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Original Research Paper

Effects of solvents on characteristics of crystalline lactose extracted in ternary and quaternary systems

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ABSTRACT

In a technique referred to as lactose extractive crystallisation, a volatile solvent was added to a solution of lactose dissolved in water. As this second solvent was miscible in water, its presence in the saturated or supersaturated lactose solution would reduce the lactose solubility and hence lactose crystals were formed and grew in the ternary system lactose–ethanol–water. It was found that selecting ethanol as a second solvent could produce needle-shaped crystals having the lowest median size of 8 μm, and β-lactose content up to 60% at 60 °C. On the other hand, using two miscible solvents, one non-volatile and one volatile, such as by adding ethanol to the ternary system, lactose–water–glycerol, crystals having large needle-like or trapezoidal shape and β-lactose content up to 90% could be made at 70 °C. The triangle diagram comparing the solubility of lactose in the glycerol and ethanol aqueous solutions at equilibrium and at different temperatures is presented for the first time. Based on this diagram, it is suggested that the weight ratios of two solvents used and reaction temperatures could be manipulated to produce lactose crystals with different characteristic properties.

1. Introduction

Cooling crystallisation processes are commonly applied in dairy factories to manufacture α-lactose monohydrate. Edible grade lactose is a product of single batch crystallisation. Refined and pharmaceutical grade lactose is made commercially by purifying and recrystallising edible grade. The particles from a single or double crystallisation usually have median sizes in the range of 100–300 μm, pyramid- and tomahawk-shaped crystals and less than 5% of the lactose content in the β-form. The product is then milled into fine powder to be used as an ingredient in ice-cream, infant formula and other foods but cannot be used as seed crystals or drug carriers because milling damages the crystal shape and forms amorphous lactose which predisposes the product to caking.

For these food and pharmaceutical applications different approaches have been investigated to produce lactose crystals having a smaller average size without milling, a different morphology from pyramid or tomahawk shape and a higher content of β-form crystal (which dissolves more rapidly in water and is sweeter than the α-form). One of these approaches is mixing a volatile solvent with a saturated or supersaturated solution of lactose and water. As this second solvent is miscible in water, lactose solubility is decreased and lactose will crystallise. Food grade ethanol or propan-2-ol (isopropyl alcohol), is preferably used because any residual alcohol remaining in the crystalline products at the reported concentration would not cause any toxic effect. The approach referred to as "alcoholic crystallisation" however has not attracted the attention of lactose manufacturers due to the requirement of solvent recovery and more importantly accommodating the flammable solvents used at a high reaction temperature. To reduce the hazard of the process, glycerol, a non-volatile solvent for the first time is investigated here to replace a part of alcohol used in the process. Glycerol is naturally present in some dairy products and has been used in the manufacture of food, dairy and pharmaceutical products. More importantly glycerol greatly affects the mutarotation equilibrium, i.e., the equilibrium ratio of α and β lactose, which results in a product with a high content of β-form crystals.

The alcoholic approach was first applied seventy years ago to extract lactose from the whey powder [1]. More than 50 years later, Singh et al. [2] applied the same idea to the production of edible and pharmaceutical grade α-lactose from ultrafiltered (UF) sweet whey permeate at room temperature using ethanol. Dalziel [3] and recently Jones [4] focused more on the effect of different types of alcohol and reaction temperatures on the yield and some characteristic properties of extracted lactose. Vu et al. [5,6] discussed in addition to ethanol, the use of ultrasonic power and

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various solvents, supersaturation and cooling strategies in making fine particles. This work is the first to present the effects of non-volatile and volatile solvents: glycerol–ethanol on lactose solubility and characteristic properties such as average size, morphology and content of the β-form of lactose extracted from ternary and quaternary systems in isothermal and cooling crystallisations.

2. Experimental methods

2.1. Materials

Pharmaceutical grade α-lactose monohydrate used in this work was purchased from Wyndale, (Lactose NZ Ltd., Hawera, New Zealand). Reagent grade glycerol (greater than 99.0% purity) was purchased from Sigma–Aldrich. Absolute ethanol (99.9%) was supplied by Q store, Australia. Water used in the experiment was deionised and treated with a Millipore unit.

2.2. Experimental procedure and equipment

2.2.1. Solubility measurement

Aqueous solutions of ethanol or glycerol at different mass percentages from 0% to 80% were prepared in advance to ensure the same feeds were used in the experiments at different initial operating conditions. Lactose powder was dried in the oven at 70 °C for 24 h before adding to the prepared aqueous solutions. The mixtures were shaken in the C24KC refrigerated incubator shaker (New Brunswick Scientific) or in the Jalabe SW22 water-bath, set at 150 rpm and desired temperatures (from 25 °C to 70 °C) for 24 h and were left to stand for 3 h before filtering using glass filters. To measure the solubility of lactose in the mixture water–ethanol or water–glycerol, a known mass of the filtrate was put in the aluminium dish then dried in the oven at 70 °C for more than 24 h until the weight of the dish did not change. The difficulties arising from glycerol in this method are described in Section 3 of the paper. For comparison, two following analyses were performed. The concentration of the filtrate in terms of °Brix was measured, using the Bellingham and Stanley RF3 340 automatic refractometer. The filtrate was analysed for lactose content using the Shimadzu HPLC (high pressure liquid chromatography) system. Details of the equipment and method are described below. In this case the sum of the areas under both α- and β-lactose peaks was compared with the areas given by the calibration curve to determine the total lactose content.

