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Modelling of rheological behaviour of soursop juice concentrates using shear rate–temperature–concentration superposition

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ABSTRACT

The effect of temperature and concentration on rheological behaviour of freeze dried soursop juice concentrates were investigated using a rheometer over a wide range of temperatures (10–70 °C) and concentrations (10–50 °Brix) at shear rates of 0–400 1/s. The Power law is the best fitted model to the rheological data due to the high value of coefficient of determination (R^2 = 0.9989). The soursop juice concentrates exhibited shear thinning or pseudoplastic behaviour with $n < 1$. The consistency coefficients dependency on temperature and concentration were well described by Arrhenius relationship and exponential relationship respectively. The flow activation energy of soursop juice concentrates were 8.32–30.48 kJ/mol. The superposition technique with Power law model sufficiently modelled the overall rheological characteristics of soursop juice concentrates into a single master curve using shift factors based on double shifting steps with R^2 = 0.9184. This technique also showed that the soursop juice concentrates increases in viscosity and pseudoplasticity behaviour with concentration.

1. Introduction

Soursop (*Annona muricata* L.), known as *durian belanda* in Malaysia, is getting popular due to its very pleasant, subacid, highly aromatic juicy flesh and distinctive flavour. Due to the easily get bruised and damaged conditions, the soursop fruit is usually manufactured into other form of products such as juices, concentrated juices, nectars, purees, syrups, jellies and ice creams (Umme et al., 1999) to prolong its shelf life. Nowadays, concentrated fruit juices have become one of the trends to preserve the nutrients and flavours of the fresh fruit. Several methods have been used to concentrate fruit juices such as oven drying, rotary evaporation, cross-flow filtration and freeze drying. Freeze drying is one of the most widely used concentration method in the food industry, owing to its ability to maintain the nutrients, colour and flavours of the fresh fruit. A variety of fruit juices was concentrated using freeze dryer, for instance, cactus pear juice (Moßhammer et al., 2006), guava juice (Shamsudin et al., 2005), mangoes juice (Dak et al., 2007, 2006) and pummelo juice (Chin et al., 2009).

Rheology, the study of deformation and flow of matter, is very important for the processing of fruit juices especially the rheological properties of the juice. Rheological properties of fluids food is very useful for food processing and food handling which involves fluids flow in any food processing operations such as pasteurization, concentration and dehydration (Dak et al., 2006) by evaluating the quality, understanding the structure, designing the equipments and transport system and determining the pump capacity and power requirement (Boger and Tiu, 1974). Due to the importance of rheological properties in fruit juice processing, rheological models are constructed to represent the rheological data. Numerous rheological models have been used to describe the flow behaviour of food such as Newtonian (one parameter), Power law, Bingham, and Casson (two parameters) and Herschel–Bulkey models (three parameters). In general, most fluids food does not exhibit Newtonian behaviour. The Power law model has been used most extensively to describe the rheological behaviour of most fruit juices especially on handling, heating and cooling operations because it is convenient, simple and straightforward to be used (Gratão et al., 2007; Steffe, 1996).

Rheological behaviour is influenced by temperature and concentration during the juice processing. The Arrhenius relationship is often used to describe the effect of temperature on the consistency coefficient of Power law model of fluids food. Kaya and Sözer (2005) suggested that this relationship could be successfully used to estimate the temperature dependency on the rheological behaviour of sugar rich fluids food and clarified fruit juices. The effect of concentration on the consistency coefficient of Power law model of fluids food can be described either by Power law or exponential relationships. Ibarz et al. (1993) stated that Power law and exponential relationship is usually used to estimate the puree type foods and concentrated fruit juice respectively. A study found that the consistency coefficient of frozen concentrated orange juice can be successfully predicted using the exponential relationship Vitali and Rao (1984).

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Nomenclature

σ	shear stress (Pa)	T	Temperature (K)
σ_0	yield stress (Pa)	R^2	coefficient of determination
μ	viscosity (Pa s)	K_1 and n_1	constant in power equation
$\dot{\gamma}, \dot{\gamma}'$ and $\dot{\gamma}''$	shear rate (s^{-1})	K_2 and n_2	constant in exponential equation
n, n' and n''	flow behaviour index	K_3 and n_3	constant in Arrhenius and power equations
K, K' and K''	consistency coefficient (Pa s^n)	K_4 and n_4	constant in Arrhenius and exponential equations
K_0	frequency factor (Pa s^n)	a_T	dimensionless temperature shift factor
E_a	activation energy (J/mol)	a_C	dimensionless concentration shift factor
R	universal gas constant 8.314 (J/mol K)		

Master curves, is a technique used to model the overall flow behaviour of complex rheological data of many fluids food (Steffe, 1996). The idea of this technique was extracted from a novel principal which is the time–temperature superposition by determining the shift factors (Bird et al., 1987). Chin et al. (2009) reported that this technique could be successfully used to model the effect of temperatures at 6–75 °C and concentrations at 20–50 °Brix on the rheological behaviour of pummelo juice concentrates. Despite limited studies on modelling the interaction effects of temperature and concentration of tropical fruit juices using this powerful master curve technique, it can be very useful when comparing rheological data of different juice products.

