Effects of the liquid vapor oxygen transfer coefficient \((k_{L\alpha})\) on ethanol production from cassava residue and analysis of the fermentation kinetics

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**Abstract**

Cassava residue is the solid waste generated from the production of tapioca starch and has considerable reuse value. In this study, cassava residue was examined as a hydrolysate for ethanol production, and the effects of different liquid phase oxygen transfer coefficients \((k_{L\alpha})\) on the production of ethanol from cassava residue hydrolysates were studied. Based on analyses of dissolved oxygen and a set of optimal experimental schemes, dynamic models of cell growth and product synthesis were optimized, using MATLAB. When \(k_{L\alpha}\) was 85, fermentation was optimal; the ethanol titer reached 23.14 g L\(^{-1}\) at 72 h and cell growth reached 6.23 g L\(^{-1}\) at 96 h. Additionally, experiments were performed according to the dissolved oxygen curve obtained under these conditions. The resulting ethanol titer was 24.43 g L\(^{-1}\) (72 h) and the cell mass was 6.45 g L\(^{-1}\) (96 h).

**Introduction**

As one of the most ancient fermented products, ethanol has a long history of production; people had mastered wine production thousands of years ago [1]. In the modern industrial society, the applications of ethanol are more extensive. Grain is the main raw material in traditional ethanol fermentation. However, the cost of grain as a raw material is high; therefore, its use in ethanol production is limited [2].

Ethanol produced from biomass, and the main components of it including cellulose, hemicellulose, and lignin [3], as a new energy source is currently a major research area for sustainable development. The main product of cellulose hydrolysis is glucose, and hemicellulose hydrolysates are mainly xylose [4]. Microorganisms used for traditional ethanol fermentation, such as *Saccharomyces cerevisiae*, easily use glucose for alcohol fermentation, but are unable to use xylose [5]. Efficiently using xylose in fiber raw materials can increase the production of alcohol by 25% compared with that by the original materials [6]. Therefore, pentose-carbon sugar and hexose sugar fermentation for the production of alcohol is important for the application of fiber raw materials to the industrial production of alcohol [7].

Cassava is widely rooted in tropical areas and is used by the food industry as an industrial material. In 2016, total cassava production increased to 288.4 million tons.
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and increased by 18.7% from 2010. The expansion of cassava plantations in recent years should be attributed to an increased demand from industry for starch extraction and bioethanol fermentation. During the process of starch production, the pulverized cassava is screened through a mesh sieve to produce starch (<125 mm). The large particles remaining on the sieve are the cassava residue. It has been found that 1 kg of fresh cassava roots produces roughly 0.2 kg of starch, 0.4–0.9 kg of residue, and 5–7 L of wastewater.

The main components of cassava residue are carbohydrates, including starch, cellulose, hemicellulose, lignin, and small amounts of protein. It has considerable re-use value and many studies have examined its use for feed [8]. However, its large-scale industrial applications have not been examined. Cassava residue can be mixed with the yellow slurry generated during starch production to produce alcohol. However, the lack of optimized methods of fermentation and mash maturation, low alcohol content, production equipment required, labor-intensive process, and high energy consumption have limited large-scale production [9]. Many companies currently consider cassava residue a waste product, resulting in substantial waste [10]. Therefore, to facilitate various applications of cassava residue, biotechnology strategies to convert organic cassava waste into bio-energy, acetic acid, and other volatile fatty acid industrial chemicals are needed. This will not only address social goals related to sustainable development, but will also solve the problem of cassava residue disposal and promote improvement of agriculture and other related industries [11].

Oxygen availability plays a significant role in xylose metabolism by yeast. Oxygen has an important impact on cell growth, mitochondrial functioning, redox balance, and energy generation for xylose transport, and it also forms the balance between cell growth and ethanol formation. According to Jeffries et al., the fermentative activity of yeasts is induced as a response to oxygen limitation. However, there are few specific reports in the literature about the effect of oxygen availability on the efficiency of xylose-to-ethanol bioconversion by yeast.

Materials and Methods

Preparation of the cassava residue hydrolysate

Cassava residue was hydrolyzed using four enzymes, that is, amylase, glucoamylase, cellulase, and hemicellulose. The cassava residue included the following: starch, 19.36%; cellulose, 37.56%; hemicellulose, 26.35%; and other substances, 16.73%. The cassava residue mixture was an acidic suspension; therefore, an alkali was applied before hydrolysis to neutralize the solution. Samples were sterilized at 121°C for 30 min. The enzyme solution was added after the cassava residue solution was cooled to approximately 40°C and the pH was adjusted to 4.0. Samples were then maintained at 30°C on a 150 r min⁻¹ shaker [12].

