Emerging applications of ultrasonication and cavitation in dairy industry: a review

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Abstract: In recent years, there has been emerging trends and gaining popularity of researching, exploring and applying the physical and chemical effects of ultrasonication and cavitation in dairy industry. An overview of ultrasonication and other cavitation techniques is provided here. Effect of hydrodynamic cavitation (HC) and high energy low-frequency ultrasonication on milk components such as fat, protein, and other milk constituents have been highlighted here. Detailed summary of various research studies and applications of the HC and ultrasonication in dairy processing area such as homogenization, viscosity reduction, cheese, cream and yogurt making, food safety, microbial inactivation, waste management, and cleaning are provided here. Furthermore, various research and application of low-intensity high-frequency ultrasound for dairy products analysis have been outlined here. While some applications of ultrasound and cavitation are well established in other industry, the ultrasonic and HC processing of dairy ingredients and products are gaining much attention recently and it has a great potential to become a mainstream process in dairy industry in the near future.

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PUBLIC INTEREST STATEMENT

Different application of ultrasonication has been well established in the field of medical science and chemical industry. In recent years, there has been emerging trends and gaining popularity of researching, exploring, and applying the physical and chemical effects of ultrasonication and cavitation in dairy industry. In this review paper we have tried to provide an overview of effect of hydrodynamic cavitation (HC) and high energy low-frequency ultrasonication on milk components such as fat, protein and other milk constituents. Detailed summary of research studies and applications of the HC and ultrasonication in various dairy processing have been provided here. Furthermore, various research and application of low-intensity high-frequency ultrasound for dairy products analysis have been outlined here. As such, this review paper should be of interest to a broad readership including researchers, students, and industry people those interested in research and industrial application of ultrasonication and hydrodynamic cavitation in dairy industry.
1. Introduction
The phenomenon of cavitation was conjectured much earlier by L. Euler in his theory of water turbines in 1754. The word “cavitation” was originally coined by R. E. Froude and first cited by Barnaby and Thornycroft in 1895. Barnaby and Parsons (1893) were the first one to discover and study the phenomenon of cavitation and they found that the formation of vapor bubbles on the propeller blades caused the sea-trial failure of a British high-speed warship HMS Daring in 1885. Rayleigh laid the theoretical foundation for cavitation study by solving the problem of the collapse of an empty cavity in a large mass of liquid in 1917 (Li, Brennen, & Matsumoto, 2015).

Cavitation bubbles can be generated by different physical mechanisms, such as laser light, accelerated particles, electrical discharge, steam injection, acoustic, and hydrodynamic action.

There are four principal types of cavitation (Shah, Pandit, & Moholkar, 1999):

(1) Particle cavitation: This is produced by any type of elementary particle moving at a high accelerated speed through liquid medium and rupturing the liquid, as in a bubble chamber.

(2) Optic cavitation: This is a produced by rupture of a liquid using high-intensity light such as a laser.

(3) Hydrodynamic cavitation (HC): This is produced by pressure variation in a flowing liquid caused by the velocity variation in the system.

(4) Acoustic cavitation: This is produced by pressure variation in a liquid with the application of ultrasound waves pass through it.

Among these mechanisms, in the field of dairy, majority of research work is focused on acoustic (ultrasound-induced) and recently on HC.

Ultrasound technology utilizes mechanical waves at a frequency above human hearing threshold (>16 kHz). These waves can be categorized into two frequency ranges (1) low-energy (high frequency, low power) utilizing frequencies higher than 100 kHz at intensities below 1 W cm$^{-2}$ and (2) high-energy (low frequency, high power) utilizing frequencies between 20 and 500 kHz and intensities higher than 1 W cm$^{-2}$ (Mason, Chemat, & Vinatoru, 2011). Low energy ultrasound has an application in nondestructive analytical technique to measure the physicochemical properties of food such as firmness, acidity, sugar content, ripeness, protein interactions etc. (Soria & Villamiel, 2010), whereas high energy ultrasound has an application in changing physical and chemical properties of food (Soria & Villamiel, 2010) as well as inactivation of microorganisms in foods (Piyasena, Mohareb, & McKellar, 2003).

When ultrasound is transmitted through physical medium such as liquid, the waves compress and stretch the molecular spacing of the liquid medium through which it passes. This ultrasonication waves induced compression and stretching will vary the average distance between the liquid molecules as they oscillate about their mean position. When the distance between these oscillating liquid molecules exceeds the minimum molecular distance required to hold the liquid intact, the liquid breaks down and voids are created. These voids are the so-called cavitation bubbles (Hugo Miguel Santos, Carlos Lodeiro & José-Luis Capelo-Martínez, 2009). During liquid compression and stretching, these cavitation bubbles can behave in two ways (Feldman, 1989). In the first, bubbles oscillate about some equilibrium size for many acoustic cycles, which are formed at low ultrasonic intensity range 1–3 W cm$^{-2}$ and this stage is called stable cavitation (Figure 1). In the second, when ultrasound intensities used in excess of 10 W/cm², the transient bubbles expand.
through a few acoustic cycles to a radius of at least twice their initial size, before collapsing violently on compression. This stage is called transient cavitation (Hugo Miguel Santos, Carlos Lodeiro & José-Luis Capelo-Martínez, 2009) (Figure 1). Each collapsing bubble behaves like a micro-reactor where pressures higher than 1,000 atm and temperatures of several thousand degrees are created instantaneously (Suslick, Hammerton, & Cline, 1986).

Ultrasonication treatments to the material can be applied directly and indirectly. Direct application involves immersion of ultrasonic probe directly into liquid medium. One of the drawbacks with this method is that possible metal contamination forms the detached metal pieces from the probe. The indirect application involves ultrasonication bath. The limitation with ultrasonic baths is that these are not powerful devices, hence their applications are greatly limited by the lack of ultrasonic intensity (Hugo Miguel Santos, Carlos Lodeiro & José-Luis Capelo-Martínez, 2009). In ultrasound application, cavitation occurs near the tip of the ultrasonication probe and at the transducer surface in the bath. In both applications, cavitation intensity decreases exponentially as the distance increases from the probe tip and transducer surface (Gogate, 2008). Gogate and Pandit (2004) and Gogate, Tatake, Kanthale, and Pandit (2002) mentioned that intensity of ultrasound depends significantly on the power delivery and frequency. There has been extensive research done on the application of ultrasound in the dairy field; however, due to its limitations such as metal contamination, poor transmission of ultrasound energy in large volume sample, poor spatiotemporal distribution, low energy efficiencies, and higher operational cost, this has not been adopted widely on a commercial application.

