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Recovery of yam mucilage from the yam starch processing wastewater by using a novel foam fractionation column

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A B S T R A C T

It is difficult to separate a surface-active material from a wastewater with a high viscosity by foam fractionation. In order to solve the problem, a novel foam fractionation column with vertical sieve tray (VST) placed in the foam phase was developed for effectively recovering yam mucilage from the viscous yam starch processing wastewater. The effects of design parameters of VST on its foam drainage properties were investigated. The results showed that the suitable design parameters of VST were the number of trays in VST 5, the number of vertical sieve caps in each tray 4 and the number of sieve pores in each cap 28. Meanwhile, the suitable operating conditions were also determined. Under the conditions of pH 6.0, temperature 25 °C, volumetric air flow rate 50 mL/min and loading liquid volume 500 mL, the enrichment ratio and recovery percentage of yam mucilage were 5.70 and 91.21%, respectively, which were 3.77 and 1.55 times higher than those in the control column. The above results indicated that the novel foam fractionation column with VST in the foam phase could simultaneously improve the enrichment ratio and the recovery percentage of yam mucilage by strengthening foam drainage. This work was aimed at developing a novel foam fractionation column for effectively recovering a valuable byproduct from a viscous food processing wastewater and further facilitating the industrial application of foam fractionation in food industry.

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1. Introduction

Yam (*Dioscorea* spp., *Dioscoreaceae*) is a worldwide cash crop and its tuber is rich in starch and mucilage [1]. Recently, yam starch has gained the increasing attention of nutritionists and food flavorists owing to its desirable properties, such as extreme stability at a low pH, a high amylose content (26.5 g/100 g) and a restricted swelling [2,3]. During the process of yam starch production, a large volume of the wastewater with a high viscosity is yielded [4]. At present, the wastewater has been usually discharged to a sewage treatment plant and treated by biochemical methods, resulting in a massive loss of many potential high-value by-products. The high viscosity of the wastewater is primarily caused by yam mucilage, which is an important bioactive material in yam tuber. Many clinical studies have indicated that yam mucilage can exhibit various pharmacological activities, such as anti-oxidant, anti-cancer, anti-atherosclerotic and anti-aging ones [5–7]. Yam mucilage has many potential applications in food industry based on its special properties of high viscosity, emulsifiability and water-holding ability [8]. Therefore, it is significant to develop a cost-effective technology for recovering yam mucilage from the yam starch processing wastewater.

Foam fractionation is a promising separation technology and it uses bubbles as the media for achieving the separation of desired materials based on their differences in adsorption performance on the gas-liquid interface [9]. Foam fractionation is regarded as a potential green separation method alternative to solvent extraction owing to its outstanding advantageous, such as simple equipment, free reagents and easy engineering scale-up [10,11]. During the process of foam fractionation, a gas is introduced into the bulk liquid phase to generate bubbles. The surface-active materials rapidly adsorb onto the gas-liquid interface and tend to lower the surface tension between gas and liquid. Then, the generated bubbles create an emerging foam phase above the bulk liquid phase. With the foam rising, the entrained liquid drains back into the bulk liquid phase due to gravity and capillary forces [12]. Eventually, the dry foam is collected at the top of a foam fractionation column and the surface-active materials are effectively concentrated in the foamate, which is the obtained solution by collapsing the foam [13]. It is clear that interfacial adsorption and foam

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drainage are two essential factors of foam fractionation. Yam mucilage is composed of soluble mannan-like carbohydrate-protein (glycoprotein) and it can be adsorbed on the gas-liquid interface spontaneously without any addition of surfactants [14]. Thus, it is feasible to recover yam mucilage from the yam starch processing wastewater using foam fractionation for realizing the reduction of downstream processing requirements.

At present, there have been several studies on strengthening foam drainage by increasing temperature, changing the shape of foam fractionation column or adding internal components [15–17]. The increase of temperature could decrease the viscosity of a solution, thereby enhancing the liquidity of the interstitial liquid in Plateau borders and junctions [18]. Unfortunately, a high operating temperature would not only lead to the denaturation of a surface-active biomaterial, but also increase additional costs [19]. Cox et al. [20] have proposed that the traditional foam fractionation column with a certain angle inclined from vertical direction could decrease the cross-flow contact time between the rising foam and the entrained liquid, thereby strengthening foam drainage. Jiang et al. [21] designed a foam fractionation column with a 50° inclined channel to recover whey soy proteins from soy whey wastewater and the enrichment ratio of whey soy proteins approximately increased by 80%. Based on the foam-flow phenomena in sudden expansions and contractions found by Deshpande and Barigou [22], Linke et al. [23] developed a column with a sphere-shaped channel (SSC) for recovering exo-lipases from a growing fungus (*Pleurotus sapidus*). In SSC, the continuous expansions could significantly decrease the superficial flow rate of the rising foam, thereby strengthening foam drainage. As far as the space utilization is concerned, these abnormal columns will be limited in industrialization. In contrast, the development of novel internal components is more reasonable to strengthen foam drainage.