After hydrolysis, the hydrolysate was centrifuged at 5000 g for 20 min. The supernatant and unhydrolyzed cassava residue were separated. The supernatant was used for subsequent fermentation. The contents of the cassava residue hydrolysate were determined by high-performance liquid chromatography. The hydrolysate content was as follows: glucose 21.21 g L⁻¹, xylose 12.36 g L⁻¹, arabinose 3.62 g L⁻¹, galactose 2.32 g L⁻¹, and mannose 1.02 g L⁻¹. To increase the concentration of sugar in the fermentation broth, the hydrolysate was concentrated, after which the glucose content was 40.51 g L⁻¹ and the xylose content was 21.52 g L⁻¹ [5].

Methods

Preparation of seed liquid

Slant medium (1 L), including glucose (20 g), yeast extract (10 g), peptone (20 g), and agar (20 g), as well as liquid medium (1 L), including glucose (20 g), yeast extract (10 g), and peptone (20 g), was used. Candida tropicalis Dyd001 (Hefei University of Technology) was used. Liquid medium was placed in an autoclave at 121°C for 20 min and cooled to room temperature. Yeast was stored in a 4°C refrigerator in a test tube in liquid medium, placed on a shaker (120 r min⁻¹, 30°C) for 13 h, and inoculated into fresh liquid medium at 10% inoculum for 13 h. Finally, samples were centrifuged at 7000 g for 8 min. The supernatant was discarded, and the suspension was supplemented with physiological saline [13].

Fermentation process

The seed liquid in the logarithmic growth phase was inoculated into the fermentation medium (fermentation medium: cassava residue hydrolysate). The effects of different liquid oxygen transfer coefficients (k_Lα) on fermentation were examined. The main factors that determine the k_Lα value are speed and ventilation [14]. The hydrolysate (7 L) was added to a 15-L Beilang tank (Sartorius, Gottingen, Germany). The following were added: ammonium sulfate (5 g L⁻¹), potassium dihydrogen phosphate (1 g L⁻¹), yeast extract (1 g L⁻¹), and magnesium sulfate heptahydrate (1 g L⁻¹). The sterilization conditions were 121°C for 15 min. After sterilization, samples were cooled to 32°C, followed by inoculation with the yeast suspension. The fermentation temperature was set to 32°C and the initial pH was adjusted to 4.0. This experiment used
Table 1. Experimental design and results.

(A) Experiments

| Experiments | Coded levels | Real levels |
|-------------|--------------|-------------|
| A       | B            | A (rpm) B (L min⁻¹) |
| 1       | 1 1          | 300 3      |
| 2       | -1 1         | 100 3      |
| 3       | 1 -1         | 300 1      |
| 4       | -1 -1        | 100 1      |
| 5       | 0 0          | 200 2      |
| 6       | 0 0          | 200 2      |
| 7       | 0 0          | 200 2      |

(B) Experiments

| Experiments | Variables | K_Lα initial (h⁻¹) | Results |
|-------------|-----------|--------------------|---------|
| A (rpm) B (L min⁻¹) | P (g L⁻¹) | Q_P (g L⁻¹ h⁻¹) |
| 1 | 300 3 | 120 | 20.66 | 0.287 |
| 2 | 100 3 | 75  | 22.90 | 0.318 |
| 3 | 300 1 | 85  | 23.14 | 0.321 |
| 4 | 100 1 | 35  | 17.42 | 0.242 |
| 5 | 200 2 | 61  | 21.32 | 0.296 |
| 6 | 200 2 | 60  | 21.10 | 0.294 |
| 7 | 200 2 | 59  | 21.03 | 0.289 |

(C) Source SQ df MQ F P value

| Source | SQ           | df | MQ     | F   | P value |
|--------|--------------|----|--------|-----|---------|
| Model  | 5.245E-003   | 3  | 1.748E-003 | 118.91 | 0.0013*  |
| A      | 1.056E-003   | 1  | 1.056E-003 | 71.84  | 0.0034*  |
| B      | 1.562E-004   | 1  | 1.562E-004 | 10.63  | 0.0471*  |
| A-B    | 4.032E-003   | 1  | 4.032E-003 | 274.26 | 0.0005*  |
| Residual | 4.411E-005  | 3  | 1.470E-005 | 1.39   | 0.3593   |
| Lack of Fit | 1.811E-005 | 1  | 1.811E-005 | 0.13   | 0.3593   |
| Pure Error | 2.600E-005 | 2  | 1.300E-005 | 0.26   | 0.6871   |
| Cor Total | 5.289E-003 | 6  |  |  |  |

A = Agitation speed; B = Aeration rate.