HC is induced by pressure variation in a flowing liquid caused by the velocity variation in the system (Shah et al., 1999). In HC, bubbles forms in the low pressure region and moves into the higher pressure region where they collapse (Brujan, 2011). HC can be produced by using a variety of devices such as (1) venturi and orifice creating a pressure variations in a fluid flowing through constriction channel, (2) HC pump involving a mechanical rotation of specially designed rotor to create a pressure difference, (3) high-speed homogenizer and high-pressure homogenizer creating a cavitation condition. Homogenizers have a limited commercial application due to its high energy operating cost. HC pump, orifices, and venturis are reported to be the most widely used cavitating device for generating HC (Gogate & Kabodi, 2009). In both ultrasonication and HC-induced cavitation, the collapsing bubbles release localized energy and create a spots with temperature as high.
as 1,000–10,000 K and pressure as high as 100–1,000 bar (Gogate, 2011). The collapse intensity of the cavitation in HC is less compared to ultrasonication. However, the number of cavities generated is more in HC creating larger total volume of the cavity collapse, which makes HC efficient than ultrasonication. HC is easier to scale up and utilize in continuous process at commercial scale compared to ultrasonication (Carpenter et al., 2017). Based on intensity, the type of cavitation can be described as stable and transient. In stable cavitation, cavitation bubbles of low oscillating intensity are formed which oscillate at some equilibrium size for many acoustic cycles. In transient cavitation, bubbles expand to multiple of their initial size and oscillate more rapidly before their violent collapse. Transient cavitation generates intense temperature and pressure locally at the point of collapse. Ultrasonication produces mainly transient type of cavitation. (Gogate & Pandit, 2004), whereas HC can generate both stable and transient type of cavitation by varying the geometry of a cavitating device (Aniruddha et al., 2008). Cavitation-based technologies have a very wide range of applications such as homogenization, dispersion, de-agglomeration, milling and grinding, emulsification, cell extraction, cell disintegration, degassing of liquids, transesterification of oil to biodiesel, bleaching, crystallization, preservation, clean in place, etc. Ultrasonication is a rapidly emerging and promising technology gaining application in the dairy industry. Recently various researchers have tried to take advantages of ultrasonication applications in dairy industry and in last two decades, very rapid progress has been made in this field.

Our objective is to capture all research information at one place so that it will help future researches as well as industry to review and get benefited by this information. This review article provides a detailed overview of phenomena of ultrasonication and HC. This review article also provides comprehensive summary of various application of ultrasonication and HC in dairy industry.

2. Application of cavitation to modify the milk components

Various researchers studied the cavitation-based technologies (ultrasonication and HC) for modifying the physical and chemical properties of different milk constituents such as milk fat, casein, and whey proteins.

2.1. Milk fat

Application of ultrasound and HC demonstrated a promising result in modifying the milk fat and milk fat globules. Ultrasonication treatment (at 20 kHz for up to 60 min) of skim milk sample reduce the fat globule size to approximately 10 nm (Chandrapala, Martin, Zisu, Kentish, & Ashokkumar, 2012). Villamiel and de Jong (2000) reported a substantial reduction (up to 81.5%) in the size of the fat globule for the samples treated with only ultrasonication and ultrasonication in combination with heat 70 and 75.5°C displayed a better particle distribution compared to ultrasonication without heat. Crudo et al. (2014) demonstrated the effective homogenization of milk fat particle size up to nanoscale dimensions and uniform dispersion using both HC and ultrasonication treatment. Wu, Hulbert, and Mount (2000) studied the effect of ultrasonication on milk homogenization and microscopic photographs of the fat globules size distribution revealed that high amplitude ultrasound produced a good homogenization effect compared with conventional homogenization. Similar results were reported by Ertugay, Şengül, and Şengül (2004) who studied the effect of ultrasonication on homogenization of milk using microscopic imaging and ocular micrometer to determine the size distribution of fat globules. They reported that ultrasonication with high amplitude displayed better homogenization effect compared to conventional homogenization. They also reported improvement in the homogenization efficiency as the ultrasonication time and power levels were increased. In their study, the highest homogenization efficiency achieved was at power level 100 (450 W) for 10 min with the smallest fat globule diameter 3.22 and 0.725 µm. The effect of ultrasonication treatment to enhance creaming of milk fat globules in milk emulsions system was studied by Juliano et al. (2011), Leong et al. (2014), and Juliano et al. (2013) who highlighted the potential of ultrasonication treatment in enhancing separation of milk fat. Various other researchers also demonstrated the potential application of ultrasonication treatment in enhancing the fractionation of milk fat in dairy system and achieve
the separation of larger fat globules from smaller one (Leong et al., 2016; Thomas Leong et al., 2014; Ma & Barbano, 2000; O’Mahony, Auty, & McSweeney, 2005). Ramisetty, Pandit, and Gogate (2014) demonstrated that venturi-based HC (circular venturi and slit venturi) was effective in reducing the droplet size of the coconut oil. It will be interesting to see if the similar results can be achieved on milk fat system as well. Bermúdez-Aguirre, Mawson, and Barbosa-Cánovas (2008) showed disintegration of the milk fat globule membrane as a result of ultrasonication (400 W, 24 kHz, using a 22-mm probe at 63°C for 30 min). Although great deal of advances have been made on homogenizing the milk fat globule through ultrasonication and HC, these cavitation-based technologies are still awaiting their chance for being utilized in industrial application. Ultrasonication due to its design (either probe or bath type) poses challenges for its application in continuous dairy processing plants. HC has a potential of being utilized in continuous dairy processing plants; however, this is very recent emerging technology and required some more studies and effort to push it in to mainstream industrial application.

