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Emerging Food Processing Technologies and Factors Impacting their Industrial Adoption

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Abstract

Innovative food processing technologies have been widely investigated in food processing research in recent years. These technologies offer key advantages for advancing the preservation and quality of conventional foods, for combatting the growing challenges posed by globalization, increased competitive pressures and diverse consumer demands. However, there is a need to increase the level of adoption of novel technologies to ensure the potential benefits of these technologies are exploited more by the food industry. This review outlines emerging thermal and non-thermal food processing technologies with regard to their mechanisms, applications and commercial aspects. The level of adoption of novel food processing technologies by the food industry is outlined and the factors that impact their industrial adoption are discussed. At an industry level, the technological capabilities of individual companies, their size, market share as well as their absorptive capacity impact adoption of a novel technology. Characteristics of the technology itself such as costs involved in its development and commercialization, associated risks and relative advantage, its level of complexity and compatibility influence the technology's adoption. The review concludes that a deep understanding of the development and application of a technology along with the factors influencing its acceptance are critical for its commercial adoption.

Keywords: consumer acceptance; thermal technology; non-thermal technology; food preservation; industrial adoption; technology diffusion

1. INTRODUCTION

The food industry is an increasingly competitive and dynamic domain, with increasing consumers' cognizance about what they consume. Nowadays consumers demand that food products must provide among other things, convenience, diversity, sufficient shelf life and low caloric content, low cost and environmental credentials. Important characteristics defining food quality such as appearance, texture, taste and nutritional content are strongly impacted by the way foods are processed. In order to meet these consumer demands the processing of food is becoming increasingly challenging and diverse, including alterations to prevailing food processing techniques and adoption of new innovative processing technologies (Ma and McSweeney 2008, Capitanio, Coppola, and Pascucci 2010).

A range of new food processing technologies have been investigated and developed to modify or replace traditional food processing techniques so that better quality and more consumer preference oriented foods can be manufactured (Knoerzer et al. 2011). Much attention has been focused on enhancing the process efficiency, productivity, quality, safety and stability of food products in a healthier way. The demand of more resilient and sustainable food options is further complicated by the increasing global population. Prevalence of various food related disease outbreaks, consumer awareness, safety, shelf life, quality and nutritional properties of foods are now becoming the primary concern of the food industry. However, the acceptance of new food products generally depends on the possible benefits and risks associated with the foods and the processing technology adopted. Though, food processing is an ancient phenomenon, its focus from home cooking to more industrial processing has increased the emphasis on safety and nutritional quality of product (Van Boekel et al. 2010).

The nutritional quality of food is dependent on a range of factors from farm to fork including the quality of raw material, processing techniques, packaging, transportation, storage and finally cooking (Moskowitz, Beckley, and Resurreccion 2012, Falguera, Aliguer, and Falguera 2012). Fresh raw produce is transformed into a value added food products by passing through a series of unit operations. Raw materials are first processed by techniques such as washing, cleaning, drying, chilling, freezing, sorting, grading, milling storage, and homogenization. These pre-processed materials are then transformed into value added foods and ingredients by a range of conventional or novel thermal and non-thermal techniques (Boye and Arcand 2013).

In last few decades, a range of novel processing techniques have been developed to improve physico-chemical properties of foods by minimizing processing (e.g. thermal degradation) impacts. The primary focus of these innovations was to increase production and process efficiency with minimal or no changes in nutritional properties of foods, reduce energy consumption and reduce food wastage by improving shelf life. Several novel thermal and non-thermal, process technologies have been developed to help ensure product safety, quality and acceptability. However, the development of these novel technologies is of little use until their potential is exploited by their use in industrial manufacturing processes (Sun 2014). To date the adoption of available technologies by the food industry was largely determined by the need for growth, increase in revenue and productivity, while the primary factors restricting adoption of these technologies has been availability of resources, familiarity of technology usage and market risks. Now given the challenges posed by globalization and diverse consumer demands for a technology to be adopted by industry, it must be internationally competitive, produce high quality products, meet environmental standards and regulations, as well as meet consumer preferences (Chen, Anders, and An 2013).

European studies have investigated the acceptance of novel technologies and suggest that due to differences in opinions on the ‘benefits’ of the technologies, consumers do not always prefer new technologies with demonstrated clear health benefits (Siegrist 2008, Frewer et al. 2011). Others have argued that consumer acceptance mainly relies on the perceived benefits associated with the products (Olsen, Grunert, and Sonne 2010, Henchion et al. 2013, Verneau et al. 2014). Interestingly, though consumer attitudes and perceptions have been investigated, limited research has focused on other factors impacting industrial adoption of new technologies (Chen, Anders, and An 2013, Frewer et al. 2011, Rollin, Kennedy, and Wills 2011). As new technologies are increasingly being developed to improve production processes and to yield better quality products, understanding the development and application of these innovative technologies is vital. Exploring the various factors impacting their industrial adoption, such as food laws that are recognized by strong influence and interference, market and environmental factors are also key to exploiting the technological and commercial potential of these innovative technologies.

