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Influence of ultrasound on the rehydration of dried sea cucumber (*Stichopus japonicus*)

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A B S T R A C T

Rehydration capacity, water distribution, and microstructure of sea cucumbers subjected to ultrasound-assisted rehydration (UAR) were investigated. Rehydration ratio and water holding capacity (WHC) were found to increase when ultrasound power was increased from 100 W to 300 W, to increase when ultrasound frequency was decreased from 45 KHz to 28 KHz. Nuclear magnetic resonance analysis revealed that water mobility increased with increasing ultrasound power, resulting in more immobilized water and free water, which facilitated better and faster water uptake. Analysis of scanning electron microscope micrographs revealed that with the accelerated water uptake, sea cucumber swelled faster and formed a structure with higher porosity which increased water uptake even faster and led to an accelerated rehydration and higher WHC. Combined with UAR, the rehydration efficiency of dried sea cucumber was increased 12-fold, and 44 h were saved in the rehydration procedure without any negative effect on texture.

1. Introduction

Sea cucumbers (*Stichopus japonicus*) are echinoderms from the class Holothuroidea. They have been traditionally consumed as a tonic food in Asia and the Middle East for thousands of years (Bordbar et al., 2011). Sea cucumbers contain certain nutrients which are beneficial to health, such as triterpene glycosides, cerebrosides, polysaccharides, and saponins, which possess significant anti-tumor and anti-coagulant properties, and improve lipid metabolism activities (Hu et al., 2012; Luo et al., 2013; Sugawara et al., 2006; Zhang et al., 2006). In recent years, they have been widely regarded as one of the most popular functional foods in Asian countries, especially in China, Japan, and South Korea (Bordbar et al., 2011; Wen et al., 2010). Sea cucumber-derived food products, including instant sea cucumber, sea cucumber capsules, and sea cucumber caplets, can also be found on the market. Based on the rising market demand and enormous economic benefits, total production of sea cucumber is increasing rapidly. Because of the autolytic enzymes in their body, fresh sea cucumbers autolysis occurs rapidly after being harvested. More than 90% of sea cucumbers are dried to prevent autolysis as well as to facilitate their storage and sale (Aydin, 2008; Chen, 2004). Dried sea cucumber is typically rehydrated in cold, clean water for 2–3 days before further processing or cooking (Duan et al., 2008). The inefficiency of the soaking process has been the main factor restricting the growth of the sea cucumber industry. In addition, autolysis and microbial contamination might occur during the lengthy rehydration process that is traditionally used. The question of how to optimize the rehydration process, and thereby improve product quality, has been one of the major concerns of the sea cucumber manufacturing industry.

Rehydration capacity has always been used as a measurement of quality in many studies on the drying of seafood, such as squid (Chen et al., 2013; Deng et al., 2014), shark (*Carcharhinus sorrah*) (Guizani et al., 2008), Chilean abalone (*Concholepas concholepas*) (Reyes et al., 2011), and sea cucumbers (Duan et al., 2010). Products dried with innovative drying technologies such as freeze drying and microwave-freeze drying always showed good rehydration capacity and minimal loss of physicochemical qualities, such as structural changes and protein quality (Deng et al., 2014; Duan et al., 2010). Freeze-drying and microwave-freeze drying avoid the high temperatures of thermal processing and results in dried

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products with a porous structure, less shrinkage and structure changes, which are critical for when they are later rehydrated (Deng et al., 2014; Duan et al., 2010). For seafood products, such as sea cucumber, only a few studies on they rehydration process have been reported recently. In a study by Hong et al. (2014), hot air dried (AD) sea cucumber was soaked in distilled water at 90 °C for 20 min, then left in the soaking water at 70 °C for 40 h; its rehydration ratio ranged from 5 to 6 and had better texture quality than the control. Similar methods were also used in other reports by alternating hot and cool water soaking treatments (Fukunaga et al., 2004; Liu and Ko, 2002; Qi et al., 2010; Xiang et al., 2007). In traditional rehydration of salted dried sea cucumber, the product is boiled in water 2–3 times and then soaked in cold water at 4 °C for two days (Xiang et al., 2007). All the reported sea cucumber rehydration processes require at least 48 h. It would be worth mentioning that salted drying of sea cucumbers has always been conducted by first gutting and then boiling the sea cucumber, followed by curing it with salt; it is sometimes followed by solar drying or hot air drying. Because of the low cost and simplicity of the process, salted drying is still the primary method used to preserve sea cucumber for further processing (Yang et al., 2015). In fact, the osmotic pressure of the salt content could accelerate the water migration during the rehydration process; however, the traditional rehydration method would still need more than 2 or 3 days of soaking in water.