2.2. Milk protein
Milk proteins are very important component in dairy products as they influence the various physical, chemical, and sensory characteristics. Milk proteins can be modified by various physical and chemical methods; however, there is a rising demand of clean label products and hence need of chemical-free processes. Ultrasonication and HC are physical process (chemical free) and have a great potential for manipulating the milk protein structure and functionalities required for various dairy products. Chandrapala et al. (2012) investigated the effect of ultrasonication (at 20 kHz for up to 60 min) on samples of fresh skim milk and reconstituted micellar casein. They observed no change in casein micelle size, free casein content and soluble calcium concentration, small increase in soluble whey protein and corresponding decrease in viscosity, and a small but temporary decrease in pH for the skim milk sample subjected to ultrasonication treatment for 60 min. Villamiel and de Jong (2000) displayed a similar finding where no changes in the casein were observed after any of the test conditions (ultrasonication in combination with heat at 61, 70, and 75.5°C). However, in recent study Z. Liu, P. Juliano, R. P. Williams, J. Niere, and M. A. Augustin (2014a) reported a release of protein from the micellar to the serum phase and disruption of casein micelles as a result of ultrasonication (20, 400 or 1,600 kHz at a specific energy input of 286 kJ kg⁻¹ for the reconstituted skim milks (10% w/w total solids, pH 6.7–8.0, temperature <30° C). The casein micelle disruption was more at higher pH and lower frequency. They suggested a potential application of ultrasonication for developing a milk with novel functionality by altering the size of the micelles and partitioning of caseins between the micellar and serum phases. Casein micelle can be partially disrupted by ultrasonication (high energy of collapsing bubbles) particularly at high pH resulting in increased surface area, which can be helpful in enhancing rennet and acid gelation (Liu et al., 2014a; Liu, Juliano, Williams, Niere, & Augustin, 2014b). Madadlou, Mousavi, Emam-Djomeh, Ehsani, and Sheehan (2009) reported an increase in turbidity and reduction in particle diameter at any given pH value for the casein solution as the ultrasonication power increased (at frequency of 35 kHz). They also observed higher magnitude of reduction in reassembled micelles diameter at a higher pH, suggesting an interaction between ultrasonication and pH. This could be related to loose casein micelle structure at higher pH aiding ultrasonication-induced shear force action in disruption of reassembled casein micelles. Villamiel and de Jong (2000) studied the effect of continuous flow high-intensity ultrasonication (with and without heat generation) on whey proteins (α-lactalbumin [α-La] and β-lactoglobulin [β-Lg]) and reported that ultrasonication with heat generation (61, 70, and 75.5°C) displayed higher denaturation of whey proteins compared to heat alone. Also, a noticeable synergism between ultrasonic and heat was observed for denaturation of α-La and β-Lg. Ultrasonication for 15 min generated the maximum β-sheet and S-S contents, while treatment for 30 min gave the maximum dityrosine, carbonyl, and antioxidant activity. Data obtained in this study suggest that ultrasonication has a potential for improving antioxidant activity of β-Lg. Similar observation was reported by Taylor and Richardson (1980) who studied the effect of ultrasonication on the antioxidant activity of skim milk in a linoleate emulsion system using hemoglobin as a prooxidant and reported increased antioxidant activity of skim milk and casein fractions. They suggested that increased antioxidation of skim milk
could be related to increase in the effective concentration of casein as a result of possible ultrasonication-induced disruption of casein micelle. Chandrapala, Zisu, Kentish, and Ashokkumar (2012) observed progressive increase in surface hydrophobicity and reactive thiol content of pure β-Lg when subjected to ultrasonication treatment of 20 kHz (31 W) for up to 60 min, whereas α-La protein was even more affected by ultrasonication with significant increase in surface hydrophobicity. So far, great deal of work has been done to investigate the potential of ultrasonication in manipulating the milk protein characteristics and various positive outcomes are reported. However, ultrasonication application at industrial level is struggling to get its place in continuous processes. The HC has a great potential for similar application and it can be utilized in continuous processes due to its design similar to pumps. To our knowledge, so far very few studies are done to explore the potential of HC in manipulating the milk protein structure and these will be the great area to explore.

### 2.3. Effect on other milk components and their physicochemical properties

The energy released during ultrasonication and HC-induced cavitation has been utilized by many researchers in changing the physicochemical properties on different milk components. Marchesini et al. (2012) observed certain changes in milk composition as a result of ultrasonication such as, increase in free fatty acid levels, oxidation, and decreases in somatic cell count and pH. Chouliara, Georgogianni, Kanellopoulou, and Kontominas (2010) reported increased lipid oxidation, volatile compounds as a result of ultrasonication. Daniela Bermúdez-Aguirre and Barbosa-Cánovas (2008) studied the effect of ultrasonication (400 W, 24 kHz, 120 μm amplitude) in combination with heat treatment (63°C for 30 min) on milk and reported no effect on color, reduction in pH to 6.22, increase in lactic acid content by 0.015%, reduction in density and decrease in freezing point. Villamiel and de Jong (2000) studied the effect of continuous flow high-intensity ultrasonication (with and without heat generation) on alkaline phosphatase, lactoperoxidase, and γ-glutamyltranspeptidase. They reported no significant effect of ultrasonication without heat generation on enzymes compared to control sample treated with conventional heating system having similar processing conditions, whereas ultrasonication with heat generation displayed highest denaturation of enzyme in samples. Ultrasonication in combination with heat (61, 70, and 75.5°C) showed synergistic effect for the inactivation of alkaline phosphatase, γ-glutamyltranspeptidase, and lactoperoxidase, respectively. Cameron, McMaster, and Britz (2009) studied the effect of ultrasonication on various enzymes in raw milk and reported no effect on alkaline phosphatase activity (10 min treatment), no inactivation of peroxidase activity (as achieved by Ultra-high temperature treatment); however, reduction in peroxidase activity was comparable to pasteurized milk. Nandini and Rastogi (2011) demonstrated a potential application of method involving combination of two-phase extraction with ultrasonication for the concentration and purification of lactoperoxidase in the downstream processing of lactoperoxidase from milk whey.

### 3. Application of cavitation on dairy products and processing

Cavitation energy has a great potential for its application as a clean label technology in dairy products and processing. Recently ultrasonication and HC-induced technology has gained more attention from many researchers to explore and study its potential application in dairy product and processing. Zisu, Schleyer, and Chandrapala (2012) reported the effect of ultrasonication (20 kHz, batch sonication for 1 min at 40–80 W and continuous treatment delivering an applied energy density of 4–7 J mL⁻¹) in reducing viscosity (approximately 10% and 17%) of the concentrated skim milk (50–60% solids) and preventing rapid increase in viscosity of age thickened skim milk concentrate. Li, Woo, Patel, Metzger, and Selomulya (2018) demonstrated that the HC treatment on the feed milk protein concentrate (MPC80) was effective in reducing the viscosity by 20% and 56% with respective rotor speed of 25 and 50 Hz during the spray drying process. They also reported that HC did not negatively affect the powder solubility (average a solubility of 97.5% at a reconstitution temperature of 50°C, higher topped and bulk density, and improved physicochemical properties of powders). Pathania, Ho, Hogan, McCarthy, and Tobin (2018) reported that the HC was well effective in achieving the complete hydration of milk protein concentrate powders (50°C at 20% w/w solution) compared to commonly used high-shear powder inductors/mixers process.
HC treatment also displayed reduced apparent viscosity, lower sedimentation, and improved and fast solubilization of milk protein concentrate powders. Chandrapala, Martin, Kentish, and Ashokkumar (2014) demonstrated that the ultrasonication greatly accelerated the solubilization of milk protein concentrate and micellar casein powders without significantly affecting the mineral equilibrium. The ultrasonication caused the destabilization of powder agglomerates and faster release of individual casein micelles into aqueous phase. Krešić, Lelas, Jambrak, Herceg, and Brnčić (2008) studied the effects of ultrasound (20 kHz, 15 min) on thermophysical and flowing behavior properties of whey protein isolate (WPI) and whey protein concentrate (WPC) model solution of 10% (w/w). The ultrasonicated samples displayed better solubility over the pressurized control sample of both of WPC and WPI. Ultrasonicated samples showed increase in apparent viscosity and specific enthalpy, shear-thickening behavior, and decrease of initial freezing point. Ultrasonication of whipped cream for 5 min at 300 W displayed enhanced viscosity (Amiri, Mousakhani-Ganjeh, Torbati, Ghaffarinejad, & Esmaeizadeh Kenari, 2018).

