Review Article

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The effect of megasonic separation on the nutritional and physical properties of food - an overview

Abstract

There has been recent interest in the use of high frequency ultrasound, also referred to as 'megasonics', to initiate separation of immiscible particulates from fluids. This technology shows great promise in the area of food engineering, as it is capable of greatly enhancing the rate at which food nutrients can be separated from mixtures. Furthermore, the application of megasonics results in minimal deterioration of product quality such as physical appearance and nutritional value. There has been recent success in the commercialization of the technology, notably in the application of palm oil milling. Significant improvements to product recovery including a faster separation and yield enhancement not only provide better profitability, but also phytonutrient retention. This mini-review provides an overview of the important concepts pertaining to the technology. The potential effects resulting from application of ultrasonics at megasonic frequencies to selected foods for nutrient separation and retention are highlighted.

Keywords: megasonics, sonochemistry, separation, palm oil, dairy, ultrasound, sonoprocessing, bioprocessing, oxidation, nutrition

Volume 2 Issue 6 - 2015

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Received: September 20, 2015 | **Published:** Novenber 02, 2015

Introduction

In modern society, food processing plays a critical role in providing world-wide food availability and security. Continual innovation in the food processing industry is a driver for economic growth, satiating demands for new products with increased nutrition, improved shelf life, and improved taste. One of the important unit operations in food manufacturing involves the separation of components from foods to create products with specific or enhanced nutritional properties. A simple example is the separation of fat from milk to produce skim milk, a product which contains less fat and hence is desirable for consumers concerned with weight loss.

There are a number of conventional food separation processes including centrifugation, sedimentation or clarification, chemical induced flocculation, and membrane filtration. Although these operations are widely used, they have a number of potential issues including but not limited to: (1) high energy consumption; (2) excessive shear that may damage the integrity of the product; (3) product fouling that limits throughput or requires extensive cleaning; (4) slow separation rates; (5) excessive use of chemicals.

Recently, there has been interest in the application of an innovative technique for the separation of food materials using ultrasonic sound waves, known as ultrasonic or megasonic separation. Megasonic separation involves the establishment of an acoustic standing wave within a separation vessel which promotes the collision and subsequent aggregation and/or coalescence of individual particles into larger collections. The formation of these larger clusters of material subsequently sediment and/or rise much quicker than individual particulates. Megasonic separation is highly compatible with many existing separation techniques used in the food industry such as gravity separation, flocculation centrifugation, and filtration and can be used to significantly enhance process efficiencies.

There are several review articles detailing the use of high frequency ultrasound for the purpose of enhancing separation, and the reader is encouraged to visit these articles for more in depth information pertaining to different applications[1] and design aspects.[2] The potential impact that megasonic separation may have on the nutritional properties of concentrated product streams is the focus of this present review. In this mini-review, we provide an overview of some of the considerations pertaining to product quality that should be made when using megasonic separation as a method to enhance the separation of food products.

Ultrasound and acoustic cavitation

Ultrasound is an oscillating sound pressure wave with an oscillation frequency greater than ~16kHz. When ultrasound is delivered to fluids, the phenomenon referred to as acoustic cavitation may occur. This is the process of bubble nucleation and subsequent growth and collapse when subject to the acoustic sound field.[3]

There are several regimes of ultrasound that is based on the frequency of oscillation, and these may culminate with different effects. At low frequencies between ~16-100kHz, bubble collapse events are characterised by extreme temperature (up to 10,000K) and pressure release (up to several hundred atmospheres) due to large bubble expansion prior to collapse. Between 100 kHz to 1000kHz, bubble expansion and collapse become less intense. However, this region of ultrasound application to fluids results in peak sonochemical effects, due to a large population of active cavitation bubbles.[4] At frequencies greater than 1000 kHz, cavitation events become less frequent due to an increased cavitation threshold[5] and have decreased collapse intensity due to smaller bubble resonance size.

