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Application of hydrodynamic cavitation to improve antioxidant activity in sorghum flour and apple pomace

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ABSTRACT

To overcome the energy inefficiency and scale-up issues of ultrasonication, hydrodynamic cavitation was studied to release the bound phenolics in sorghum flour (SF) and apple pomace (AP) to enhance their antioxidant activity. In this study, SF and AP, naturally fermented at optimized conditions, were hydrodynamic cavitated at different flour to water (FWR) of 100, 275, 450 g/L and 50, 87.5, 125 g/L, respectively. In addition, three types of cavitators with 2, 3 and 4 rows of holes in rotor were used to cavitate SF and AP for the cavitation temperatures as 30, 35, 40 °C and 40, 45, 50 °C, respectively. For SF and AP, optimized conditions were determined as 100 g/L and 87.5 g/L FWR, 3 and 4 rows of rotor holes, 35 °C and 45 °C cavitation temperature, respectively. At these conditions, total phenolic content (TPC) and antioxidant activity (AA) of SF were 39.5% and 38.6%, respectively higher than the control SF, while for AP, these numbers were observed as 42% and 97%, respectively. IVSD in SF showed 4.7% increase, whereas AP exhibited 7.6% increment in TDF as compared to that of control samples. The study suggests that hydrodynamic cavitation can be successfully used for the preparation of processed foods with increased levels of phenolic antioxidants.

1. Introduction

In recent years, different cereals have been identified and accepted as functional foods and nutraceuticals because of good sources of dietary fibers, proteins, minerals, vitamins, and antioxidants required for human health (Charalampopoulos et al., 2002). Sorghum is one of the crops that contains phenolic compounds mainly in the forms of phenolic acids and flavonoids (Hahn et al., 1984). These compounds have potentiality to impact positively on human health because of their antioxidant and antiradical properties (Awika and Rooney, 2004). Sorghum utilization can be improved by incorporating it into mainstream human diet in different innovative ways such as extrusion and baking. Most of the phenolic compounds in plant are present in the bound form with the carbohydrates, lignin, pectin and proteins (Acosta-Estrada et al., 2014; Ajila et al., 2011). This bound nature of phenolics as glycosides reduces their ability to function as good antioxidants. Therefore, by liberating these bound phenolics using some pretreatments, the antioxidants rich sorghum flour can be introduced to the human diet.

Apple pomace (AP), byproduct from juice and cider processing industries is mostly used for direct disposal to soil in a landfill, and for pectin recovery usage (gelling agent, stabilizer and source of dietary fiber). Despite of that, tons of AP remains unutilized and causes serious environmental threats. Therefore, studies have got momentum to valorize the AP for other purposes also. AP as a rich source of antioxidant compounds could be used for increasing the stability of foods by preventing lipid peroxidation and also for protecting oxidative damage in living systems by scavenging oxygen radicals. Apple pomace has potential source of polyphenolic compounds and most of these compounds are present in bound forms with carbohydrates, lignin, pectin

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and proteins (Acosta-Estrada et al., 2014; Ajila et al., 2011) that reduces their antioxidant efficacy. Therefore, release of these bound phenolics can improve their health functionality.

In recent years, acoustic or ultrasonic cavitation (UC) has been used to release the bound phenolics that resulted in enhance in antioxidant activity in sorghum (Zhao et al., 2008) and apple pomace (Ajila et al., 2011; Lohani and Muthukumarappan, 2015). There are several processes that enhance the liberation of bound phenolics. Germination, malting, fermentation and thermo-mechanical processes such as extrusion cooking and alkaline hydrolysis are most popular (Acosta-Estrada et al., 2014). Fermentation can be used in combination with the cavitation. Fermentation improves the functional properties, i.e., starch–protein digestibility, water absorption index and water solubility index (Alka et al., 2012; Pranoto et al., 2013).

In terms of energy efficiency and scale-up capability, hydrodynamic cavitation (HC) is a possible alternative to ultrasonication. Cavitation is a combined phenomenon of formation, growth and collapse of microbubbles occurring in milliseconds. It provides a high energy densities locally resulting in high pressure and temperature in a range of 100–5000 bars and 1000–10,000 K, respectively at millions of locations (Kim et al., 2015). HC can be simply generated by the passage of liquid through a constriction resulting in increase in velocity at the expense of local pressure. Cavities are generated when the pressure falls below than the vapor pressure of medium at the operating temperature. Subsequently, the pressure recovers at liquid jet expansion resulting in collapse of the cavities. The cavitation in the liquid depends on size, shape, location of the body, its surface condition, microbubble dimensions, solid particles constituting the cavitation nucleus, Cavitation, Reynolds and Weber numbers characteristic (Cai et al., 2009).

As a dimensionless parameter characterizing the cavitation conditions in hydraulic systems, the cavitation number *K* has generally been used to relate the flow conditions with the cavitation intensity (Save et al., 1997). It is defined in the following form:

$$K = \frac{P - P_v}{\frac{1}{2}\rho v_0^2} \tag{1}$$

where P is fully recovered downstream pressure, P_v is the vapor pressure of the liquid, ρ is the density of liquid and v_0 is the velocity of the liquid at the constriction.