Liu et al. (2014b) in their study, on effect of ultrasonication (at 20 kHz) on the renneting properties of reconstituted skim milk (10% w/w total solids at natural pH 6.7 or alkali-adjusted to pH 8.0, 30°C), observed significant improvement in the curd firming rate, curd firmness, rennet gelation time, and the connectivity of the rennet gel network for the milk samples ultrasonicated at pH 8.0 and adjusted back to pH 6.7 compared to milk samples sonicated at pH 6.7. Also, these renneting properties were improved in milk sonicated at pH 6.7 compared to non-sonicated control milk. They suggested that ultrasonication-induced changes in milk protein contributed to these improved renneting properties. This study demonstrated the potential application of ultrasonication to manipulate the renneting properties of milk for more efficient manufacturing of cheese. Chandrapala, Zisu, Kentish, and Ashokkumar (2013) reported a change in the protein surface hydrophobicity and no change in the protein surface charge as a result of ultrasonication (20 kHz and 31 W for up to 30 min) for the micellar casein solution gels (5 wt.%) formed by addition of 7.6 mm tetra sodium pyro phosphate (TSPP). Firm gel with a fine protein network and low syneresis was observed in case of sonication before the addition of TSPP, whereas inconsistent weak gel-like structure with high syneresis was observed in case of sonication after TSPP addition. Their results showed that ultrasonication can have a significant effect on the final gel properties of casein systems. Leong et al. (2018) studied the effect of ultrasonication and heating on functional interactions between casein and whey proteins in dairy systems with different casein–whey protein ratios. The ultrasonication (20 kHz at 20.8 W calorimetric power for 1 min) improved the gelation and reduced viscosity, which was due to breaking down of heat-induced protein aggregates, whereas heated control sample displayed reduction in gelation functionality and increased viscosity for casein system (9% w/w) without added whey proteins. Zisu, Bhaskaracharya, Kentish, and Ashokkumar (2010) studied the effect of ultrasonication (continuous flow-through reactor US system, 20 kHz, 4 kW) on the functional properties of different dairy ingredients such as reconstituted WPC, whey protein and milk protein retentates, and calcium caseinate. They reported a considerable improvement in gel of the heat coagulated sample in combination with ultrasonication and reduction in particle size of samples containing 18–54% (w/w) solids. Marchesini et al. (2012) observed improved coagulation properties of milk as a result of ultrasonication, which could be potentially used in cheese making as an advantage. Zisu et al. (2011) for whey protein concentrate solutions reported a reduction in the size of the suspended insoluble aggregates and increased the clarity, increased gel strength (heated at 80°C for 20 min), reduction in gelation time, and lower syneresis as a result of ultrasonication treatment (20 kHz in a batch process for 1–60 min). Microstructure analysis of the whey protein gels indicated compact network of densely packed whey protein aggregates as a result of ultrasonication. Similar changes were not observed in case of WPI solutions, which may be due to difference in composition or absence of larger aggregates in the initial solution. Gajendragadkar and Gogate (2016) reported that when ultrasonication (low frequency, high intensity) used along with preheat treatment on cheese, whey resulted in reduced thickening or gelling properties, improved heat stability, reduced blockage of orifice of spray dryer atomizing device, and better quality of final product (WPC powder). Meletharayil, Metzger, and Patel (2016) demonstrated that HC can be effectively used as a tool.
to manipulate the titratable acidity values, rheological properties, water holding capacity, and gel microstructure in the production of Greek-style yoghurt. Chandrapala, Bui, Kentish, and Ashokkumar (2014) investigated the application of ultrasonication (high intensity low frequency for a very short time after a preheating step at ≥70°C) in improving the heat stability of calcium-fortified milks and reported break up in whey/whey and whey/casein aggregates and these aggregates did not reform during subsequent heating and thereby improving the heat stability. They also studied the acid gelation of these samples and reported that ultrasonication alone did not affect the gelation properties whereas combination of preheating (72°C/1 min) followed by ultrasonication resulted in lower gelation time, reduced gel syneresis, and higher milk viscosity compared to preheating alone. Overall, they suggested potential application of ultrasonication in improving the heat stability of calcium-fortified dairy products and enhanced gelation properties when ultrasonication and heating used in combination.

Koh et al. (2014) observed considerable reduction in the heated whey protein aggregate size and viscosity as a function of ultrasonication which did not alter after reheating. Ashokkumar et al. (2009) demonstrated a potential application of very short duration ultrasonication on reducing the increase in viscosity of whey products by breaking down the whey protein aggregates formed during prior heating step.

Nguyen, Lee, and Zhou (2012) investigated the role of ultrasonication on carbohydrate metabolism during milk fermentation using Bifidobacterium infantis, Bifidobacterium breve ATCC 15700, Bifidobacterium longum (BB-46), and Bifidobacterium animalis subsp. Bifidobacterium lactis (BB-12). They reported accelerated reaction rate of lactose hydrolysis and the transgalactosylation in fermented milk (24 h fermentation) samples treated with ultrasonication compared to control sample. They also reported an increase in lactose consumption by 2, 4, 3, and 2.5 times, respectively, for BB-46, BB-12, B. breve, and B. infantis. Wu et al. (2000) reported that ultrasonication after inoculation reduced the total fermentation time by 30 min. They also observed that sample treated with higher ultrasonication amplitude level before inoculation displayed significant improvement in viscosity, water holding capacity, and reduction in syneresis, whereas ultrasonication after inoculation did not reduce the syneresis but did increase viscosity and water holding capacity. Sakakibara, Wang, Ikeda, and Suzuki (1994) evaluated the effect of ultrasonication (450 cm$^3$ bioreactor) on milk fermentation with Lactobacillus delbrueckii. They observed increased lactose hydrolysis in ultrasonicated milk samples and decreased cell viability. However, when the ultrasonication stopped the count of viable cell increased again, since ultrasonication did not affect the ability for cell to propagate. The samples treated with ultrasonication (power 17.2 kW m$^{-2}$ for 3 h) had a 55% lactose hydrolysis and viable cell count of $4.9 \times 10^8$ cfu cm$^{-3}$ as compared to 35.6% lactose hydrolysis and viable cell count of $2 \times 10^9$ cfu cm$^{-3}$ for the control sample. Nobuyoshi and Etsuzo (2002) displayed possibility of shortening of fermentation time using ultrasonication and they suggested that this reduction in fermentation time depends on the irradiation sound pressure. However, at the high sound pressure which produces cavitation, fermentation is suppressed.

Nucleation and crystal growth are two important aspects of industrial lactose manufacture from supersaturated solutions. Zisu et al. (2014) during the investigation of ultrasonication (20 kHz, energy density from 3 to 16 J mL$^{-1}$, 30°C, flow rates of up to 12 L min$^{-1}$ in a noncontact approach) on lactose crystal recovery from whey (32% lactose) reported a rapid formation of large amount of lactose crystals and increased crystallization rate compared to stirring method for approximately 180 min. However, between 120 and 180 min, it slowed down as the metastable limit was reached. Introduction of second ultrasonication (energy density of 4 J mL$^{-1}$) at 120 min improved nuclei formation and rate of crystallization was maintained for >300 min. Despite increased rate of crystallization, smaller crystal size, and narrower crystal size distribution, there was no significant improvement in the yield due to limited lactose solubility. The studies on the effect of ultrasonication in combination with anti-solvent (ethanol at 85% v/v effective concentration) on lactose recovery from model lactose solutions (17.5% w/v), acid whey (3.85–4.95% w/v of lactose), and
concentrated acid whey (15.0–15.5% w/v of lactose) reported faster (5–30 min) and improved yields of lactose (>90%) (Bund & Pandit, 2007a, 2007b, 2007c). It appears that the lactose solubility factor that was limiting the recovery of lactose (with sonication only) could be overcome by using anti-solvents. However, it is difficult to assume the similar results at industry-relevant concentrations (50–60% w/v of lactose) without further investigation and it may not be commercially feasible to use anti-solvent during industrial manufacture of lactose. Mortazavi and Tabatabaei Yazdi (2008) reported that application of ultrasonication can generate air bubbles in ice cream and promote ice nucleation to accelerate the heat and mass transfer during freezing process and it can shorten the freezing process time, improve the quality of ice cream e.g. reducing crystal size and preventing incrustation of freezing surface.

