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The mass transfer of sugar in sweet sorghum stalks for solid-state fermentation process

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HIGHLIGHTS

- A modified kinetic model was developed to describe the sugar transfer of sweet sorghum.
- The modified kinetic model was the first related to the structure of sweet sorghum stalks.
- The modified kinetic model was well fitted to the extraction process.

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ABSTRACT

Solid-state fermentation of sweet sorghum stalk is a cost-effective technology for bioethanol production. Sugar transfer from the interior of sweet sorghum plant cell to the surface is one of the key factors affecting the fermentation process because the system takes place in the absence of free water. Mass transfer of sugar from the interior of the sweet sorghum to the surface of substrates is mainly driven by the sugar concentration gradient. A mass transfer model based on three steps process was developed. Taking into consideration of the different tissue structures of sweet sorghum stalks, a two simultaneous first-order kinetic model of sugar transfer with two parameters characterizing the tissue structure difference was developed to describe the sugar transfer process in sweet sorghum. Solid-liquid extraction experiments were used to gather experimental kinetics data of sugar transfer. Four factors impacting the mass transfer of sugar including particle sizes, stirring speed, temperature, and osmotic pressure were investigated. The results showed that the newly modified model fitted well the kinetics of sugar transfer in different varieties of sweet sorghum. This model could be helpful in optimizing solid state fermentation of sweet sorghum stalks. Moreover, the kinetic model with the added structural parameters based on difference in plant tissue structure can also be used to describe the extraction of any active substance from types of feedstocks with similar chemical compositions and biomass structures.

1. Introduction

The depletion of fossil fuel and environmental concerns has focused worldwide attention on research for energy crops suitable for ethanol production [1–3]. Sweet sorghum is attractive as a non-food feedstock for biofuel production because it is easily adaptable to diverse climate and soil conditions [4,5]. It is a *C*4 plant characterized by high photosynthetic efficiency, high fermentation sugars and high yield of green biomass (with 20–30 dry tons/ha). It has low requirements for fertilizer, high efficiency in water usage (1/3 that of sugarcane and 1/2 that of corn), and a short growth period of 120–150 days [6].

Solid-state fermentation (SSF) has become a promising technology to convert biomass into bioethanol due to its relatively simple process, low energy consumption and low wastewater production [5,7]. However, the SSF process has limits due to its particular operational conditions [8]: it is a heterogeneous system without free water, and growth of contaminated microorganisms.

The performance of SSF is affected by many factors, such as particle size, temperature, stirring speed and moisture [8]. In the SSF technology, each individual sweet sorghum particle could be regarded as a single fermentation unit. The mass transfer of sugar

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in each unit is critical for optimization of the production process. Unfortunately, the mass transfer of sugar in this system has not been studied.

Although no free water was observed in the SSF technology, mass transfer of sugar occurred in particles with water moisture above 70% [9]. In each particle unit, the sugar diffusion is driven by the sugar gradient between the interior and exterior of the particle. Because the apparent mass transfer of sweet sorghum sugar was originated from the adduct of each micro unit, the kinetic of sugar transfer in SSF process of sweet sorghum was investigated by solid-liquid extraction experiments. In the present paper, various factors impacting the sugar transfer from sweet sorghum cells to the surface in SSF were studied. These factors included particle size, stirring speed, osmotic pressure and temperature.

2. Materials and methods

2.1. Sweet sorghum

Two sweet sorghum varieties were used. Chuntian # 1 was harvested in Cangzhou, Hebei. H110 was harvested in Shijiazhuang, Hebei. Leaves and husks were removed from the fresh stalks by hand and the stalks were stored at ambient temperature with bacteriostatic agent for long-term storage. All sweet sorghum were gifted by the Institute of Millet of Hebei Academy of Agriculture and Forestry. The sweet sorghum stalks without the bark were cut into cylinder with heights of 2, 4, 6, 8, 12, 16 mm. The diameter of cylinder was about 22 ± 2 mm.

2.2. Analytical method

Total sugar contents (glucose, fructose and sucrose) were analyzed by flowing injection analyzer (FIA) (AA3, SEAL, Germany). Thirty grams of sweet sorghum particles were stirred in a blender with 300 mL distilled water at room temperature for 2 min. The mixture was sonicated for 15 min. The clear supernatant liquid was used to measure the concentration of sugar. The experiments were carried out in triplicates.