The composition of the cassava residue hydrolysate was determined by high-performance liquid chromatography (Agilent 1260; Santa Clara, CA, USA). The HPX-87 Sugar Analysis Column was used. The mobile phase was 5 mmol L⁻¹ H₂SO₄, and the solution flow rate was 0.6 mL min⁻¹. The column temperature was 65°C [16].

The ethanol content was determined by gas chromatography (Agilent 6890N) using the DB-624 column. The column temperature was 100°C (1 min), followed by an increase by 15°C min⁻¹ to 190°C (3 min). The column flow for high-purity nitrogen was 30 mL min⁻¹ (constant current). The gas flow was hydrogen at 300 mL min⁻¹ and air at 400 mL min⁻¹. The inlet temperature was 200°C and detector temperature was 250°C [17].

The cell weight was measured by drying at a constant temperature.

**Determinations of the oxygen transfer coefficient (K_Lα)**

The initial volumetric oxygen transfer coefficient (K_Lα) was determined using the dynamic gassing-out methodology (physical method). The uninoculated medium was deoxygenated using nitrogen to reduce the dissolved oxygen content to zero within the fermentor [18]. The agitation speed and air flow conditions were fixed immediately and the same conditions used in the fermentation experiments.
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were applied. The dissolved oxygen concentration was measured at 5 sec intervals throughout the aeration process using a serializable galvanic electrode (INPRO 6800 series; Mettler–Toledo, Columbus, OH, USA) connected to a Teflon-silicone-Teflon membrane. The equipment was previously calibrated at atmospheric pressure. The dissolved oxygen mass balance in the liquid phase can be expressed as follows:

$$\frac{dC_i}{dt} = k_i \alpha (C^* - C_i) - r_{o_2} = OTR - OUR,$$

where $C_i$ is the dissolved oxygen concentration and $C^*$ is the saturated oxygen concentration in the liquid. OTR represents the rate of oxygen transfer. When the oxygen uptake rate OUR = 0, the mass balance in the oxygen liquid phase can be simplified as follows:

$$\frac{dC_i}{dt} = k_i \alpha (C^* - C_i) - r_{o_2} = OTR.$$

The initial $k_i \alpha$ value was obtained based on the straight-line slope representing the oxygen mass balance integration in the absence of microorganisms:

$$\ln \left( 1 - \frac{C_i}{C^*} \right) = -k_i \alpha \times t.$$

**Kinetic model for fermentation of the glucose-xylose mixture**

Model establishment is a key step in the analysis of fermentation dynamics. For modern fermentation processes, effective model establishment often relies on the correct formula derivation and appropriate analysis software. After transformation, various parameters are converted to a linear form, and a regression analysis of the coefficients obtained for the parameters can be performed. Software is often used to establish models of fermentation kinetics. In this study, the model was established using MATLAB. The initial values for each parameter were given, and the valid input data were simulated until the parameter value was obtained. The complete model was established according to previously described methods [19].

Yeast growth is commonly described by the Verhulst–Pearl equation (i.e., the logistic equation) as follows [20]:

$$u = u_m \left( 1 - \frac{x}{x_m} \right).$$

Finally, the cell growth function can be derived as follows:

$$x = x_m \cdot \exp \left( u_m \cdot t + c \right) \cdot \frac{1}{1 + \exp \left( u_m \cdot t + c \right)}.$$

The derivative form of the cell growth function is as follows:

$$\frac{dx}{dt} = x_m \cdot u_m \cdot \exp \left( u_m \cdot t + c \right) \cdot \frac{1}{(1 + \exp (u_m \cdot t + c))^2},$$

where $u_m$ is the maximum-specific growth rate (h$^{-1}$), $x_m$ is the maximum cell concentration (g L$^{-1}$), $X$ is the cell concentration (g L$^{-1}$), $C$ represents empirical parameters, and $t$ is the fermentation time (h).

