Emerging Technologies in Dairy Processing: Present Status and Future Potential

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Abstract Milk and Milk products are consumed by people across all ages and countries. Being highly nutritious, dairy products are known to be susceptible to microbial and enzymatic spoilage and thus mandate improved processing methods. In recent years, the development of various non-thermal technologies like high pressure processing (HPP), pulsed electric field, ultra-sonication, membrane filtration and cold plasma, have demonstrated the potential to produce shelf stable dairy products with retained nutritional parameters. On one hand where growing awareness about the effect of nutrition and bioactive compounds on human health has paved the way for emergence of state-of-art methods of food fortification, on the other, the liability of sustaining the ever-increasing and dispersing population resulted in innovations in food processing technologies; together which supported motto of 'healthy food for all'. Specifically, focusing on impacts on safety, quality and nutritional value, the chapter discusses the principle, scope, merits and limitations of emerging technologies with respect to dairy products.

Keywords Milk products · Spoilage · Thermal processing · Cold processing · Pulse electric field · High pressure processing

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Introduction

A part of dairy processing is art, while other part is science. All dairy products start with milk, but each product entails a precise amount of proteins, fats, and nutrients. A report published by European Milk Forum in 2017, describes milk products to compose lactose, casein, fatty acids, vitamins, minerals, and various essential trace elements. The demand for dairy products is growing rapidly since they are nutrient rich and supposed to provide nutrient security. Moreover, the health benefits of dairy products have been established in prevention of various metabolic disorders osteoporosis, cardiovascular disease, and cognitive disorders (Hess et al. 2016). In agreement, Food and Agriculture Organization (FAO) reported that by 2025, there would be around 12.5% rise in world per capita dairy consumption (IDFA 2016). Further, dairy product processing provides small-scale dairy producers an opportunity to reach urban markets and earn higher cash incomes. Also, the processing of raw milk into processed milk and products, aid in generating employment in the form of milk collection, transportation, processing and marketing, and, help in dealing with seasonal dairy product shortage. Therefore, there is cumulative necessity to evolve efficient dairy processing techniques to meet product safety standards and shelf-life.

Thermal processing which involves and sterilization and pasteurization is predominantly used in dairy industry for microbiological safety (Misra et al. 2017). However, it causes extensive protein denaturation, deterioration of nutritional value with vitamins and flavour loss, reduction in physiological and sensory properties, non-enzymatic browning and freezing point depression (Mosqueda-Melgar et al. 2008; Barba et al. 2012). Therefore, to meet the consumer demand for nutritious, minimally processed, appetizing, safe and healthy dairy product with increased shelf-life, many non-thermal processes have recently been developed. The non-thermal techniques should meet microbial food safety standards with improved aroma, flavour, nutritional and physiochemical characteristics (Amaral et al. 2017; Barba et al. 2017).

To identify the emerging dairy processing techniques, the related abstracts from PubMed database was acquired and through text-mining a word cloud was obtained (Fig. 1). The lightly highlighted word (with small frequency and thus size) is representative of potential new techniques on the verge of exploration. These methods include cold plasma, high hydrostatic pressure, pulsed electric field, ultrasound, ultra sonication and membrane filtration.

Plasma

Quite popularly, plasma is defined as the fourth state of matter. The plasma state is achieved when gas (noble) is subjected to magnetic, thermal or electric energy at radio or microwave frequencies resulting in the ionization of gas. The plasma is electrically neutral in nature, i.e., it has negative charges and positive charges in