Rehydration of food is a complex mass transfer process that involves different physical mechanisms such as water absorption, internal diffusion, convection at the surface and within large open pores, and relaxation of the solid matrix (Mulet et al., 2003). Several approaches, such as the use of ultrasound (Tao and Sun, 2015), high hydrostatic pressure (Chawla et al., 2011), high electrical field pulses (Loginova et al., 2011; Xue and Farid, 2015), and vacuum (Fito, 1994) have been applied in the rehydration process to improve the solid–liquid mass transfer. Of these, ultrasound, a form of energy generated by sound waves of high frequencies above 16 kHz (Misra et al., 2011), is widely considered as one of most effective technologies. This has contributed to the fact that a series of effects associated with acoustic energy are responsible for increasing the mass transfer rate without significantly heating the material (Garcia-Perez et al., 2007). Actually, ultrasound has been applied to enhance mass transfer in many food systems, such as solid–liquid extraction (Szydłowska-Czerniak et al., 2015), ultrafiltration (Muthukumaran et al., 2007), osmotic dehydration (Rodrigues et al., 2009), and drying (Ozuna et al., 2011). Increased mass transfer was observed in all the procedures that proved ultrasound could accelerate the corresponding processes. Industrial ultrasonic filtration systems and sonic-extraction reactors have been developed on an industrial scale and have been used for extraction of food and pharmaceutical additives (Chemat et al., 2011). Regarding the rehydration of dried food products, ultrasound-assisted rehydration (UAR) processes were recently reported for brown rice (Cui et al., 2010; Wambura et al., 2008), chickpeas (Yildirim et al., 2011, 2013), navy beans (Ghafoor et al., 2014), and sorghum (Patero and Augusto, 2015). Little is known about the application of ultrasound-assisted rehydration (UAR) processes on seafood products, which have different composition than grains or legumes which could lead to different mass transfer properties. Thus far, no studies on the UAR of sea cucumber have been reported.

Therefore, the main objective of this study was to investigate the additional effect of ultrasound treatment at different frequencies and powers on the rehydration behavior of salted dried sea cucumber. The effect of ultrasound treatment on moisture distribution, microstructure, and textural properties of the rehydrated samples was also evaluated.

2. Materials and methods

2.1. Materials

The raw material for this experiment was salt-dried sea cucumber (*S. japonicus*) provided by a local company (Fujian Hongfengtai Marine Biological Development Co., Ltd., Fuzhou, China). Sea cucumbers of same size and shape were dried under the same conditions. The samples had a weight of 12.39 ± 1.19 g, a water content of 58.13% ± 2.47%, a salt content of 31.68% ± 2.31%, a protein content of 5.78% ± 0.37%, and a volume of 13.41 ± 1.19 cm^3.

2.2. UAR process

Experiments to obtain the UAR of sea cucumber were performed with the UAR bath shown in Fig. 1. The UAR bath consisted of a container whose temperature is controlled by a thermostatic bath (overall dimensions: 350 mm × 250 mm × 300 mm; internal dimensions: 300 mm × 200 mm × 150 mm, homemade) with a constant temperature recirculating water jacket. Ultrasonic transducers were attached to the bottom of the outer surface of the liquid container, and the liquid was irradiated with ultrasonic waves from the surface of the liquid container.

The dried sea cucumbers were soaked in deionized water in the UAR bath with the ultrasound feature turned on for 1 h. The temperature was kept at 4 °C. Three frequency levels (28, 35, and 45 KHz) and four ultrasound power levels (0, 100, 200, and 300 W) were used. Then, the calcareous mouth and abdominal muscle was removed. The sample/water ratio (1:50) was fixed to ensure an excess of water, avoiding a possible limitation in the mass transfer phenomenon due to the lack of water. Samples were divided evenly into groups. Each experimental group had six replicates.

2.3. Rehydration ratio (R_R) and water holding capacity (WHC)

Water absorption by sea cucumbers was determined after rehydration. The rehydrated sea cucumbers were blotted with absorbent paper to remove excess water from their surface. R_R is expressed as a percentage of the water absorption and is calculated by the following equation: $R_R = m_f/m_0$, where m_0 and m_f are the weights of the sea cucumber before and after rehydration, respectively.

Samples obtained as described above were centrifuged in an Allegra X-30 benchtop centrifuge (Beckman Coulter, Brea, CA, USA) for 10 min at 3000 g at 4 °C. WHC were expressed as grams of water retained in the sample per 100 g of water present in the sample before and after centrifugation.

2.4. Low-field nuclear magnetic resonance and Magnetic Resonance Imaging

A low-field pulsed NMI 20-analyst (MesoMR23-060H-I NMR and MRI, Shanghai Niumag Electronic Technology Co., Ltd., Shanghai, China) with 22.6 MHz was used in the experiment to determine the water migration within sea cucumber. Each sample was placed in a 15 mm glass tube and inserted into the low-field nuclear magnetic resonance (LF-NMR) probe. Carr-Purcell-Meiboom-Gill (CPMG) sequences were employed on a ^1H NMR spectrometer to measure the spin–spin relaxation time, T_2. The multi-exponential decay curve was obtained from the NMR relaxation measurement using the following mathematical model:

$$M(t) = \sum_{i=1}^{n} A_i e^{(-t/T_{2i})} \quad (1)$$