Product synthesis is more commonly described by the Luedeking–Piret model as follows:

$$\frac{dp}{dt} = K_1 \cdot \frac{dx}{dt} + k_2 \cdot X.$$

Finally, the following product synthesis function can be deduced:

$$p = -\frac{k_1 \cdot x_m}{1 + \exp (u_m \cdot t + c)} + k_2 \cdot \frac{x_m \cdot \ln (1 + \exp (u_m \cdot t + c)) + C'}{u_m},$$

where $p$ is the product concentration (g L$^{-1}$), $K_1$ is the product synthesis constant associated with the cell growth rate, $K_2$ is the product synthesis constant associated with cell growth, and $C'$ is the experimental parameter [21].

**Results and Discussion**

**Fermentation results for various initial $k_{L\alpha}$ values (72 h)**

The results obtained for different agitation speeds and aeration rates are shown in Table 1B. Higher agitation speed and aeration rate were associated with higher $k_{L\alpha}$ values. Extensive research and production practice has indicated that the factors that affect the $k_{L\alpha}$ value are the agitation speed and aeration rate, physicochemical properties of the fermentation broth, foam state, shape of the air distributor, and structure of the fermentor. However, the main factors are the agitation speed and aeration rate. The stirrer in the fermentor maintains a uniform temperature and nutrient concentration in the fermentor, dispersing the air introduced into the fermentation broth in small bubbles to increase the gas–liquid contact area and the turbulence of the fermentation broth, thereby increasing the $k_{L\alpha}$ value. An increased aeration rate will increase $k_{L\alpha}$, but when it is too large, the agitator exhibits the “air pan” phenomenon, and $k_{L\alpha}$ no longer increases. An aeration rate that is too large is not conducive to the dispersion and maintenance of air in the tank, leading to the concentration of the fermentation solution, which affects the transmission of oxygen. However, when the aeration rate is too low, metabolic
emissions cannot be discharged quickly and oxygen transfer is affected [22].

The parameter values for the broth obtained after 72 h of fermentation under each condition are shown in Table 2. The ethanol titer was up to 23.14 g L\(^{-1}\) when \(k_L \alpha\) was 85, and the lowest titer of 17.42 g L\(^{-1}\) was obtained for \(k_L \alpha\) of 35. The highest growth rate \(\mu_m\) was 0.094 h\(^{-1}\) when \(k_L \alpha\) was 120, indicating that a high aeration rate and agitation speed were suitable for the metabolic activity of yeast. The cell weight at 72 h was approximately 5.6 g L\(^{-1}\), indicating that yeast growth was good under different conditions; the growth of the cells was only slightly inhibited when \(k_L \alpha\) was 35.

The yeast growth curve, indicating that yeast growth was high in glucose or xylose, is shown in Figure 1. After approximately 12 h, the logarithmic growth phase was reached. Figure 2A shows the change in glucose content during the fermentation process. Glucose is the most important carbon source for yeast. Glucose use was most efficient when \(k_L \alpha\) was 35. For low \(k_L \alpha\) values, yeast cannot engage in normal aerobic metabolism, and anaerobic respiration is necessary to maintain life activities. However, the anaerobic respiration capacity is small; accordingly, large amounts of glucose must be consumed. Before 60 h, glucose consumption was fast. At 60 h, the glucose content was only the initial sugar content of 12.5–25%. At 72 h, fermentation was close to the end point at \(k_L \alpha\) values of 35 and 85. The amount of residual sugar was almost zero. However, the residual sugar content for the remaining \(k_L \alpha\) conditions was close to 10% near the end of the fermentation period at 84 h.

The change in xylose content during the fermentation process is shown in Figure 2B. The use of xylose has always been a major problem in ethanol fermentation. Strains capable of xylose fermentation from ethanol are rare. Additionally, the efficiency of xylose alcohol production is typically very low. In our analysis, the rate of xylose use in the first 36 h was very low. In the presence of glucose, yeast first uses glucose before using xylose. Between 48 and 72 h, the use of xylose was very fast. At this point, xylose became the main source for yeast fermentation. The rate of xylose utilization was similar among different \(k_L \alpha\) conditions. At 72 h, near the end of the fermentation period, the amount of residual xylose sugar was <5%.

