Abstract

In this doctoral thesis, cavitation techniques (ultrasound and hydrodynamic) have been utilized with an intensifying approach for producing oil in water (O/W) emulsions with higher attributes such as minimum droplet size, enhanced stability and higher encapsulation efficiency. This research work aims to advance the understanding of ultrasonic and hydrodynamic cavitation based emulsification process. The motivation of this work was to understand the fundamentals related to the kinetic stability of oil in water emulsions of cavitationally prepared emulsions which are yet to be fully elucidated. This research work deals with the detailed study on the formulation, stability and encapsulation characteristics of mono and multilayer nanoemulsions prepared using ultrasonic and hydrodynamic cavitation. It also considers the impact of ultrasonic and hydrodynamic cavitation parameters on the physicochemical properties of emulsions as well as the significance of the effect of these cavitation process parameters on the emulsion properties such as droplet size, encapsulation stability and chemical stability.

This thesis contains an introduction outlining the background information on the emulsion science and fundamentals of cavitation techniques for the generation of O/W emulsions. The overall study in this research work consists of four major parts which are described as follows:

In the first part of thesis, the mustard oil in water nanoemulsions stabilized by Span 80 and Tween 80 were prepared using ultrasonication with detailed optimization of the various process conditions. Effects of various operating parameters such as HLB (Hydrophilic Lipophilic Balance) value, surfactant volume fraction (φ_S), oil volume fraction (φ_O) and power amplitude were investigated and optimized on the basis of minimum droplet size and stability of nanoemulsions. It was observed that minimum droplet size of about 87.38 nm was obtained within 30 min of ultrasonication at an optimum HLB value of 10, φ_S of 0.08 (8%, v/v), φ_O of 0.1 (10%, v/v) and ultrasonic power amplitude of 40%. The detailed statistical analysis was also conducted using response surface methodology and Analysis of variance technique to describe the significance of the process parameters on the emulsion droplet size. It has been observed that the oil fraction was found to be the most significant factor affecting the droplet size of emulsion. The significance level was found to be in the

order as $\varphi_O > \varphi_S >$ %Amp > Time > HLB. The stability of the nanoemulsion was measured through visual observation and it was found that the unstable emulsions got separated within 24 hours whereas, stable emulsions never showed any separation until 90 days. In addition to that, the kinetic stability of the prepared nanoemulsions was also assessed under centrifuge and thermal stress conditions. The emulsion stability was found to be unaffected by these forces as the droplet size remained unchanged. The ultrasound prepared emulsion was found to be stable even after 3 months of storage at ambient conditions without any visual evidence of creaming and phase separation and also remained kinetically stable. FTIR analysis of the emulsions at different sonication conditions was carried out to examine the possible impact of ultrasonically induced chemical effects on the oil structure during emulsification and it was found that the oil molecular structure was unaffected by ultrasonication process. This work illustrates the formation and stability of mustard oil in water nanoemulsion using ultrasound cavitation which may be useful in food and cosmetic based applications.

In the second part, nanoemulsions were prepared with the same system but with a different cavitation technique i.e. hydrodynamic cavitation (HC) and compared with ultrasonication process. In this work, detailed geometrical analysis of hydrodynamic cavitating devices was carried out to investigate the effect of geometry (orifice and venturi of different shapes) and geometrical parameters on the formation and stability of mustard oil in water nanoemulsion. The optimization of geometrical parameters was carried out based on the lowest droplet size obtained and droplet size reduced per unit pass. It was observed that the single hole orifice plate of circular shape having lower perimeter and higher flow area than other orifice devices, was found to be an efficient device which produced emulsion of lowest droplet size i.e. 87 nm at an optimum C_V of 0.19 (10 bar optimum operating pressure) in 90 min of processing time. A mathematical correlation was also developed using dimensionless analysis approach for understanding the effect of various operating and geometrical parameters of HC. The mathematical expression to calculate the droplet size was found to be the function of dimensionless numbers such as Reynold number, Weber number and cavitation number. Moreover, the kinetic stability of the nanoemulsion was also assessed under centrifugal and thermal stress conditions and it was found to be unaffected by these forces as no change in the droplet size observed during the assessment. The prepared nanoemulsions were found to be stable up to 3 months indicating the potential of HC over high energy techniques for producing highly stable nanoemulsion on a large scale. Furthermore HC was found to be 11 times more energy efficient than acoustic cavitation/ultrasonication in the preparation of nanoemulsion.

