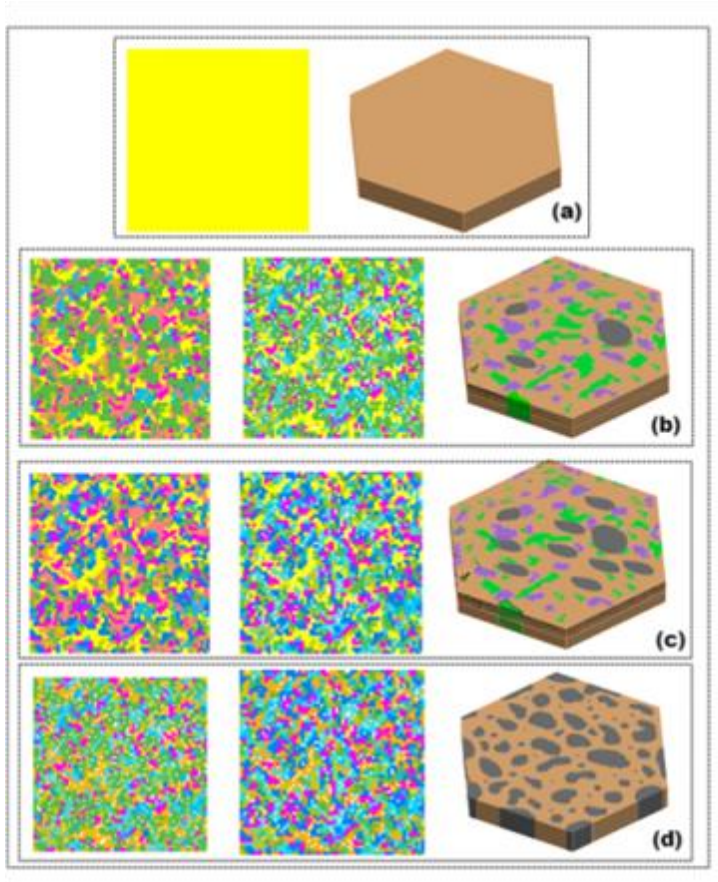


Fig. 20. Micro/micro performance model of fermentation process

Prospects of Photosynthesis-fermentation Coupled Hydrogen Production

Photosynthesis and fermentation coupled control technology have shown high flexibility and scalability in hydrogen production. However, the key issue is how to improve the efficiency of photosynthesis and fermentation processes. This article explores the impact of photosynthetic bacteria – hydrogenase bacteria on hydrogen production rates.

After fine crushing treatment, microorganisms and straw are added for fermentation. The organic components such as cellulose, hemicellulose, and lignin within the biomass are decomposed through a series of complex reactions. As a result, sugar substances that can be further fermented and utilized are released. Hydrogen-producing bacteria are added to the liquid containing sugar substances to produce hydrogen. The ideal equation for sugar-based hydrogen production is: $2CH_3COOH+2H_2O \rightarrow 4H_2+2CO_2$.

The effect of photosynthetic bacteria strains – carrier adjuvants on hydrogen production by hydrogenase bacteria

To deeply study the effects of hydrogen production by hydrogenase bacteria alone and in combination with photosynthetic bacteria, numerical analysis was conducted. Figures 21(a) and 21(b) respectively show the numerical calculation results of hydrogen production by hydrogenase bacteria alone and in combination with photosynthetic bacteria.