Though, cavitation can be achieved even at higher cavitation numbers, for maximum benefit from the reactor, the flow conditions and the geometry should be adjusted in such a way that the cavitation number lies in the range of 0.1–1. For smaller cavitation numbers (*K*), the number of bubbles produced per unit time increases as well as the intensity of the cavitation process (Ozonek and Lenik, 2011). The lower limit for operating cavitation number is called choked cavitation number. At choked cavitation number, the number density of cavities is very high, so these cavities start coalescing with each other and form a cavity cloud. Energy produced by the collapse of some cavities is taken up by the neighboring cavities. Thus the net energy available for cell disruption decreases. Hence cavitation device should be operated at a cavitation number higher than choked cavitation number.

In past years, HC has been used for sterilization of food (Milly et al., 2007), microbial cell disruption (Balasundaram and Harrison, 2006a,b; Balasundaram and Pandit, 2001; Save et al., 1997), water disinfection (Arrojo et al., 2008; Jyoti and Pandit, 2001, 2003; Mezule et al., 2009), wastewater treatment (Pradhan and Gogate, 2010; Sivakumar and Pandit, 2002; Wang and Zhang, 2009), and enzymatic hydrolysis of oil (Sainte Beuve and Morison, 2010). Application of HC in the area of food processing in order to increase in nutritional or functional values is lacking. Therefore, in this study, HC was applied to release the bound phenolics from sorghum flour (SF) and apple pomace (AP) to enhance the antioxidant activity. The objective was to study the effect of flour to water ratio, number of rows of holes in rotor and cavitation temperature on total phenolic content (TPC), antioxidant activity (AA), total dietary fiber (TDF) and in-vitro starch digestibility (IVSD) of SF and AP.

2. Materials and methods

Sorghum flour and apple pomace provided by ADM Milling Co. (Overland Park, KS), and Tree Top, Inc. (Selah, WA), respectively were stored at −20 °C before experimental utilization. The fermentation of SF (450 g/L) and AP (125 g/L) was carried out in a controlled environment with temperature 30 ± 1 °C for 12 h and 24 h, respectively. Fermented slurry of SF and AP was further diluted to keep different flour to water ratio (FWR) as one of the variables for further hydrodynamic cavitation.

2.1. *Hydrodynamic cavitation*

APV hydrodynamic cavitator (215 TC, SPX flow technology, Pasteursvej, Silkeborg, Denmark) was used for the cavitation of SF and AP. This cavitator had specially designed stator and rotor assembly. Rotors had surface indentations that influenced the flow trajectory of the samples inside the cavitator. There were a total of 44, 66 and 88 indentations placed equidistant from each other on the 200 mm diameter rotors with 2, 3 and 4 rows of holes, respectively. The speed of the rotor which determines the extent of cavitation was controlled with a variable frequency drive. The gap between the rotor and stator for 2 and 3 rows of rotor holes was 3 mm while for the rotor with 4 rows of holes, it was 6 mm. The speed of the rotor which determines the extent of cavitation was controlled with a variable frequency drive attached to a 7.5 kW motor. Cold water as a coolant was used to subdue the heat generated by motor. Due to high speed of rotor, very high surface velocities are generated as liquid is passed through the gap between the stator and the rotor. Due to the rotary action, liquid at high velocity enters the indentation of the rotor and comes out of the indentation due to centrifugal flow. It creates a low pressure region/vacuum near the upper surface of the indentations resulting into cavitation. Pressure drop across the surface of the rotor and indentation is sufficient enough for cavitation to occur.

Rotor speed corresponding to frequency and cavitation temperature ranges for SF and AP was decided from preliminary trails. SF and AP samples were cavitated at three frequencies of rotor, i.e., 20, 40 and 60 Hz. It was observed that time taken at 20 Hz and 40 Hz was more than three and six times, respectively than time taken at 60 Hz to extract the insignificantly ($p > 0.05$) different phenolics from respective samples (data not shown). Therefore, rotor speed of 3490 rpm corresponding to frequency of 60 Hz was used and the downstream pressure was maintained at 100 kPa with the help of backpressure valve to generate the phenomenon of cavitation during the sample flow through the device. To finalize the temperature range, both the samples were cavitated at two initial temperatures, i.e., 10 °C and 25 °C and re-circulated till the final temperature of 40 °C reached. The total time of cavitation taken with the former pair of temperature (10–40 °C) was higher than the time taken with latter pair of temperature (25–40 °C). Both the samples of SF and AP had insignificant ($p > 0.05$) difference in their TPC and AA indicating that cavitation time did not have any significant ($p > 0.05$) effect during cavitation (data not shown). Therefore, cavitation temperature was opted as one of the independent variables for this study instead of cavitation time. Sample of 10 L was fed into the cavitator through a positive displacement pump. Sample was recirculated till it reached desire experimental cavitation temperature. Flour to water ratio (FWR), rows of rotor holes