The significant effect of ultrasonic treatment (frequency, 20 kHz; power, 100 and 300 W, 5, 10, and 15 min) was reported on rheological properties of whipped cream. Whipped cream overrun, stability, and storage modulus were increased as a result of low power ultrasound treatment. Decline in these properties was observed with increase in ultrasound input energy. Ultrasound-induced denatured and opened protein chains covered to fat cells desirably to improve whipped cream propriety (Amiri et al., 2018). Chandrapala et al. (2016) demonstrated a potential application of ultrasonication in achieving homogenization of cream at much lower temperatures (<10°C) compared to conventional homogenization at temperatures of around 50°C, which can be exploited for low energy and cost homogenization.

Martini, Suzuki, and Hartel (2008) evaluated the potential application of ultrasonication in eliminating trans-fatty acids from lipid-based food formulations. Use of high-intensity ultrasonication on milk fat-based lipid model system displayed the reduction in the induction time of crystallization (faster crystallization) at a constant crystallization temperature and generated smaller size crystal and higher viscosity of crystallized samples. They suggested that degree of supercooling in combination with ultrasonication can be used as an effective tool in manipulating the crystallization behavior of lipid-based food formulations.

Muthukumaran, Kentish, Ashokkumar, and Stevens (2005) studied the potential effect of low-frequency ultrasound to improve cross-flow ultrafiltration of dairy whey solutions. They reported that ultrasonic irradiation at low power levels has a potential of significantly enhancing the permeate flux with an enhancement factor of between 1.2 and 1.7. The combination of turbulence promoters (spacers) in combination with ultrasound can be used as an effective tool on doubling in the permeate flux. Ultrasonication helps to lower the compressibility of both the initial protein deposit and the growing cake layers without altering the membrane integrity and concentration profile of the whey proteins.

Holsbrink and Schildauer (2009) mentioned about the application of thermal energy generated by high-frequency ultrasonic vibrations in the welding and sealing of packaging material. Industry is currently successfully using this application specifically in sealing on UHT packages.

Ultrasonication application in sealing on UHT pack has been well established and used at industrial level since some time now. However, ultrasonication-based technology is still facing challenges for its application in continuous dairy processing plants; on the other side, HC-based technology has gained its entry for the application in manufacturing of high protein yoghurt with smooth texture. Also the application of HC in reducing the milk concentrate viscosity during evaporation has shown promising potential for its application at industrial level.

4. Effect of cavitation on dairy product sensory
While the ultrasonication and HC method have many promising applications, care should be required to avoid any sensory-related negative impact on the dairy products. Different researches tried to understand the impact of ultrasonication on the dairy products. Marchesini et al. (2012) performed sensory evaluation of the ultrasonicated milk samples and reported significant increase
in a burnt off-flavor with increasing intensity and duration of the ultrasound treatment. However, addition of CO₂ helped in significantly reducing the burnt off-flavor. They also reported improved coagulation properties and enhanced sour flavor for the ultrasonicated milk samples. Chouliara et al. (2010) reported that ultrasonicated raw and pasteurized milk in a taste scored equal to or lower than that of untreated milk, whereas ultrasonicated thermized milk taste scored higher than its untreated milk on day 4 of storage. Juliano et al. (2014) investigated the effect of ultrasonication on lipid oxidation in different types of milk (raw milk, pasteurized skim milk) using different frequencies (20, 400, 1,000, 1,600, and 2,000 kHz), temperatures (4, 20, 45, and 63°C) and times. They reported that lipid oxidation in milk can be controlled by decreasing the sonication time and the temperature. Riener, Noci, Cronin, Morgan, and Lyng (2009) studied the chemical nature and possible genesis of volatiles produced with the ultrasonication. They treated 200 mL of milk (1.5% fat) for varying time (2.5, 5, 10, 15, and 20 min) using ultrasonication system fitted with an ultrasonic horn (diameter 22 mm) set at a maximum acoustic power output of 400 W (frequency 24 kHz). Posttreatment analysis of sample showed presence of various volatile compounds such as benzene, toluene, 1,3-butadiene, 5-methyl-1, 3-cyclopentadiene, and a series of aliphatic 1-alkenes, which were predominantly hydrocarbons. These compounds were believed to be of pyrolytic origin and possibly generated by high localized temperatures associated with ultrasonic cavitation. On similar line, Torkamani, Juliano, Ajlouni, and Singh (2014) studied the effects of ultrasonication on the lipid oxidation in freshly pasteurized cheddar cheese whey for 10 and 30 min at 37°C. In their study, they found that the whey treated between 400 and 1,000 kHz had the highest concentration of hydroxyl radical. They did not observe any changes in phospholipid composition, free fatty acid composition, and increase in lipid oxidation of the whey treated at different frequency in the range 20–2,000 kHz in comparison with non-sonicated sample. They suggested the use of ultrasonication in whey processing applications without having any negative impact on whey lipid profile and oxidation. Vercet, Oria, Marquina, Crelier, and Lopez-Buesa (2002) reported improved rheological properties of yogurt made with process involving combined treatment (manothermosonication) of milk with ultrasonication (12 s at 20 kHz) and moderate pressure (2 kg pressure, 40°C).

While applying the ultrasonication to the dairy products, its effect on sensory properties should be considered. To our knowledge, no study has been done so far to study the impact of HC treatment on sensory properties of dairy products. We believe that the HC will have less negative impact on the sensory properties compared to ultrasonication because the collapse intensity of the cavitation in HC is less compared to ultrasonication.

5. Cavitation application in food safety
The energy released during ultrasonication and HC-induced cavitation has a great potential to improve the food safety by destroying the spoilage and pathogenic microorganisms and also to detect the foreign material. The early application of ultrasound in inactivation of microbes was reported in the late 1920s (Harvey & Loomis, 1929); however, the overall lethal effects were limited on spoilage microorganism to achieve sterilization. Rapid advancements in cavitation-related technologies over the last few decades have again generated the interest of application in microbial inactivation. Recently, there has been an emerging trend of nonthermal technologies as an alternative to heat treatment for food processing. On similar trend, application of ultrasound technology has been explored for pasteurization and preservation of dairy foods through microorganism and enzyme inactivation.