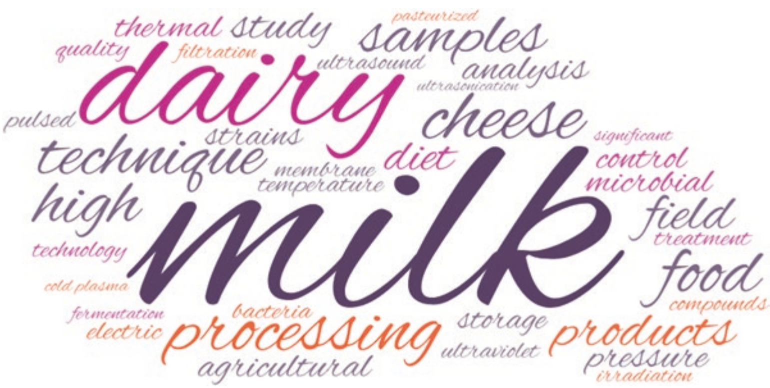

Fig. 1 Word cloud of the abstracts obtained for "Dairy processing technique" from PubMed search. A preprocessing of word-list data is done for developing an informative cloud

equal concentration (Ekezie et al. 2017).The nature of plasma will depend upon the process parameters and gas used (Phan et al. 2017).

Types of Plasma

Depending on the method of generation, plasmas can be divided into two groups as thermal plasma (TP) and non-thermal plasma (NTP) or cold plasma or non-equilibrium plasma. Cold plasma is generated under atmospheric pressure or vacuum at 30–60 °C, requiring low energy. The electrons are at high temperatures, whereas protons and neutrons have lower temperatures and are at non- equilibrium state (Thirumdas et al. 2015). Generation of thermal plasma takes place at higher pressures ($>10^5$ Pa) and high power (up to 50 MW) (Liao et al. 2017). Thermal plasmas are in thermal equilibrium state and are suitable for treating heat-sensitive foods because the uncharged molecules and ions are at low temperatures (Phan et al. 2017; Pankaj et al. 2018). Based on pressure differences, plasmas can be categorized as high-pressure, atmospheric and low-pressure plasma. The cold plasma based processing has recently gained much popularity due to its excellent performance with respect to -maintaining nutritional and sensory properties of dairy products, and -increasing shelf life through microbial inactivation (Coutinho et al. 2018).

Generation of Cold Plasma

The common sources for the cold plasma generation at atmospheric pressure are dielectric barrier discharges (DBD),corona discharges, microwave discharges and plasma jets.

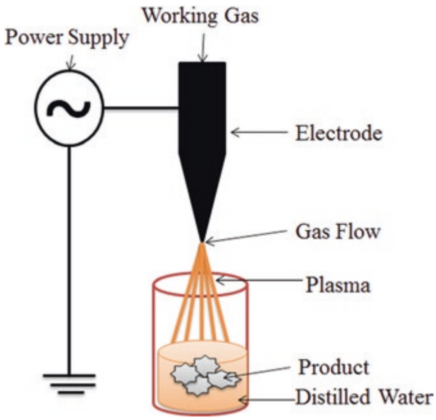

Fig. 2 Simple schematic flow of cold plasma processing

Dielectric barrier discharge (DBD) devices comprises of two metal electrodes, where one of the electrode is concealed with a dielectric barrier which stops electric current to flow and prevents the formation of sparks (Moreau et al. 2008). Plasma jet consists of two concentric electrodes between which noble gases such as helium or argon flows at a high rates (>10 slm). The inner electrode is connected to a radio frequency power at 13.56 MHz resulting in ionization of the gas, producing excited atoms, molecules and free radicals which leave the nozzle at high velocity giving a 'jet-like' appearance (Misra et al. 2016).Microwave discharges are produced by magnetron, directed to the process chamber using a waveguide, where they extent to the electrons present in the working gas (Tolouie et al. 2017). These microwaves are absorbed by the electrons causing an increase in their kinetic energy and thus resulting in gas ionization (Schlüter and Fröhling 2014).Corona discharge is the luminous plasma veil which is produced when the air surrounding a conductor or electrode gets ionized (Phan et al. 2017). Irrespective of the source, cold plasma processing can be simply represented as been depicted in Fig. 2.