2.2.2. Isothermal and cooling crystallisation of lactose

Crystallisations of lactose were performed a ternary system: lactose–ethanol–water and a quaternary system: lactose–glycerol–ethanol–water. A mass of 150 g of ethanol kept at the experimental temperatures (from 25 °C to 70 °C) was added to 50 g of filtrate described in Section 2.2.1. The mixtures were shaken. After 24 h, lactose crystals were separated from the mother liquor, washed with ethanol to ensure no glycerol remained in the product, and dried in the oven at 70 °C for 48 h. The β-lactose content of the dried powder was analysed in the Shimadzu HPLC system, using a C18 column (Aqua 5 μm 125A, Phenomex Australia) with deionised water. The HPLC method was based on that outlined by Listiohadi [7] and Jones [4]. The dried powder was then analysed for particle size and size distribution using the Malvern Mastersizer S2000, and crystal morphology using the polarised light microscope (Leica Mikroskopie and Systeme GmbH – Wetzlar with a Panasonic colour CCTV camera) and a PHILIPS SEM505 scanning electron microscope (SEM).

The following experiments were performed to find the ratio of solvents to be used in the lactose crystallisation. A total mass of 180 g of a mixture of ethanol and glycerol (at various ratios shown in Table 1) kept at 75 °C was added to 50 g of a saturated lactose solution at the same temperature and crystallisation allowed to proceed over 24 h at 75 °C (isothermal crystallisation) or according to a cooling strategy. The dried powder was analysed for average size, β-lactose content and crystal morphology.

Table 1
Effect of solvent ratios and reaction temperatures on crystalline lactose properties.

No.	G/TS (100% w/w)	TS/LS (w/w)	Temperature	Size (μm)	β-Lactose (%)
1	25	3.6	75 °C	114.8	80
2	20	3.6	75 °C	49.6	82
3	15	3.6	75 °C	36.0	93
4	10	3.6	75 °C	38.6	84
5	25	3.6	Cooling	13.7	59
6	15	3.6	Cooling	13.0	66
7	25	2.4	Cooling	165.8	74
8	25	1.2	Cooling	523.8	53

Notes: G stands for mass of glycerol, TS for mass of glycerol and ethanol, and LS for mass of saturated lactose solution at reaction temperature.

3. Results and discussion

3.1. Lactose solubility in ethanol and glycerol aqueous solutions

Due to many excellent physical properties glycerol has already been used in various food, beverage and dairy products in the presence of lactose and other sugars. The boiling point of pure glycerol is at 290 °C but the boiling point of glycerol in water falls with increasing glycerol content. The boiling point of the 10% glycerol aqueous solution is slightly above that of water at 100.7 °C [8]. Replacing ethanol having the boiling point at 78 °C with glycerol can possibly increase the reaction temperature beyond 70 °C. The solubility of lactose in the glycerol aqueous solutions at one low and one high temperature, i.e., at 25 °C and 70 °C must be calculated and compared with the lactose solubility in the ethanol aqueous solutions at the same temperatures. The experiment would be pointless if this comparison revealed that the partial replacement of ethanol by glycerol reduced the extraction yield of the process. The high boiling point of glycerol makes the alcoholic crystallisation process less hazardous but at the same time greatly affects the selection of methods to measure solubility. Determination of the residue by drying the samples in the oven was described in Section 2.2.1. This method is commonly used to assess the solubility of lactose in ternary systems with volatile solvents such as

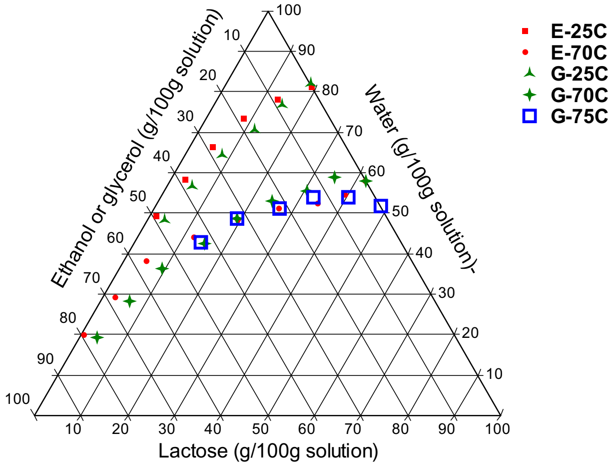

Fig. 1. Experimental ternary phase diagram of the systems lactose–water–glycerol compared to that of lactose–water–ethanol at 25 °C and 70 °C (E stands for ethanol and G for glycerol).