Chouliara et al. (2010) investigated the combined effect of ultrasonication and heat treatment on total viable counts and psychrophrophs in raw, thermized, and pasteurized milk and found a 1–2.1-log cfu mL⁻¹ reduction in total viable counts and psychrophrophs for all three types of milk samples up to 6 days of storage. Crudo et al. (2014) in their study demonstrated that the HC and ultrasonication performed in loop reactors can be effectively used for homogenization and microorganism inactivation for untreated milk. In case of the HC, the percentage of microorganism reduction was the function of number of cavitational events per volume
unit, inlet pressure toward the cavitational element, geometry of the cavitator plate, and the volume of vapor generated. The highest volume of vapor and reduction in microbial load (up to 88%) was obtained with single centered rectangular hole HC plate. In case of ultrasonication, they were able to achieve 95% inactivation efficiency; however, it required addition of CO₂, higher applied power, and 10 min of treatment time. They suggested that HC combined with a suitable gas would be more feasible for commercial application. Şengül, Erkaya, Başlar, and Ertugay (2011) studied the effect of ultrasonication (400 W and 24 kHz with a 22-mm diameter probe) on the viable count of total bacteria and coliform in raw milk. Ultrasonication for 30 min showed 1.31 and 4.01 log cfu mL⁻¹ reduction for total and coliform bacteria as compared to 3.29 and 5.31 log reduction for total and coliform bacteria for the heat-treated samples (at 65°C for 30 min). Cameron et al. (2009) in their study reported 100% elimination of Escherichia coli in milk samples (treated for 10 min of ultrasonication) inoculated with $1 \times 10^4$ and $1 \times 10^6$ cfu mL⁻¹ E. coli, 99% and 99.14% elimination of Listeria monocytogenes for the milk samples respectively inoculated with $1 \times 10^4$ and $1 \times 10^6$ cfu mL⁻¹ L. monocytogenes, whereas in case of milk sample inoculated with $1 \times 10^4$ and $1 \times 10^6$ cfu mL⁻¹ of Pseudomonas fluorescens required ultrasonication respectively for 5 and 6 min to achieve 100% elimination. Bermúdez-Aguirre and Barbosa-Cánovas (2008) studied the effect of ultrasonication (400 W, 24 kHz, 120 μm amplitude) in combination with heat treatment (63°C for 30 min) on the inactivation of Listeria innocua with respect to variation in fat content in milk. They reported inactivation of Listeria cells in fat free milk; however, inactivation rate decreased as the fat content in milk increased. They also observed reduction in the growth of mesophiles. Cameron, McMaster, and Britz (2008) observed reduction in both E. coli and Saccharomyces cerevisiae by >99% (for both saline solution and UHT milk suspension media), 72% reduction of Lactobacillus acidophilus in saline solution, and 84% reduction of L. acidophilus in UHT milk from the initial inoculation level of $1 \times 10^4$ cfu mL⁻¹ as a result of ultrasonication (750 W, 20 kHz, at 100%). Transmission electron microscope micrographs suggested that ultrasonication caused extensive external and internal damage on all three “test” microbes, in case of E. coli formation of unique minute lipopolysaccharide vesicles from the fragmenting cell envelope as a result of ultrasonication induced emulsification. D’Amico, Silk, Wu, and Guo (2006) reported a 5-log reduction in total aerobic bacteria in raw milk, 5-log reduction of L. monocytogenes in ultrahigh-temperature milk, and a 6-log reduction in E. coli O157:H7 in pasteurized apple cider as a result of ultrasonication (20 kHz, 100% power level, 150 W acoustic power, 118 W cm⁻² acoustic intensity) in combination with mild heat (57°C) for 18 min. Second-order polynomials inactivation regressions suggested an initial period of rapid inactivation, eventually tailing off. Skiba and Khmelev (2007) studied the fundamental possibility of milk sterilization and pasteurization by ultrasonic fluctuations.

Milly, Toledo, Harrison, and Armstrong (2007) reported a reduction of 0.69 and 2.84 log cfu cycles (Clostridium sporogenes putrefactive anaerobe 3,679 spores) respectively for the skim milk treated at 3,000 and 3,600 rpm rotor speeds (HC). Application of HC has been also investigated in various food applications for the inactivation of microorganism (Lee & Han, 2015; Li, Song, & Yu, 2014; Wu et al., 2012).

Almalki and Anand (2016) demonstrated that ultrasonication (20 kHz frequency, 500 W power, and 80% amplitudes for 10 min each) was effective in reducing the biofilm forming ability of various spores (Geobacillus stearothermophilus, Bacillus licheniformis, and Bacillus sporothermodurans) on stainless steel surface. Vercet, Lopez, and Burgos (1997) studied the combined effect of heat (110–140°C) and ultrasound under moderate pressure (manothermosonication) on the resistance of extracellular lipase and protease from P. fluorescens. The manothermosonication was more efficient in inactivation of both enzymes compared to heat treatment alone. Porova, Botvinnikova, Krasulya, Cherepanov, and Potoroko (2014) in their study reported a potential application of low-frequency (20 kHz) ultrasound for heavy metal decontamination of milk without affecting its physical, chemical, and microbiological properties.
Although ultrasonication and HC have been reported to be effective in reducing the microbial load, its application in combination with traditional industrial methods (heating) will be more effective and cost efficient in improving the food quality and safety.

6. Ultrasound-based analytical methods

Where HC has a more potential for its application in continuous processing at industrial scale, low-intensity high-frequency ultrasonication has a great potential of its application in food analysis at industrial level. Low-intensity (power levels <1 W cm$^{-2}$) high-frequency (>100 kHz) ultrasonication has found its application in noninvasive analysis in dairy industry. When low-intensity high-frequency ultrasound waves are transmitted through a solid, liquid, or gas medium, their structural and elastic properties are being affected. The interaction of ultrasound waves with the medium though which they transmit changes the ultrasonic wave’s characteristics such as velocity, amplitude, wavelength, pressure, frequency, and period (Awad, Moharram, Shaltout, Asker, & Youssef, 2012). In case of dairy industry, the analytical methods developed so far are mostly based on changes in ultrasonic attenuation factor, velocity, and acoustic impedance (McClements, 1995).