2.3. Solid-liquid extraction experiments

A beaker with 300 mL water was preheated for 30 min in a water bath at the experimental temperature. The sweet sorghum particles (20 g) were added to the beaker, incubated at the stated experiment temperature until the end of the extraction experiments. The beaker was sealed with a piece of plastic film to avoid water lost during the experiment. One mL of solution was taken out to determine the sugar concentration at the indicated times. Experimental conditions were varied as stated with six particle sizes (2, 4, 6, 8, 12 and 16 mm), four stirring speeds (100, 250, 500 and 750 Rpm), four kinds of osmotic pressure (1.2, 1.4, 1.9, 2.2 $\times$ 10^3 KPa) and five temperatures (20, 30, 40, 50 and 60 °C). All experiments were repeated in triplicates. Extraction kinetics of sugar from sweet sorghum was monitored by sugar concentration in the solution.

2.4. Kinetic model

The kinetic models used in this study is list below.

Two simultaneous first-order kinetic model was described by the following equation [10–12]:

$$C^* = C_1^*(1 - e^{-k_1 t}) + C_2^*(1 - e^{-k_2 t}) \quad (1)$$

where $C^* = C/C_\infty$, C was the solute concentration in the solution during the extraction process, C_∞ was the equilibrium solute concentration, $C_1{}^* = C_1/C_\infty$, C_1 was the final solute concentration in the solution due to the broken and surface cells alone, $C_2^* = C_2/C_\infty$, C_2 was the final solute concentration in the solution due to the intact cells alone, k_1 (min^{-1}) was the rate constant for broken and surface cells and k_2 (min^{-1}) was the rate constant for the intact cells.

2.5. Statistical analysis

The model parameters were determined by non-linear regression to the experimental data using data analysis software Origin 8.5(Origin Lab Corporation, USA).

3. Results and discussion

3.1. Model of sugar transfer in the solid-state fermentation of sweet sorghum

In contrast to liquid fermentation, there is no continuous liquid phase in SSF. SSF involves the growth of microorganisms on moist substrates in the absence of free water, which makes the system quite different from submerged fermentation (SmF) [13]. In particles with water moisture above 70%, sugar transfer from the interior of sweet sorghum plant cell to the surface is driven by sugar concentration gradient. The schematic diagram of sugar transfer in a sweet sorghum particle was shown in Fig. 1. From the microscopic view, the sugar transfer from the interior to the surface of substrates through the plant cell membrane is driven by the concentration gradient. The sugar transfer from each particle takes places in three steps. The first one is the sugar migration from the interior to the exterior of the plant cell. The second is moving into the interface between the solid substrate, the plant cell wall, and the liquid phase on the surface of the plant cell. This interface is defined as the liquid membrane. The third is dissolving into the bulk liquid phase on the surface. However, it is so thin liquid film. Although the system seems to be complex, the kinetic parameter is described by a simple diffusion model because the driven force of the entire system is sugar concentration gradient.

The yeast, *Saccharomyces cerevisiae*, grows in the thin liquid film at the particle surface and reproduces asexually by budding. It does not extend into the gaseous region or inside of substrate like other fungi [14]. Fermentable sugars are extracted continuously from sweet sorghum substrate and consumed simultaneously by yeast.

In SSF, sugar consumption by the propagation and metabolism of yeast creates the concentration gradient, which drives the continuously sugars diffusion to the surface of the particles. In this

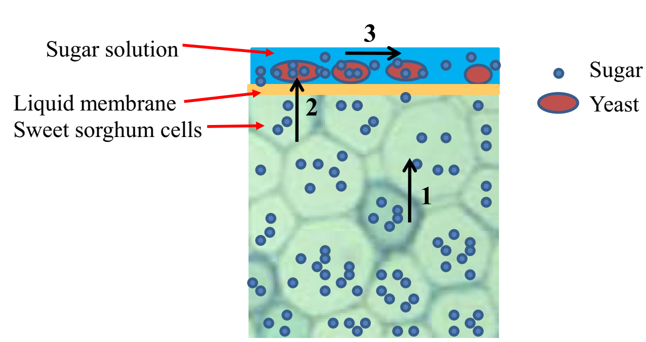

Fig. 1. Structure of SSF systems at the microscopic scale and local mass transport processes for sweet sorghum fermentation process. The processes occurring are 1, sugar transferring from the interior of plant cell to the surface of substrates; 2, sugar diffusion through liquid membrane and consumed by yeast. 3, bulk liquid phase diffusion.