In the third part, a different kind of emulsion i.e. multilayer O/W emulsion was prepared using layer by layer approach which is a potential system that can be utilized particularly in food and pharmaceuticals for the encapsulation of various nutraceuticals. The ultrasonication method was used for the preparation of multilayer O/W emulsion stabilized with whey protein isolate (WPI) and sodium alginate (SA). Ultrasonication was employed in both batch and recirculating flow configurations. The effect of process parameters such as pH, SA concentration, and sonication time on the droplet size, zeta potential, morphology, physical and oxidative stability of the multilayer emulsion was studied using batch process. It was observed that the emulsion prepared at pH 5, 0.2 wt% SA and 60 sec sonication had good bilayer interaction between WPI and SA molecules. Moreover, it was found that sonication, if given for a controlled time period can improve the physical and oxidative stability of the emulsion. Further, the ultrasonication based recirculating flow configuration (RFC) was utilized for the preparation of multilayer emulsion at the optimum operational conditions obtained in the batch studies. Emulsions prepared using RFC were found to have better physical and oxidative stability than using batch ultrasonication at the optimum flow rate of 0.5 L/min with 6 recirculation passes. RFC was found to be 2.5 times more energy efficient than batch ultrasonication process for the synthesis of multilayer emulsions.

In the fourth part of this thesis, the multilayer emulsion prepared using ultrasonication process was utilized as a carrier system for the encapsulation of a bioactive compound i.e. curcumin. Curcumin is a natural polyphenol compound which is obtained from the turmeric plant, having numerous health promising benefits. In order to deliver the curcumin into the human body, it is necessary to develop an efficient carrier system for its encapsulation such that the physico-chemical properties of curcumin can be preserved during the storage. In this study, the encapsulation stability, antioxidant activity and release properties of curcumin encapsulated in the primary emulsion (PE, stabilized by whey protein isolate) and secondary emulsion (SE, stabilized by double layer of whey protein isolate/sodium alginate) prepared using ultrasonication was analyzed. It was observed that the formation of a double layer coating of secondary biopolymer over the primary coated droplet enhanced the encapsulation efficiency and antioxidant activity of the curcumin during the storage of 3 weeks. Moreover, the multilayer emulsions were freeze dried in order to see the effect of dehydration of emulsion on the stability of multilayer coated droplets. FTIR analysis indicated the presence of all the constituents including curcumin after the freeze drying of the emulsions. SEM images showed that the microstructure of emulsion droplets was found to be uniformly distributed in case of SE. The antioxidant activity of curcumin encapsulated in SE was found to be higher during storage whereas it was significantly reduced in other encapsulated systems like PE, olive oil and ethanol. In vitro release of curcumin from the multilayer emulsion was carried out under the simulated intestinal conditions of pancreatin enzyme and bile salt. The maximum release of 73% and 64% was obtained in SE and PE, respectively within 2 h of digestion. The different kinetic models such as zero order, first order and Higuchi model were fitted to understand the release kinetic of curcumin. The best fitting was obtained with zeroth order kinetic model based on the regression analysis of the data. Overall this study provided useful information on the formation of multilayer emulsion as a carrier system for better protection and controlled release of curcumin for the food and pharmaceutical applications.

Overall this research work highlights the efficient utilization of both the cavitation techniques i.e. ultrasound and hydrodynamic cavitation for the preparation of different oil in water emulsions which has potential application in food, pharmaceutical and cosmetic industries. Efforts have been made to improve the efficiency of the ultrasonication process not only to get the high stability emulsion but also to improve the throughput capacity of the emulsification process. On the other side, the HC proved its potential for the synthesis of emulsion on a large scale with desired stability and thus can be a good substitute to the other high energy extensive techniques used in the industries. The potential of cavitationally prepared multilayered emulsion for the encapsulation of bioactive compound was thoroughly investigated and it was concluded that the cavitation process is a viable and feasible technique for the production of emulsions as an encapsulating system for the various bioactive compounds that are useful in food, cosmetic and pharmaceutical industries.