The manipulation of particulates in an acoustic standing wave field is driven by what is known as acoustic radiation forces. The theory of these forces was first established by King[6] and refined later by Yosioka and Kawasima[7] and Gor'kov.[8] Within a standing wave field, particles with specific density or compressibility that is different to the bulk medium, will experience a force that drives them towards regions of high local pressure (pressure antinodes) or minimal local pressure (pressure nodes). Once moved towards these regions, additional forces in the system increase the likelihood that they will collide together and form larger collections of material. These larger aggregates have a higher propensity to float or sediment than the individual particles themselves, thereby resulting in enhanced rates of separation. The magnitude and hence effectiveness of the acoustic forces in moving particles is dependent on a range of parameters, and scales with increased ultrasound frequency, particle size of the material and acoustic energy density.

Since the formation of chemical radicals is usually at peak rates within the frequency range, this may result in unwanted oxidation of food materials. Furthermore, temperature increase from the application of ultrasound resultant from bubble collapse, attenuation and absorption of acoustic energy, and dissipation of heat from the transducer, can lead to excessive macro-scale increases in temperature.

Chemical effects of ultrasound

In aqueous solutions, the energy released upon bubble collapse is sufficient to split water molecules into H and OH radicals. Under suitable conditions, the following series of reactions may take place:[9]

$$H2O+O^{\cdot} \rightleftarrows O^{\cdot}H+O^{\cdot}H \quad (1)$$

$$H2O+H^{\cdot} \rightleftarrows O^{\cdot}H+H2 \quad (2)$$

$$HO2+H^{\cdot} \rightleftarrows O^{\cdot}H+O^{\cdot}H \quad (3)$$

$$H2O+H^{\cdot} \rightleftarrows H^{\cdot}+O^{\cdot}H \quad (4)$$

Equations 1-3 are comparatively lower energy pathways compared with Equation 4.[10] This means that radical production will occur even with low bubble collapse temperatures. These radicals can cause a range of oxidation and reduction reactions,[11] and may negatively impact upon the nutritional qualities of food products.

Peak sonochemical production of radicals occurs in the frequency range between 400 to 800kHz.[4,12] Note that radical production is also dependent on the energy density of the applied ultrasound. Incidentally, the ultrasonic frequencies most suitable for use in separation applications range between 400 kHz to 2000kHz.

Physical effects of ultrasound on food materials

In the frequency regime between 400 to 2000kHz, the physical effects are relatively benign and so the structural damage to food materials tends to be minimal.[12] Many of the concerns pertaining to high power ultrasound use, i.e. 20 to 100kHz ultrasound, such as metallic particle formation contaminating products[13] and physical disruption and homogenization of materials[14] can be avoided at these higher frequencies.

One must still be mindful of excessive temperature increase in the fluid, especially with high acoustic energy input. High energy dissipation should be monitored and if excessive, controlled[2] to avoid damage to food materials by heating. Reaching such temperatures during ultrasound separation will decrease the nutritional qualities of the final product since excessive temperature will denature or damage proteins, vitamins and other structures. Appropriate cooling systems or shorter residence time within the vessel should be employed to minimize potential heat damage.

Effects on nutritional properties in selected applications

Palm oil

One of the issues in palm oil milling is the loss of viable product into waste streams. In typical operating facilities, approximately 2 to 10 % of product is lost as waste, which if recovered, will greatly reduce the environmental impact and increase profitability of operations. Recently, megasonics has been implemented into a typical commercial at 45t/hour, showing enhanced recovery of palm oil product that almost eliminated any loss of product as waste.

The ultrasonic frequency used for palm oil separation is typically 600 kHz, which is within the peak radical formation region. Tests demonstrated that tocols (tocotrienols, tocopherols) and other phytonutrients such as carotenoids, contributing to the orange-redish colour of the oil are not modified when subject to megasonic separation for about 60min (Table 1).[15] An enhanced rate of oil recovery due to megasonic processing can provide opportunities for decreasing traditional extraction temperatures below 90°C and therefore provide with crude palm oil of higher nutrient content.