The objectives of this study were to investigate the effect of temperature and concentration on the rheological properties and flow behaviours of soursop juice concentrates using available rheological models. The effect of temperature via the Arrhenius relationship and concentration via the Power law and exponential relationships on the consistency coefficient of soursop juice concentrates were determined. The overall rheological characteristics of soursop juice concentrates at various temperature and concentration were modelled further using the master curve technique by shear rate–temperature–concentration superposition method using shift factors in extension of Chin et al.'s (2009) work on pummelo juice concentrates, by using this double shifting.

2. Materials and methods

2.1. Materials

Fresh harvest soursop fruits (*Annona muricata* L.) at mature green stage were obtained from Sungai Ruan, Pahang, Malaysia. The soursop fruits were allowed to ripe at room temperature for 2–3 days prior to processing. Initial total soluble solids of fresh soursop fruits was 13.34 ± 0.16 °Brix at 25 °C.

2.2. Preparation of soursop juice samples

The soursop juice was extracted following the optimised extraction method via microwave oven (Quek et al., 2012). The soursop fruit was washed thoroughly under running tap water to remove the impurities on the skin before the fruit was cut into a few blocks using a sharp knife. The fruit skin was cut and seeds were removed. About 1.2 kg of fruit pulp was homogenised for 1 min using a high speed blender (MFM-202, Ta Feng Electrical Appliances Co. Ltd., Taiwan). Each 100 g of homogenised pulp weighed using an analytical balance (B204-S, MKII, Mettler Toledo, Switzerland) was added with 100 ml of distilled water at a ratio of 1:1 (weight to volume) in a rectangular polypropylene container (0.155 × 0.100 × 0.065 m). The container was then placed centrally on a turntable in a microwave oven (EM-B756A, Sanyo, United Kingdom) at the microwave extraction power of 850 W for an extraction time of 2 min. The mixture was centrifuged at 6000 rpm for 10 min using a centrifuge (Biofuge primo, Heraus, United Kingdom) to obtain the juice 1 l of juice. The juice was then sampled into 10 rectangular polypropylene containers with 100 ml each. The juice containers were placed and concentrated in a laboratory vacuum freeze dryer (Model SB4, Pump Model RV8, Edward High Vacuum International, Crawley Sussex, England), with a drying temperature programmed from 25 °C to −24 °C for 48 h. During the freeze drying process, the juice was frozen and the surrounding pressure was reduced to allow the frozen water in the juice to sublimate. The sublimed ice in the vacuum chamber was then pulled out by using the vacuum pumps. The total soluble solids of freeze dried concentrated juice obtained was about 56.30 ± 0.99 °Brix. In order to acquire different juice concentrations for rheological test, the concentrated juice was diluted with distilled water to 10, 20, 30, 40 and 50 °Brix.

2.3. Rheological measurements

A rheometer (ARG2, TA Instruments, New Castle, USA), equipped with a peltier concentric cylinder double gap geometry (rotor inner radius = 20.38 mm, rotor outer radius = 21.96 mm, rotor height = 59.5 mm, cup inner radius = 20 mm), was used to investigate the rheological behaviour of the soursop juice concentrates. In each rheological test, 6.5 ml of sample juice was pipetted into the concentric cylinder cup. During test, a solvent trap was used to minimize moisture loss. The rheometer consists of a temperature controlled system to control the experimental temperature. The rheological measurements of soursop juice concentrates were performed at seven levels of temperatures, 10, 20, 30, 40, 50, 60 and 70 °C for five levels of concentrations, 10, 20, 30, 40 and 50 °Brix over a shear rate range of 0–400 s^1 in a continuous increasing shear rate manner.

2.4. Data analysis and modelling

The entire experiment was conducted and duplicated in an identical manner from two batches of fruits from the same cultivars. There were some of the variations in the two sets of experimental data obtained. Therefore, one set of the experimental data was shifted downwards at shift factor of 1.431 ± 0.2533. The mean, standard deviation and standard deviation of means (error bars) were calculated using Microsoft Excel 2007 (XP Edition, Microsoft Corporation, USA).

2.4.1. Modelling of fluid flow using rheological models

The experimental data of soursop juice concentrates was fitted to several rheological models, namely, Newtonian, Power law, Bingham, Casson and Herschel–Bulkley as shown in Table 1. The solver function in Microsoft Excel was used for the curve fitting. Generalised reduced gradient 2 (GRG2) nonlinear optimisation code was adopted in determining the rheological parameters, K,