Mechanism of Action

The composition of cold plasma is so complex that different reactive agents produced during plasma formation contribute to microbial inactivation. The microbial cell death by plasma is attributed to the reactive species mainly reactive oxygen species (ROS) such as atomic oxygen O, singlet oxygen $^1O_2$, superoxide anion $O^-{}_2$and ozone $O_{3;}$ and reactive nitrogen species (RNS) such as atomic nitrogen N, excited nitrogen $N_2(A)$, nitric oxide NO which causes damage to microbial cells possibly by oxidation of cytoplasmic membrane, protein and DNA strands (Bourke et al. 2017)

Application

Song et al. 2009 reported the effect of cold plasma on sliced cheese against *Listeria monocytogenes*. The study showed reduction in viable cell count after 125 s exposure to plasma treatment at atmospheric pressure.

Gurol et al. 2012 studied the effect of plasma against *Escherichia coli* in whole, semi-skimmed and skimmed milk at different time intervals in the range of 0–20 min. The noteworthy reduction in *E. coli* population was detected after 3 min irrespective of the fat content.

Kim et al. 2015 inoculated raw milk with *S. typhimurium, E coli and L. monocytogenes*, and demonstrated that 10 min plasma treatment reduced the bacterial count by around 2.4 log cfu/ml.

Ultrasonication

Ultrasound is one of the emerging techniques in food processing sector deployed to enhance the quality and safety of food products. The sound waves greater than the frequency of human hearing(>16 KHz) are known as ultrasound waves.

Types of Ultrasound

The ultrasound technology can be categorized into two, based on difference in frequency ranges i.e., low and high energy ultrasound. The low intensity ultrasound has frequency higher than 100 kHz at intensities below 1 Wcm^{-2} whereas, high-energy (high-intensity) ultrasound works at frequencies between 20 and 500 kHz at intensities higher than 1 Wcm^{-2} (Mason et al. 2011). The frequency range commonly employed in ultrasonic technology lies between 20 and 500 MHz (Yusaf and Al-Juboori 2014).

Mechanism of Action

The propagation of sound waves through the liquid medium involves alternating expansion and compression cycles. As ultrasound waves travels through the medium, the liquid bubbles oscillate and expand in size to the point when they can no longer absorb enough energy, causing bubbles to collapse known as cavitation which results in the mechanical, chemical and thermal effects. Mechanical effects comprise of collapse pressure, turbulences, and shear stresses (Yusaf and Al-Juboori 2014), while the chemical effects consist of free radicals (H^+ and OH^-) generation (Lateef et al. 2007). The cavitation causes formation of localized hot spots with

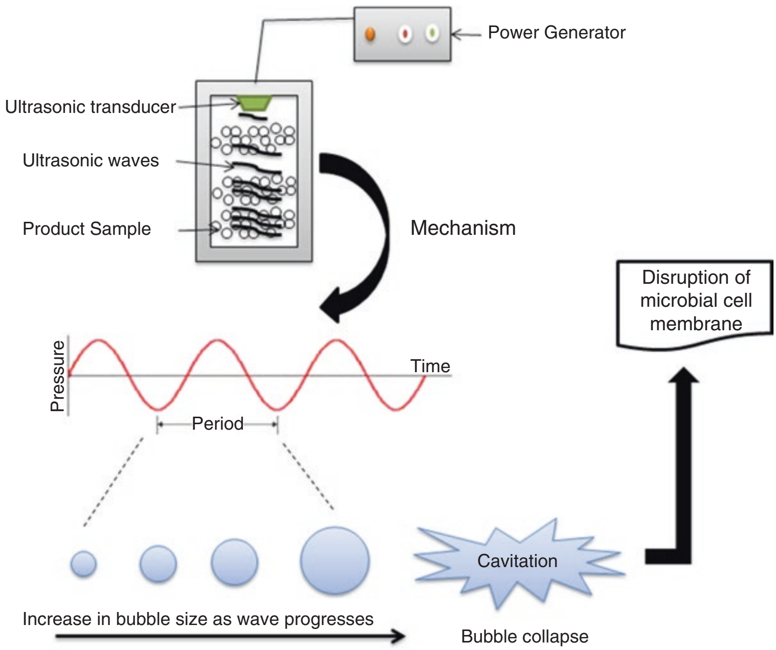

Fig. 3 Schematic diagram for ultrasound mediated product processing

enormously high temperatures of (5000 K) and pressures of 1000 atmosphere (Soria and Villamiel 2010). This pressure change produces shock waves that cause the disruption of bacterial cell membranes resulting in cell lysis(Cameron et al. 2008). Figure 3 illustrates the ultrasound mediated product processing.