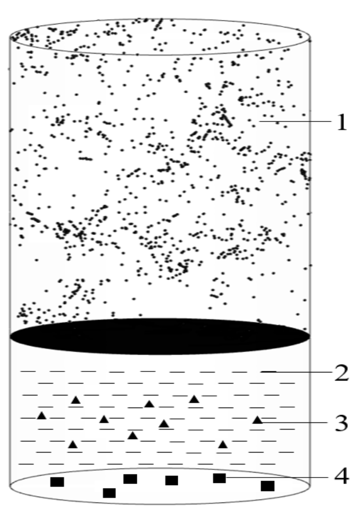


Fig. 21(a) Hydrogen production by hydrogenase adding bacteria

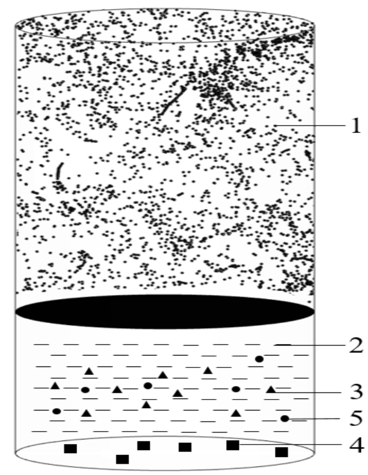


Fig. 21(b) Hydrogen production by hydrogenase bacteria and photosynthetic bacteria

1-Hydrogen molecule; 2-Liquid; 3-Hydrogenase bacteria; 4-Sediment; 5-Photosynthetic strain

From Figure 21(a), it is clearly observed that after the introduction of hydrogenase-producing bacteria, the hydrogen content within the container space significantly increased, and the efficiency of hydrogen production remained at a stable level. A further comparison between Fig. 21(a) and Fig. 21(b) reveals that when photosynthetic bacteria were added to the hydrogen production system, there was a significant improvement in the efficiency of hydrogen production. The root cause of this phenomenon lies in the fact that the addition of photosynthetic bacteria effectively increased the temperature environment of the sludge, which in turn promoted the growth and activity of the hydrogenase-producing bacteria, ultimately achieving a significant enhancement in the efficiency of hydrogen production.

Temperature is one of the key factors affecting the efficiency of biohydrogen production. Firstly, increasing the temperature can accelerate the decomposition of organic matter in biomass, thereby increasing the yield of hydrogen gas. For example, under high-temperature conditions, substances such as cellulose and carbohydrates in biomass are more prone to pyrolysis, generating more volatile materials. These materials can be converted into hydrogen gas in subsequent reactions. Secondly, temperature also has a significant impact on the activity of catalysts. Within an appropriate temperature range, catalysts can effectively promote the progress of reactions, increasing the rate of hydrogen production.

Analysis of the effect of photosynthetic bacterial strains and auxiliary carriers on the hydrogen production efficiency of hydrogenase bacteria

To study the effect of photosynthetic bacteria-strain and auxiliary carrier on the hydrogen production efficiency of hydrogenase bacteria, this paper analyzed the amount of hydrogen produced. Figure 22 shows the comparison between the amount of hydrogen produced from 1 mole of liquid with only hydrogenase bacteria added and the amount produced when hydrogenase bacteria work together with photosynthetic bacteria-strain and auxiliary carrier.