Ultrasonic velocity is a function of elasticity and density of the medium, where higher elastic properties are associated with higher ultrasonic velocity. The elasticity and density of medium depends on its composition, physical characteristics, and structure and hence velocity measurement can be useful in studying these properties (McClements, 1995). Attenuation factor can be defined as any factor which transforms the acoustic energy to attenuate ultrasound waves while travelling through medium (Coupland & Saggin, 2002). Attenuation factor depends on compressibility, wall material, viscosity, scattering, and adsorption properties of the medium and hence it can be used in the application of studying and measuring the mediums physical properties such as viscosity, concentration, and microstructure (Awad et al., 2012). Changes to scattering and attenuation in the food materials have been used in various applications in food quality assurance (Chandrapala, Oliver, Kentish, & Ashokkumar, 2012). Dalgleish, Verespej, Alexander, and Corredig (2005) demonstrated that changes in ultrasonic properties (ultrasonic velocity and the ultrasonic attenuation based) can be used for studying the complete profile of the changing mineral distribution of milk and permeate and changes in ultrasonic properties, as a function of pH. Their study demonstrated that these ultrasonic properties were mostly dependent on permeate composition and were not affected by state of casein micelle, which can make this method very much suitable for studying release of calcium and the progress of acidification in milks. Nobuyoshi and Etsuzo (2002) reported abrupt increase in attenuation and sound velocity of milk at the point of coagulation and with that they proposed possibility of developing an automatic contact-free and continuous measurement system to monitor the fermentation process for the anaerobic fermentation under sealed tank condition. Alexander and Corredig (2007) suggested a great potential of high-resolution ultrasonic spectrometers in studying and measuring the various physical chemical changes such as gelation, aggregation, phase separation, etc. through measurement of changes in the velocity or attenuation of a sound wave propagating through the sample. Koc and Ozer (2008) developed a nondestructive ultrasonic measurement system to monitor the rennet-induced coagulation of whole milk during cheese manufacturing, which involved determination of ultrasonic attenuation coefficient during milk coagulation by measuring ultrasonic wave amplitude and time of flight for a known distance. When compared with coagulation start time determined using viscosity method, the ultrasonication-based method produced similar results. Wang, Bulca, and Kulozik (2007) found that ultrasonic velocity-based method was more sensitive to measure the enzymatic hydrolysis by rennet and the following aggregation process for the whey protein-free casein solution compared to oscillating rheological method. However, ultrasonic method was not as sensitive to detect formation of a casein gel. The coagulation time determined by ultrasonic method was linearly correlated with results obtained by oscillating rheological method. Gunesekaran and Ay (1996) used velocity and attenuation of ultrasonic waves to determine the coagulation cut-time of rennet set skim milk curd to develop nondestructive method. They found that ultrasonic attenuation measurements are suitable for distinguishing the effect of different experimental variables (three levels of temperature, rennet, and CaCl$_2$) and based on attenuation
change rate during the coagulation process, they proposed a turning point at attenuation rate change of ~0.1 neper m$^{-1}$ min$^{-1}$, the cut-time was proposed to be 20 min from the time the turning point was observed. The cut-times predicted by method were statistically similar to the time determined by manual method currently used in the industry. Corredig, Alexander, and Dalgleish (2004) studied the changes in ultrasonication properties (ultrasonic velocity and attenuation) during gelling of various dairy systems (renneted milk, acidified milk, and heat-gelling whey proteins). In all three systems, ultrasound was able to detect different stages of gelling reactions through measuring changes in the constituent gelling particles. The changes in ultrasonic velocity and attenuation parameters at the gelling stage in acidified milk were very small as other changes (changes in the structures of the casein micelles) occurred in the system before the gelation stage whereas gelation was more clearly observed in renneted milk and heated whey proteins. Cho and Irudayaraj (2003) demonstrated good correlation between ultrasound velocity and mechanical properties of cheeses (hardness and toughness of different types of cheeses) and these results were comparable with the mechanical properties measured using Young’s modulus. The thickness measurement of cheeses using this noncontact ultrasound method displayed excellent performance with an accuracy of 99.98%. They suggested a great potential of ultrasound technique for nondestructive and accurate measurement of mechanical properties of cheeses. Lee, Luan, and Daut (1992) studied the potential of developing an online ultrasonic rheological sensor for noninvasive and nondestructive evaluation of foods such as cheese and dough of various moisture contents. They found good qualitative agreement between the ultrasonic technique and traditional rheometry for these samples. Richard et al. (2012) demonstrated possible application of ultrasonication to evaluate the interaction of solvent with milk powder and to predict its reconstitution behavior. Their study suggested that, during the powder dispersion process, the time required by the solvent to penetrate primary particles was strongly associated with the time required by the ultrasound attenuation parameter to relax. They tested various dairy powders of different classifications and found a good agreement between powder rehydration time and ultrasound relaxation time. They suggested that ultrasonication-based instrument can be a powerful tool to evaluate the reconstitution ability of dairy powder quickly with low material costs. Buckin and Kudryashov (2001) demonstrated the application of the thickness shear mode resonator technique (MHz frequency range) for the measurement of viscoelastic parameters of weak particle casein gels (in the time scale $10^{-7}$–$10^{-9}$ s). This noninvasive technique can be used for the continuous measurement at different frequencies and it requires small amount of sample (0.1 mL). Born et al. (2010) demonstrated that quantification of protease activity on casein hydrolysis was possible by ultrasonic resonator technology (ultrasonic velocity signals) and results were comparable with UV–vis/ninhydrin assay method. Lopez, Corredig, and Alexander (2009) studied the diffusing wave and ultrasonic spectroscopy of rennet-induced gelation of milk in the presence of high-methoxyl pectin. Gülseren, Alexander, and Corredig (2010) used acoustic spectroscopy to the study the colloidal systems physical–chemical changes in situ, without dilution. They observed increased ultrasonic attenuation of skim milk with increase in concentration of milk and frequency. They also calculated the average colloidal particle size using frequency dependence of attenuation, which was about 0.15 μm for both unheated and heated milk. Ouacha et al. (2015) used velocity and attenuation-based ultrasound method to study the nondestructive characterization of the air influence on the quality of UHT milk.

Acoustic impedance is related to the proportion of transmission and reflectance of the ultrasound waves at the boundary between component phases (Coupland & Saggin, 2002) and it depends on the microstructure and composition of the transmission medium (Mohanan et al., 2002). Acoustic impedance has found its application in various analytical and measurement applications. Gan, Pallav, and Hutchins (2006) demonstrated the potential application of acoustic impedance in measuring gel formation in dairy products.

Eskelinen, Aläväntunki, Hägström, and Alatossava (2007) demonstrated that ultrasound can be effectively used to monitor the gas–solid structure of the Swiss-type cheese during the ripening process. They used a single-transducer 2 MHz longitudinal mode pulse-echo setup and
captured the volumetric ultrasonic image of a cheese sample featuring gas holes (cheese-eyes) and defects (cracks). These images were in close comparison with the images taken by an optical reference image method. Pollow, Hutchins, and Gan (2009) demonstrated a potential application of ultrasound for detecting nonmetallic foreign body objects in packaged product like cheese. Hæggström and Luukkala (2001) used ultrasound (concept based on an ultrasound reflection measurement with an echo classifier, frequency 5 MHz, probing depths were 25, 50, and 75 mm) to detect foreign bodies (ranged from bone to steel, size 1-14 mm in diameter) in commercial cheese samples. Mohanan et al. (2002) demonstrated the US-based methods to detect the added chemical preservatives in branded milk. Withers (1996) studied the potential application of ultrasonic and optical-based techniques for the noninvasive detection of fouling in food processing equipment. Elvira et al. (2006) studied the effectiveness for detecting microorganism growth in UHT packed milk using eight-channel ultrasonic-based (amplitude and time of flight of an ultrasonic 800 kHz tone burst) noninvasive device. Some more studies on quality monitoring and analytical applications of ultrasound in the milk and dairy foods are provided in Table 1.