Ultrasound can be applied by following methods

- Applying directly to the product.
- Coupling with the device.
- Submerging in an ultrasonic bath

Application

Adulkar and Rathod (2014) illustrated the application of ultrasound treatment in the removal of fat from dairy wastewater by lipase enzyme as a catalyst. Ultrasonic imaging has been used to study the rheological properties of cheese (Lee et al. 1992), changes in the structure of cheese due to heating (Mulet et al. 1999) and cheese maturity (Benedito et al. 2000). The studies conducted has shown the more potential effect of ultrasound combined with other techniques such as heating (thermosonication) and pressure(manothermosonication) against the spoilage microbes and

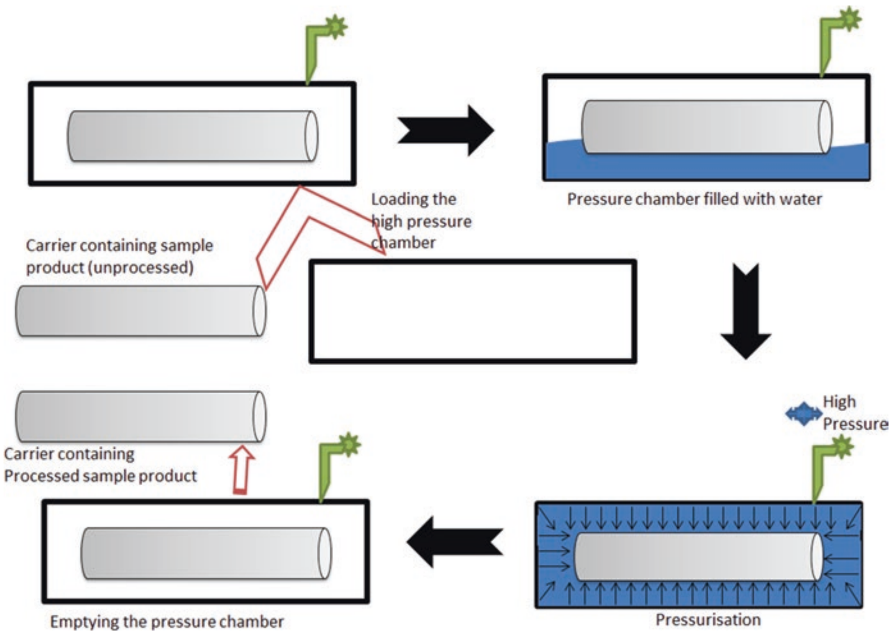

Fig. 4 Schematic flow diagram for high pressure processing

enzymes. Bermúdez-Aguirre et al. 2009, reported the enhanced inactivation effect of thermosonication for *Listeria innocua* and mesophilic bacteria in raw whole milk. Khanal et al. 2014, depicted the positive effect of high-intensity(80–100% amplitude, 1–10 min) ultrasonication for the inactivation of endospores of *Bacillus licheniformis, Bacillus coagulans* and *Geobacillus stearothermophilus* in nonfat milk.

High Pressure Processing

High Pressure Processing (HPP) inactivates harmful pathogens and vegetative spoilage microorganism by using intense pressure instead of heat. The technique involves working at pressure range of 100–1000 MPa. The HPP can be used to treat liquid as well as solid (water-containing) foods (Fig. 4).

Mechanism of Action

In HPP the packed food product is loaded in the pressure vessel, the process chamber is filled with the pressure transmitting medium commonly water. The chamber is pressurized up to the desired pressure-time combination. The food product attains the pressure of the surrounding medium and the pressure is distributed uniformly throughout the product. After the desired hold time, the chamber is depressurized and the processed food product is removed. The high pressure technique involves the following two principles:

Le Chatelier's principle: whenever stress (high pressure) is applied to a system in equilibrium, the system will counteract to the applied stress, promoting reactions that result in reduced volume causing the inactivation of microorganisms and enzymes.