Table 1 Quality parameters of palm oil separated from pressed oil palm fruit feeds after 400kHz ultrasound processing. Data is compared with a commercial sample of palm oil using the conventional palm oil milling process taken on the same day in a palm oil mill (Adapted from) Juliano et al.,[15]

Quality parameter[a]	Oil recovered after 600kHz processing[b]	Commercial oil
FFA (%)	4.33±0.38	4.16
DOBI value	2.53±0.09	2.49
α-T (mg/kg oil)	177±11	180
Σ T3 (mg/kg oil)	773±54	830
Σ Vit E (mg/kg oil)	950±61	1010
α-T:T3	0.23±0.01	0.22

a Palm oil quality parameters : Free fatty acid (FFA) content, DOBI value, α-tocopherol (α-T) and tocotrienols (T3) content, total vitamin E and α–T:T3 ratio
bValues are the average of 5-6 independent runs ±standard error

Milk/dairy

Megasonic separation can be used to initiate size-based fractionation of product streams.[16] It is an alternative technique to membrane filtration.[17] Studies in the dairy science field have recently shown that milk fat globules of different sizes have different nutritional properties.[18–20] Smaller sized fat globules have different concentrations of saturated and unsaturated triglycerides within the core of the globule compared with large sized fat globules.[20] Notably, smaller globules contained more medium chain length fatty acids and less stearic acid compared with larger sized globules. Furthermore, the composition of phospholipids and protein compounds located on the surface of the milk fat globule membrane[18,19] differs between small and large sized globules. Examples of nutraceutical benefits from such compounds include anti-breast cancer and anti-Alzheimer proteins. The ability to concentrate small or large sized globules in their natural state by ultrasonic separation would enable generation of new milk products with highlighted nutritional properties.

In addition to nutritional value, the flavour and sensory properties of many dairy products are dependent on the micro-structure imparted by small and large sized fat globules.[21] Parmesan cheese for example, which is made in Northern Italy from semi-skimmed milk formed using natural gravitational sedimentation, purportedly to enhance the volume fraction of small sized fat globules in the cheese matrix, which enhances flavour development. The ability of this technology to facilitate more products with flavour and nutritional enhancements is promising.

Numerous studies have been made to evaluate the detrimental effects of ultrasound to specific dairy components such as fats and proteins. The oxidation of unsaturated lipids present in milks is of concern, due to the development of rancid flavours. The generation of 'metallic' and 'burnt' flavours, when excessive energy input was used to process milks has been reported.[22] The volatile profile of milk, can be significantly modified when processed by low and/or high frequency ultrasound (up to 1 MHz) when using very high specific energy.[23] This can be avoided by using short processing durations. Careful application of acoustic energy to the system should be made, such that milk is not over processed detrimentally. It should be noted that in most milk processing applications, pasteurization is necessary and this already alters or destroys the nutritional benefit of many of these components.

Fermentation systems

Ultrasonic separation can be used as an alternative cell-retention system for fermentation and cell culturing applications.[24] Recombinant proteins, amino acids and anti-bodies are examples some of the high value products which can be delivered in these applications. Studies have shown that selective retention of viable versus non-viable cells is possible[25] reducing the need to 'bleed-out' product during operation, thereby improving production. Such systems are commercially available with the development of BioSepTM, and could also be readily implemented into food applications such as fermentation tanks in the beer and wine industry.

The advantage of ultrasound separation in such applications is that the technique is relatively simple and offers nearly maintenance free operation by reducing the need to periodically bleed out product. The high frequency ultrasound employed limits any potential physical or chemical change to the product, thereby preserving the quality. For example, no significant damage to blood cells was reported at frequencies between 0.5 to 3.5 MHz with the exception of cases where excessive power caused cavitation at frequencies below 1MHz.[26] Similarly, Maitz et al.,[27] also demonstrated no significant alteration to physical integrity of plant cells when subject to ultrasonic separation.

Concluding remarks

Megasonic separation is a promising technology that can produce great benefit in a variety of food processing applications. It can be used as a tool to enhance the nutritional value of separated streams by fractionation or temperature reduction resulting from increased throughputs. Furthermore, the application of high frequency ultrasound in the MHz region means that detrimental physical and chemical effects resultant from megasonic application are minimal. To date, there is limited commercial-scale implementation of the technology, with prominent examples only being in the palm oil and bioproducts industries. Additional research in the scale-up aspects of the technology is required in order to bring its benefits to a wider range of applications in the food industry.

Acknowledgements

None.

Conflict of interest

Author declares that there is no conflict of interest.

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Citation: Leong T, Juliano P. The effect of megasonic separation on the nutritional and physical properties of food - an overview. *J Nutr Health Food Eng*. 2015;2(6):228–229. DOI: 10.15406/jnhfe.2015.02.00085