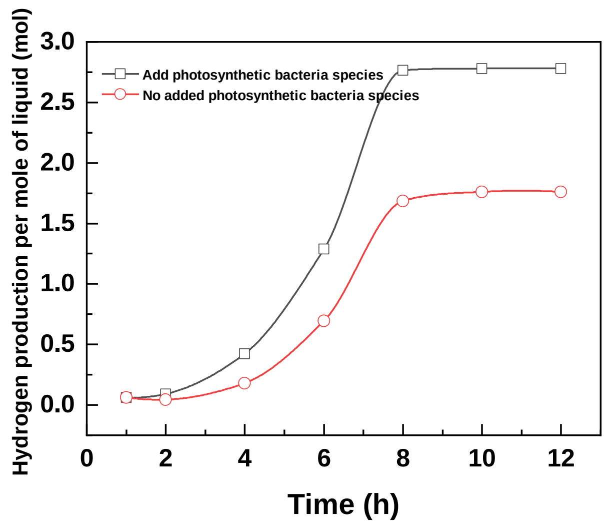


Fig. 22. Effect of photosynthetic strains on hydrogen production

The red curve clearly shows the trend of hydrogen production when hydrogenase bacteria are added alone. The data indicates that as time progresses, the amount of hydrogen produced gradually increases, but the growth rate is relatively slow between 1 to 6 hours. Specifically, by the 6th hour, the hydrogen production reaches 0.69 mol; and by the 8th hour, the production peaks, with 1 mol of liquid producing 1.76 mol of hydrogen after being acted upon by hydrogenase bacteria. The black curve depicts the hydrogen production effect when hydrogenase bacteria are combined with photosynthetic bacteria and auxiliary carrier. The results show that this combination significantly promotes the increase in hydrogen production at the early stage of the reaction, and the growth rate is more rapid. Specifically, by the 6th hour, the hydrogen production has reached 1.69 mol; and ultimately, the hydrogen production from 1 mol of liquid under the effect of this combination is as high as 2.78 mol, which is 1.58 times the amount produced by hydrogenase bacteria alone. Comparing the two, it is evident that the combination with photosynthetic bacteria and auxiliary carrier significantly improves the efficiency of hydrogen production. This discovery is expected to provide a new approach to reducing the cost of hydrogen production and further promote the vigorous development of the hydrogen energy industry.

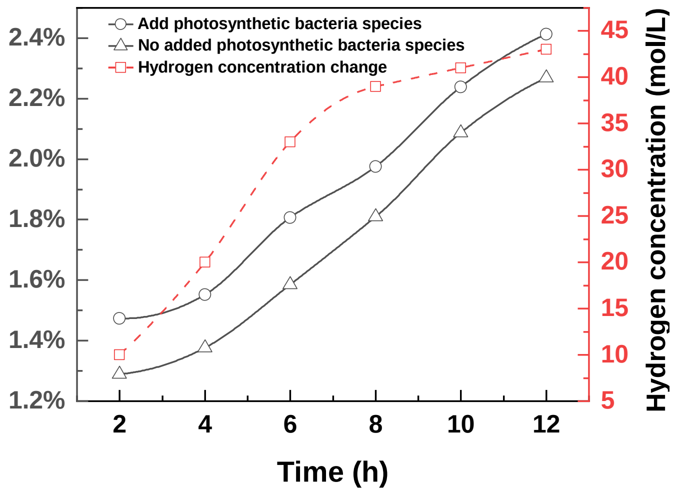


Fig. 23. The effect of photosynthetic bacterial strains on hydrogen production rate and the change in hydrogen concentration

Figure 23 demonstrates the improvement in hydrogen production efficiency achieved solely by adding hydrogenase bacteria, as well as the enhanced hydrogen production efficiency through the synergistic effect of hydrogenase bacteria and photosynthetic bacteria as a helper carrier, and presents the corresponding changes in hydrogen concentration. The results in the figure show that after adding the photosynthetic bacteria-helper carrier, the hydrogen production efficiency increases proportionally with time. After two hours, the hydrogen production efficiency without the addition of photosynthetic bacteria-helper carrier was only 1.23%, while with the addition of photosynthetic bacteria-helper carrier, the efficiency increased to 1.47%. It can be seen that at 12 hours, the hydrogen production efficiency with the addition of photosynthetic bacteria-helper carrier increased to 2.4%.

Future Work Planning and Prospects

In the upcoming work plan, the authors will study the characteristics of biogas hydrogen production, mainly conducting experimental tests and integrating data. Furthermore, to ensure the accuracy and reliability of the experimental results, the goal is to use numerical simulation methods to verify and analyze the experimental data. Through this dual approach, the goal is to gain a more comprehensive understanding of the potential and application prospects of photosynthetic bacteria in the field of biohydrogen production.

CONCLUSIONS

This article summarizes research progress on gas production from the fermentation process using livestock manure and straw as mixed raw materials and discusses the key factors affecting the differences in gas production rates. By combining simulated experiments with literature reviews, an analytical model for the differences in fermentation gas production rates was constructed, and based on this model, operational parameters for optimizing the fermentation process were proposed. Through analysis, this study presents the gas production variation curves under different raw material ratios and fermentation conditions, providing a scientific basis for the optimization of fermentation processes.

ACKNOWLEDGMENTS

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Author Contribution Statement

Enhai Liu: Writing -original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Gengyang Chen:** Supervision, Data curation. **Zhanghui Guo:** Writing - review and editing, Data curation. **Yine Jiang:** Reference for research, provide background materials. **Erdeng Dua; Biaocai Bai; Xiaoyong Wei; Pu Li *et al.*:** Review data and verify. The author team hereby declares that this article is written by the author team.

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