The cell weight curve during the process of fermentation is shown in Figure 2C. Cell growth was fast for \(k_L \alpha\) of 120, and \(u_m\) was 0.094 h\(^{-1}\). Cell growth was slowest for \(k_L \alpha\) of 35, and \(u_m\) was 0.069 h\(^{-1}\). Although the rate of cell growth was different among different \(k_L \alpha\) values, the rate of growth in the first 12 h was significantly higher than that after 12 h. Additionally, at 72 h, the cell weight was approximately 5.6 g L\(^{-1}\) because yeast at 12 h was in the logarithmic growth phase. The maximum cell weight was 6.23 g L\(^{-1}\) for an initial \(k_L \alpha\) of 85, and this was significantly higher than the maximum cell weight under other \(k_L \alpha\) conditions.

The change in ethanol titer during the fermentation process is shown in Figure 2D. Ethanol was the target product.

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**Table 2.** Parameter estimates for fermentation results for various initial \(k_L \alpha\) values.

| Parameters                           | \(k_L \alpha\) initial (h\(^{-1}\)) |
|--------------------------------------|-----------------------------------|
|                                      | 35      | 60      | 75      | 85      | 120     |
| Residual sugars concentration of glucose (g L\(^{-1}\)) | 1.23    | 6.32    | 4.36    | 0.85    | 2.35    |
| Residual sugars concentration of xylose (g L\(^{-1}\))  | 1.35    | 1.22    | 2.35    | 3.56    | 2.98    |
| Cell concentration (g L\(^{-1}\))     | 5.12    | 5.86    | 5.69    | 5.74    | 5.68    |
| Ethanol production P (g L\(^{-1}\))   | 17.42   | 21.10   | 22.90   | 23.14   | 20.66   |
| Ethanol productivity Q_P (g L\(^{-1}\) h\(^{-1}\)) | 0.242   | 0.293   | 0.318   | 0.321   | 0.287   |
| Biomass yield Y_{x/s} (g g\(^{-1}\))  | 0.086   | 0.108   | 0.103   | 0.100   | 0.100   |
| Ethanol yield Y_{p/s} (g g\(^{-1}\))  | 0.293   | 0.387   | 0.414   | 0.401   | 0.364   |
| \(\mu_{max}\) (h\(^{-1}\))             | 0.069   | 0.078   | 0.070   | 0.074   | 0.094   |

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**Figure 1.** Growth curve of yeast.
The maximum ethanol titer was obtained when $k_L\alpha$ was 85. The maximum ethanol titer of 23.14 g L$^{-1}$ was obtained at 72 h. The conversion rate of sugar to alcohol was 0.401 g g$^{-1}$ (the theoretical titer of yeast-metabolized xylose was 0.46 g ethanol g$^{-1}$ xylose and the glucose ethanol fermentation titer was 0.51 g ethanol g$^{-1}$ glucose) [23]. The minimum ethanol titer was 17.42 g L$^{-1}$ at a $k_L\alpha$ of 3 (72 h). At a lower agitation speed and aeration rate, yeast growth is poor and alcohol production is low. However, irrespective of the initial $k_L\alpha$ conditions, the final fermentation ended near 72 h; after 72 h, the ethanol content decreased because the yeast required energy to maintain growth. The amount of residual sugar was almost zero because all of the yeast consumed ethanol to obtain energy.

**Response surface analysis**

As shown in Table 1C, A (the agitation speed), B (the aeration rate), and their interaction had significant effects on ethanol titer. The missing items were not significant. The effect of the interaction between A and B is summarized in Figure 3A and was essentially parabolic, with a maximum point, indicating that the interaction had a significant effect on the response variable. The agitation rate is related to the uniformity of the temperature and nutrient concentration in the fermentation tank; air entering the fermentation broth is dispersed in small bubbles to increase the gas-liquid contact area and strengthen the turbulence of the fermentation broth, thereby reducing the mycelial knot and improving the $k_L\alpha$ value. Accordingly, an appropriate increase in agitation speed and reduction in aeration rate improve the oxygen supply capacity of the fermentation tank.

**Dissolved oxygen analysis**

The initial dissolved oxygen quantity was set to 100%, and the plot in Figure 4 shows the change in dissolved oxygen for a $k_L\alpha$ of 85.
As shown in Figure 3B, the amount of dissolved oxygen declined rapidly in the first 24 h and tended to decline less rapidly after 60 h. According to this capacity curve, a series of experiments was performed to simulate similar dissolved oxygen curves. The simulation results are as follows.