Although a number of studies have demonstrated the potential of low-intensity high-frequency ultrasonication application in measuring the various parameters in dairy products, only very few studies have been in application at industrial level at present. We believe that more collaborative efforts involving instrument manufacture will be helpful in such situation.

7. Cleaning

Ultrasonication has found its place in very wide range of application and recently there has been gaining interest from researchers to dwell in this area. Lin and Chen (2007) investigated the effect of ultrasonication on milk fouling and found that ultrasonication was able to reduce the heat-induced milk fouling. They suggested that the ultrasonically induced movement of the depositing species around the heating surface region does not allow the molecules to stay at the heating surface long enough to from the film deposits. They suggested to conduct a more detailed and systematic investigation in this field. Koh et al. (2014) found that ultrasonication pretreatment of WPC prior to ultrafiltration resulted in alleviated membrane fouling to a small extent. However, ultrasonication after heating resulted in reduced pore blockage in membrane and retarded growth of the foulant cake as compared to heating alone. At higher solid content, the extent of changes to pore blockage and cake growth was higher. The permeate protein concentration in all test conditions remained unchanged. This work demonstrated the potential application of ultrasonication in WPC process to reduce energy requirements in the ultrafiltration as the combination of heat and ultrasound produced a lower viscosity feed solution. Muthukumaran, Kentish, Ashokkumar, Vivekanand, and Mawson (2004) demonstrated the potential usefulness of ultrasound effect in reducing the number of repeat cleaning cycle required for the full cleanliness of membrane.

Muthukumaran et al. (2004) investigated the effect of ultrasonication bath on the cleaning of whey-fouled small single sheet membrane and the variables that influence this effect. Their study demonstrated that ultrasonication enhanced the flux recovery following fouling, the extent of flux recovery was independent of the length of sonication time and increases with ultrasonic power. They also reported a synergistic effect when ultrasonication combined with surfactants. Their longer duration study repeated several times for over a month period did not show any signs of damage to the membrane surface. Satu and Gun (2007) showed the potential application of ultrasonication (temperature under 60°C) in combination with different cleaning agents to reduce the overall cleaning time.

8. Waste management

Application of cavitation in waste management has been well established in other fields; however, in the field of dairy, it is something fairly recent and gaining more attention for research in this area with the time. Adulkar and Rathod (2014) illustrated the application of ultrasound in a dairy waste water treatment for the removal of fat using enzyme as a catalyst where the enzymatic prehydrolysis of fat under the influence of ultrasound drastically reduces the reaction time from 24 h to 40 min as compared to conventional stirring with improved yield. Seo, Yun, Lee, and Han (2015)
| Product | Application | Mechanism | References |
|---------|-------------|-----------|------------|
| Milk    | Determine the concentration of soluble protein and casein micelles | Ultrasound attenuation | Griffin and Griffin (1990) |
|         | Determination of antibiotic residues | Ultrasound assisted in combination with liquid chromatography–mass spectrometry and high performance liquid chromatography | Garcia, Junza, Zafra-Gomez, Barron, and Navalon (2016), and Karageorgou, Myridakis, Stephanou, and Samanidou (2013) |
|         | Detection of plasticizer residues in milk (phthalates and melamine) | Ultrasound assisted in combination with gas chromatography–mass spectrometry and ionization mass spectrometry | Tuncel and Şenlik (2016) and Zhu, Gamez, Chen, Chingin, and Zenabi (2009) |
| Cheese  | Monitor cheese maturity and moisture content determination | Ultrasonic velocity | Benedito, Carcel, Sanjuan, and Mulet (2000) |
|         | Online milk coagulation monitoring during cheese making | Ultrasonic velocity and ultrasonic attenuation | Budelli, Perez, Negreira, and Leno (2017) and Jiménez et al. (2017) |
|         | Thickness measurement | Ultrasonic velocity | Cho and Irudayaraj (2003) |
|         | Monitor fresh cheese composition | Ultrasonic velocity | Telis-Romero, Váquiro, Bon, and Benedito (2011) |
| Butter  | Droplet size distribution and fat content determination | Ultrasonic attenuation | Dukhin, Goetz, and Travers (2005) |
|         | Determine solid fat content and monitor crystallization of fat | Ultrasonic attenuation | Martini, Bertoli, Herrera, Neeson, and Marangoni (2005) |
| Yogurt  | Monitor the progress of lactic acid fermentation | Ultrasonic velocity and ultrasonic attenuation | Masuzawa, Kimura, and Ohdaira (2003) |
| Dairy powders and ingredients | Milk protein concentrates—rehydration characterization | Acoustic resonance | Vos et al. (2016) |
|         | Whey protein isolates, native phosphocaseinate and lactose powders—monitor powder reconstitution properties | Ultrasound attenuation | Richard et al. (2012) |
|         | Casein dispersions—measure particle size distribution | Ultrasound spectroscopy | Pavey, Golding, Higgs, and Wang (1999) |
|         | Lactose crystallization—measure crystallization kinetics | Ultrasound attenuation | Yucel and Coupland (2011) |
|         | Infant formulas—iron and zinc determination | Ultrasound-assisted flame atomic absorption spectrometry | Machado, Bergmann, and Pistón (2016) |
during their study of evaluating the effect of HC treatment on H₂ production from cheese whey found that the 15 min of HC treatment was able to yield higher H₂ compared to heating and sonication treatment. When combined with alkaline conditions, the HC was more effective in increasing the soluble nutrient, complete removal of methanogens, increased purity of H₂ gas (48%), and higher lactose yield. They also demonstrated that HC pretreatment in combination with alkaline conditions can be efficiently used to pretreat organic-rich wastewater and cheese whey to reduce scale-up problem and improve H₂ production.

9. Conclusion
The application of ultrasound has been successfully exploited in medical field since late 1960s. In the food industry, the application of ultrasonication has gained popularity in various fields, such as nondestructive testing, homogenization, extraction, degassing, cutting of frozen or soft food, antifouling, microbial destruction, etc. Recently, researchers have shown great deal of interest in harnessing the potential of ultrasound in the field dairy industry. Various researchers have demonstrated the potential of ultrasound application in modifying milk components, improving efficiency of milk and milk product processing, food safety and microbial destruction, nondestructive analysis, equipment surface cleaning, and waste management. Similarly, potential of application of HC in dairy industry has been studied by many researchers. Some of these knowledge have been successfully applied in dairy industry such as ultrasound-assisted sealing of UHT packaging and HC-based process to improve yoghurt. However, still a great deal of further research is required to extend application of these techniques at industrial level. One of the limitations of ultrasonication is its challenge to use it in continuous process at higher flow rate. HC has some advantage in this case as it has a potential of application in continuous process; however, very limited research is available on HC compared to ultrasonication. There is a need of exploring the application of HC in dairy industry as well as other cavitational equipment such as venturi. Most of the ultrasonication and HC-based research were focused on dairy products such as milk, cream, cheese, yoghurt, and milk protein-based ingredients; however, to our knowledge, no study is done on other milk products such as anhydrous milk fat and butter. It would be interesting to see what ultrasonication and HC can do to these products as well.

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