It was reported that the internal components, such as spiral [24] and wall [25], could induce interior channels to decrease the liquid holdup of the rising foam, but their effects of strengthening foam drainage were limited in the treatment of _viscous wastewater because its high viscosity increased the flow resistance. In order to solve this problem, a new foam fractionation column was used for recovering yam mucilage from the wastewater. In the column, vertical sieve tray (VST) with the downcomers was placed in the foam phase for improving the separation performance. First, the properties of VST with different design parameters (including the number of trays in VST, the number of vertical sieve caps in each tray and the number of sieve pores in each cap) were evaluated. Subsequently, the effects of operating parameters (including pH, volumetric air flow rate, temperature and loading liquid volume) on the enrichment ratio and recovery percentage of yam mucilage were investigated for effectively recovering yam mucilage. The objective of this work was expected to provide some new ideas for recovering a valuable byproduct from the viscous food processing wastewater and facilitate the industrial application of foam fractionation in food industry.

2. Materials and methods

2.1. Materials

Tubers of common yam rhizome (*Dioscorea* spp., *Dioscoreaceae*) were obtained from the local market in Hongqiao district, Tianjin, China. Hydrochloric acid and sodium hydroxide were purchased from Yingdaxigui Reagent Factory Co. Ltd., Tianjin, China. Coomassie brilliant blue G-250 was purchased from Beijing Dingguo Biotechnology Co. Ltd., China.

2.2. Process of yam starch production

Yam starch production was conducted using the method of Daiuto et al. [4]. The yam tubers were cleaned, peeled, sliced in sequence and then 58 g of the sliced yam tubers were crushed into the homogenate by adding 1 L of distilled water. The homogenate was filtrated by using a 250 μm sieve and kept at 4 °C for 8 h. The upper layer was the wastewater containing yam mucilage which would be treated in this work and its viscosity was 2.1 mPa·s.

2.3. Equipment

The schematic diagram of VST foam column used in this work is illustrated in Fig. 1. The VST was composed of a transparent polycarbonate plate of 2 mm in thickness and 50 mm in diameter with several vertical sieve caps of 14 mm in diameter and 50 mm in height. Each vertical sieve cap was drilled for a few rows of the aligned pores of 3 mm in diameter, each row had 7 pores and the center distance between the adjacent two pores was 7 mm. Besides, the downcomers of 10 mm in diameter and 70 mm in height were installed on both sides of the plates in order to form a liquid backflow system within the foam phase. And the assembly process should guarantee the sealing performance between the internal and the foam column.

The control foam column without any internals and the experimental column with VST were all constructed by a transparent plexiglass tuber of 1000 mm in height and 50 mm in internal diameter. A sintered glass filter of 125 μm in average pore size was installed at the bottom of the foam column as the gas distributor. A certain volume of the wastewater containing yam mucilage was loaded into the column and the air was bubbled through the sparger into the column by an air compressor. A rotameter was used to monitor and control volumetric air flow rate. In this work, the operation parameters of pH, temperature, volumetric air flow rate and loading liquid volume were in the ranges of 4.0–8.0, 25–60 °C, 25–125 mL/min and 300–700 mL, respectively. All experiments were operated in batches for 90 min.

2.4. Measurement of viscosity

The viscosity of the wastewater containing yam mucilage was measured by using a NDJ-5S rotational viscometer (Jingke Scale Corporation, Shanghai, China) at 60 rpm on Rotor No. 0 and 25 °C for 2 min [8].

2.5. Measurements of foamability and foam stability

Foamability and foam stability of the wastewater containing yam mucilage were determined by using a DFA 100 foam analyzer (KRÜSS, Germany) [26]. First, 100 mL of the wastewater were loaded into a transparent glass column of 40 mm in inner diameter. Then, a foam was generated by bubbling the air through a gas distributor of 16–40 μm in pore diameter into the column at a volumetric air flow rate of 0.2 L/min for 10 s, and then the maximum foam height (H) and the half-life period ($time_{1/2}$) for foam decay were recorded by the foam analyzer for evaluating fomability and foam stability, respectively.

2.6. The correlation between wastewater viscosity and yam mucilage concentration

On the basis of the process of yam starch production, the viscosity of the wastewater mainly depended on the concentration of yam mucilage. The linear-fitting equation is expressed as follow.

$$\mu = 0.04815C_{yam} + 0.0163,\ R^2 = 0.9997, \tag{1}$$

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