Isostatic principle: It states that compression of food products occurs due to uniform pressure from every direction and regains their original shape on release of pressure. The compression of the products is independent of the size and shape of the product, because transmission of pressure to the center is mass/time independent (Carlez et al. 1994).

Though HPP is a non-thermal technique, it results in adiabatic rise in temperature (Ohlsson and Bengtsson 2002). The rendering of high pressure causes increase in the temperature of the liquid component of the food by approximately 3 °C/100 MPa. In case of food with significant amount of fat (butter/cream), the temperature increases by 8–9 °C/100 MPa (Rasanayagam et al. 2003).

Application

Jankowska et al. (2005) revealed that use of high pressure treated milk for manufacturing of yoghurt produced curd with improved firmness and reduced its syneresis. The studies showed HP-treated cheese have higher retention for total free amino acids, salt and moisture content as compared to raw or pasteurized milk cheeses (Trujillo et al. 2002). Vachon et al. 2002 reported that dynamic high pressure treatment of milk causes the in inactivation of *Listeria monocytogenes*, *Escherichia coli* and *Salmonella enteritidis* present in it. The pressure processing combined with mild heat treatment activates spores to germinate after which they lose their resistance against pressure and heat and get destroyed (Gould and Sale 1970; Knorr 1995; Gould 2000). The high pressure resistant gram-positive microorganisms requires pressure of 500–600 MPa at 25 °C for 10 min to inactivate whereas gram-negative microbes are inactivated at 300–400 MPa pressure, 25 °C temperature for 10 min (Alpas and Bozoglu 2002). Rodriguez et al. 2005 claimed the HPP treated milk causes inactivation of *E. coli* O157:H7 at 300 MPa pressure 10 °C for 10 min. Huppertz et al, 2006 has reviewed the available literature regarding the effect of HPP on bovine milk and provided a detailed account of reported changes in protein composition due to casein micelles formation; however, the efficacy of HPP on dairy products remain inconclusive due to limited equipment and instrumentation facility.

Pulsed Electric Field

The pulsed electric field (PEF) technology is considered to be one of the efficient techniques for microbial and enzymatic inactivation at mild temperatures. PEF in combination with sub-pasteurization temperatures can attain the potential levels of microbial inactivation in milk at par to conventional thermal pasteurization.

Mechanism of Action

Pulsed electric field (PEF) technology involves small bursts of high intensity electric fields (10–80 kV/cm) applied for microseconds to liquid food positioned between two electrodes. The electrical current is transmitted to each point in the liquid due to the presence of the charged molecules present it (Zhang et al. 1995 and Jose et al. 2010). There are two widely accepted theories of microbial inactivation through PEF: electrical breakdown and loss of cell membrane functionality. The former hypothesizes the microbial cell to be a membrane bound dielectric cytoplasm matrix as capacitor and the surrounding food system as medium with differing electrostatic setting: thus creating a difference in electrical conductivity on either side of microbial cell membrane thereby generating transmembrane potential. In the instance of an external electric field, the ions in the two medium moves, where ions with opposing charge are attracted towards each other causing reduction in membrane thickness and eventually pore formation and membrane breakdown (Jeyamkondan et al. 1999). The latter hypothesis suggests that due to application of PEF, the integrity and arrangement of membrane biomolecules, like proteins and phospholipid, is disordered, causing the prolonged opening of ion/protein channels thereby forming irreversible pores and disruption of microbial cell (Buckow et al. 2014). Nevertheless, a general scheme of PEF based processing is represented through Fig. 5.

Application

Craven et al. 2008 showed the effect of PEF application on ultra-high temperature treated skim milk inoculated with *Pseudomonas* spp., the major spoilage microorganism in milk. The treatment was significantly effective in the inactivation of the microbial population at 31 kVcm^{-1}, 19.2 μs, 55 °C thereby extending the shelf life of the treated milk up to 8 days at 4 °C.