To obtain a dissolved oxygen curve similar to that for a $k_{L}a$ of 85, the amount of dissolved oxygen was controlled in stages by adjusting the agitation and aeration rates. Figure 3C shows the amount of dissolved oxygen in the phased control and Figure 3D shows a curve for the change in agitation and aeration coupling conditions. These results indicate that an increase in pre-aeration and decrease in agitation help to increase the dissolved oxygen level, which is beneficial to the growth of yeast. As the dissolved oxygen decreases, the aeration rate gradually decreases, and the agitation speed increases slowly. The agitation speed increased by nearly 300 r min$^{-1}$ and the aeration rate was reduced to 1.0 L min$^{-1}$ in the later stage of fermentation. At this time, it was beneficial to reduce the viscosity of the fermentation broth and increase fermentation. The final cell concentration was 6.45 g L$^{-1}$ and the ethanol concentration was 24.43 g L$^{-1}$.

**Fermentation kinetics analysis**

**Cell growth kinetics**

A logistic regression analysis was used to estimate $u_{m}$ and the parameter $c$, $u_{m} = 0.0759$, $c = -2.155$. The growth kinetics equation was used for condition verification and simulation of the curve of the model as follows.

As shown in Figure 4A and B, although this model reflects the growth of yeast in the fermentation process, the relative error and the absolute error were still large. Therefore, to improve the practical application of the
model, Figure 4E shows the MATLAB program used to optimize the cell growth to accurately reflect the final fermentation process. The final optimization parameters were $u_m = 0.052$ and $c = -1.509$. Thus, the final parameters were inserted in the cell growth kinetics equation as follows:

$$x = \frac{6.45 \cdot \exp(0.052 \cdot t - 1.509)}{1 + \exp(0.052 \cdot t - 1.509)}.$$  

**Product synthesis kinetics**

A logistic regression analysis using the Luedeking–Piret model provided the following parameter estimates: $K_1 = 6.563$, $K_2 = -0.026$, and $C' = 34.826$. Conditional equations for product synthesis were verified and the curve of the ethanol titer was obtained.

As shown in Figure 4C and D, the model reflects product synthesis in the fermentation process and although
the absolute error was small, the relative error was still large. Therefore, Figure 4F shows the model optimized using MATLAB to reflect product synthesis in the final fermentation process. The final optimization parameters were as follows: \( K_2 = 6.521, K_3 = -0.0253, \) and \( C' = 34.57. \) These parameters were inserted in the product synthesis kinetic equation as follows:

\[
P = \frac{-6.521 \cdot 6.45}{1 \cdot \exp (0.052t - 1.509)} - 0.025 \cdot \frac{6.45}{\ln (1 \cdot \exp (0.052t - 1.509)) + 34.57}.
\]

**Conclusion**

In this study, the effects of different liquid oxygen transfer coefficients (\( k_{L\alpha} \)) on ethanol production from cassava residue hydrolysates were determined. The agitation speed and the aeration rate have a great effect on \( k_{L\alpha} \), and the interaction is obvious. The maximum ethanol titer was obtained when \( k_{L\alpha} \) was 85. The maximum ethanol titer was obtained at 72 h, with an ethanol titer of 23.14 g L\(^{-1}\). The conversion rate of sugar to alcohol was 0.401 g g\(^{-1}\) (the theoretical titer of yeast-metabolized xylose was 0.46 g ethanol g\(^{-1}\) xylose, and the glucose ethanol fermentation titer was 0.51 g ethanol g\(^{-1}\) glucose). The dissolved oxygen curve was simulated to inform a set of experiments. The resulting ethanol titer was 24.34 g L\(^{-1}\) (72 h) and the cell concentration was 6.45 g L\(^{-1}\) (96 h). The coupling curve of the agitation speed and the aeration rate were obtained. Initial increases in the agitation rate and reductions in the agitation speed and subsequent improvements in the agitation speed and reductions in the aeration rate improved the ethanol titer. Finally, a kinetic analysis was performed, and dynamic cell growth and product synthesis models were optimized using MATLAB.

**Acknowledgments**

This study was supported by the Science and Technology Plan Projects of Anhui Province (No: 15CZZ03100) and the National Natural Science Foundation of China (No: 31601465).

**Conflict of Interest**

The authors declare no conflict of interest.

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