Bermudez-Aguirre et al. 2012 studied the effect of PEF in skim milk (0.3% fat) against *B. cereus*, known to cause food-borne illness like diarrhoea and abdominal cramps, nausea and vomiting. The study showed that treatment at 40 kVcm^{-1}, 50 μs, 60 °C resulted in 1.5 $\log_{10}$ reduction whereas at 35 kVcm^{-1}, 25 μs, 78°Conditions, 3

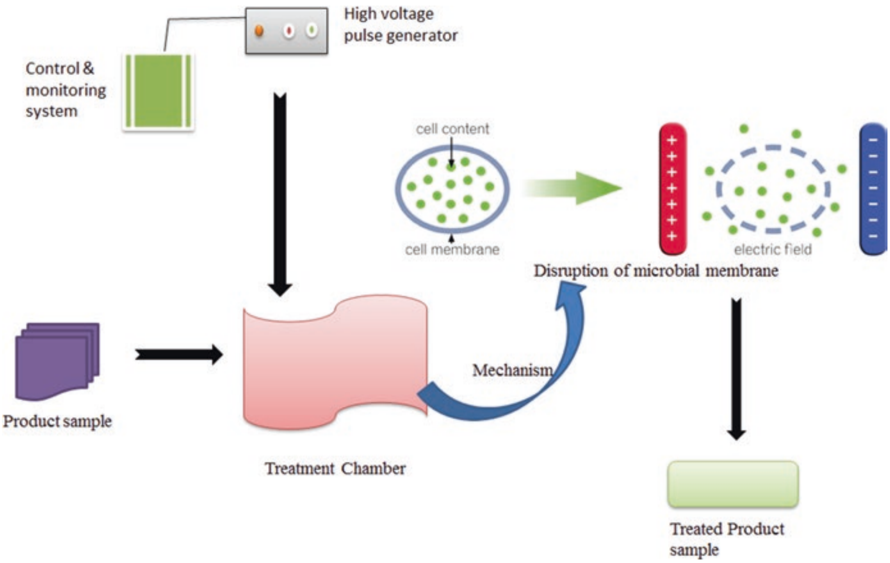

Fig. 5 Schematic flow diagram for Pulse Electric field based product processing

$\log_{10}$ reduction in the microbial population was observed. Jaeger et al. (2010) demonstrated the effect of PEF in raw milk against Alkaline Phosphatase enzyme. The treatment at 38 kVcm^{-1}, 12.3 μs, 44 °C resulted in 10% inactivation of enzyme while treatment at 38 kVcm^{-1}, 21.2 μs, 60 °C showed 27% enzyme inactivation. In a similar experiment, the continuous PEF treatment with 2 ms monopolar pulses and monopolar square wave at 35 kVcm^{-1}, 19.6 μs, 60 °C inactivated the activity of alkaline phosphatase by 67% (Shamsi et al. 2008).

Membrane Filtration

The membrane filtration refers to the separation processes by using different types of semi-permeable membranes. Specific types of membranes are used in the food industry for various purposes such as concentration, fractionation and purification of food products, extending the shelf life of many food products. The usage of membrane ensures that any undesired components like, sediment or microorganism, which may deteriorate the quality of product, be removed; thus increasing the shelf life of the final product.

Mechanism of Action

Membrane filtration employs a specific semi-permeable membrane which allows the passage of selective compounds, known as "permeates", through it to fractionate a liquid into various constituents. The effectiveness of membranes is dependent on the concentration gradient of the liquids and thus formed resultant transmembrane potential across the membrane (Winston Ho and Sirkar 1992).

Types of Membrane Filtration

The types of membrane based separation technologies in the descending order of pore size are: nano-filtration, micro-filtration, reverse osmosis (RO)and ultra-filtration. Microfiltration (MF) process is analogous to ultrafiltration (UF) but has larger membrane pore size allowing passage of 0.1–10 μm size particles and uses less pressure than that of UF process. The UF membranes having1–100 nm membrane pore size are occasionally used for the retaining proteins and other macromolecules (van Reis and Zydney 2007). The procedure involves the usage of 40 psi pressure, temperatures of 50–60 °C with a cutoff value of 10,000 MW using polysulfone membranes. A type of reverse osmosis technique, nanofiltration (NF) allows the passage of monovalent ions. Reverse Osmosis (RO) is a membrane filtration process driven by usage of high pressure thus giving entrance to solutes with very low molecular weight. The process requires700 psi, with a cutoff value of 100 MW, and temperature of 40 °C and 70–80 °C for cellulose acetate and composite membranes respectively (Kumar et al. 2013).Electro Dialysis (ED) involves the movement of ions under the applied electric potential through the membrane which is cation- or anion-selective, allowing either positive ions or negative ions to pass through. Cation-selective membranes are polyelectrolytes having negatively charged matter, passing positively charged ions whereas opposing the entry of negatively charged ions and vice-versa.

Application

The MF casein concentrated milk is more suitable for cheese production due to enhanced firmness of curd. The cheese has improved shelf-life quality by removal of bacteria and spores, accelerated ripening and reduced additive concentration (Pierre et al. 1992; Caron et al. 1997; Maubois 2002; Schafroth et al. 2005).The utility of microfiltration has been well demonstrated for the separation of whey protein from skimmed milk (Govindasamy-Lucey et al. 2007; Lawrence et al. 2008).Nanofiltration has been used for desalting whey and production of lactose free milk. Greiter et al. (2002) conducted the demineralization of salt and acid rich

Table 1 Advantages and Limitations of Dairy processing techniques

Technique	Advantages	Limitations	Reference
Cold Plasma	– Low running cost	– Suitable gas should be used (basically noble gases)	
Ultrasonication	– Non-toxic – Environment friendly – Cheap – No need of sophisticated machinery	– Formation of free radicals leading to undesirable changes in food	Majid et al. 2015
High Pressure Processing	– Increases the microbiological safety – Modifies functional properties of foods	–Works for food with water as entire process is based on compression –Increases free fatty acid levels –Denatures whey	Kim et al. 2008 Chawla et al. 2011
Pulsed electric field	–Requires less processing time –Low processing temperature		Jose et al. 2010
Membrane Filtration	–Simple –Cost effective method	– Fouling of membranes which requires timely membrane cleaning	Kumar et al. 2013

cheese whey using electrodialysis and ion exchange process to prevent the environment menace on being used.

Advantages and Limitations

Although the modern processing techniques have several merits over the conventional method of thermal processing; these techniques also have some limitations. The advantages and shortcomings of the recent processing techniques are mentioned in Table 1.

Conclusions

Dairy processing is growing promptly around the globe to meet the growing appetite for milk-products from an ever-growing population. Milk is a valuable nutritious food having short shelf-life. It requires careful handling, since it is an excellent medium for the growth of microorganisms and thus highly perishable. The appropriate processing technique allows the preservation for extended period of time and thus reducing the microbial load, and thereby reduces chances of spoilage and that of food-borne illnesses. The thermal processing techniques has demonstrated its merits but with many caveats, such as nutritional and physiochemical quality loss.

Consequently, with growing concern, many other methods have emerged. These techniques have high perspective in food industry and better alternative to thermal processing. Nevertheless, each method has some advantages and limitations. Therefore, the selection of technique is based on the context of requirement: duration of shelf-life desired, safe and healthy, or better sensory appeal.

The aforementioned emerging technologies have promising role in obtaining dairy products with enhanced sensorial, nutritional and microbiological aspects; however, a comparative study across all the techniques is warranted for inferring the most suitable method for particular product type. In the era of precision medicine, further research and analysis is required to be properly channelized towards meeting the consumer health requirement and efficacy. There is always the scope for improvement of existing one and exploration of new method for realizing the goal of 'white revolution'.

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