2. NOVEL THERMAL TECHNOLOGIES

2.1 *Radio Frequency Heating*

Radio frequency (RF) heating or dielectric heating is a thermal process wherein a RF generator creates a high-frequency radio wave or alternating electric field to heat a dielectric material. This endogenous (volumetric) heating is a characteristic feature of RF technology wherein heat is generated instantaneously, selectively, uniformly and accurately at the centre of the food product, regardless of its thermal conductivity, density or size (Maloney and Harrison 2016). Dielectric energy induces molecular friction in water molecules to produce heat, therefore RF heating is influenced in part by the moisture content of the food. It is evident that every food product has certain dielectric properties and these properties are dependent on viscosity, water content, chemical composition, temperature and other physiochemical properties of the food (Alfaifi et al. 2013, Uyar et al. 2015). RF is a promising technology with numerous applications in the food industry which can be applied for continuous and batch heat processes. However its usage for continuous pasteurization and sterilization of food products has not been fully investigated (Huang, Marra, and Wang 2016, Hussein, Yetenayet, and Hosahalli 2014). Compared to conventional thermal processing, RF requires less energy and penetrates deeply, rapidly and uniformly even in large size food particles (Zheng et al. 2016, Maloney and Harrison 2016, Jiao, Tang, and Wang 2014).

Commercially**,** RF heating is suitable for use in many processing applications in the food industry (Table 1). The first and most widely reported applications of RF technology in the food industry are post-baking drying of biscuits, crackers and breakfast cereals. According to STALAM, an Italian RF equipment manufacturer, a full baking process (without convention heating) using electromagnetic waves can be achieved by distributing the appropriate amount of energy on to a dough matrix (Awuah, Ramaswamy, and Tang 2014). Whereas, Thermex-Thermatron, a USA based RF unit manufacturer recently introduced a conveyor based RF drying system (Fig. 1) with sustained power output levels of up to 120 kW which can provide the desired heat and heating rate using a PLC systems for real time response (Nagaraj et al. 2015). The technology is suitable for quick defrosting of frozen fish, meat and other raw or processed food products (Alfaifi et al. 2013, Awuah, Ramaswamy, and Tang 2014, Ha et al. 2013). Furthermore, baking of bread, thawing of food products, disinfestation and sanitization of dry food commodities such as grains, seeds, legumes and dry fruits, and sterilization of packaged solid or viscous liquid food products may also be carried out using RF heating (Jiao, Tang, and Wang 2014, Huang, Marra, and Wang 2016, Uyar et al. 2015, Zhou and Wang 2016, Mishra and Sharma 2016). Consumer concerns over product quality and increasing production costs have motivated industry to adopt novel drying technologies such as radio frequency. However as start-up costs are high and the technologies are relatively complicated as compared to conventional drying techniques, their current applications are mainly limited to small categories of fruits and vegetables only (Zhang et al. 2006). Strayfield (UK), STALAM (Italy), PSC (USA), Thermex-Thermatron (USA) and Radio-Frequency Company (USA) are suppliers of RF heaters for commercial applications worldwide (Awuah, Ramaswamy, and Tang 2014).

2.2 Microwave Heating

Microwave heating is a thermal process involving microwave electromagnetic radiations (1-100 GHz) or high-frequency alternating electric field and heat transfer. The rapidly varying electric and magnetic fields generate heat, and any food material that is exposed to these radiations is heated up. In microwave heating, electromagnetic waves oscillate within the oven at the most effective frequency range for dielectric heating which lies between 0.915 and 2.45 GHz. (Leonelli and Mason 2010). The absorption of microwave energy is dependent on the dielectric and magnetic properties of the treated material. In the context of microwave heating, the electrical properties of materials are known as dielectric properties, and these properties influence how food materials interact with electromagnetic energy. When liquid foods are treated with microwave as the presence of water in liquid foodstuffs enables them to absorb electromagnetic energy very rapidly. Slight changes in dielectric properties influence the microwave conditions of food products considerably (Ahmed and Ramaswamy 2004). Microwave intensity weakens as microwaves travel into the food product, the outer food surface absorbs more energy and heats up faster than the inner region. This results in uneven heating in deeper regions along with nutrient loss due to high surface temperature (Maloney and Harrison 2016, Leonelli and Mason 2010, Roselló-Soto et al. 2016).

The application of microwave in domestic and industrial food processing is rapidly increasing. The food industry has adopted the technique because of its rapid and uniform energy transfer, selective and volumetric heating, easily controllable and clean environment at the point of use (Maloney and Harrison 2016, Tang 2015, Leonelli and Mason 2010, Chen et al. 2016). The food industry is developing more and more products especially well-suited to microwave heating. Microwave heating may be efficiently used in both domestic and industrial operations for drying of foods, baking of biscuits and breads, precooking and cooking of meals, cereals, meats and meat products, thawing of frozen food products, blanching of vegetables, pasteurization and sterilization of fast food, meals and various other food products (Leonelli and Mason 2010, Liu and Lanier 2016, Monteiro, Carciofi, and Laurindo 2016, Roselló-Soto et al. 2016, Ozkoc, Sumnu, and Sahin 2014, Valero, Cejudo, and García-Gimeno 2014, Shaheen et al. 2012, Lee, Choi, and Jun 2016). Because of the minimum come-up time (CUT) to reach the desired process temperature, microwave heating is preferred for high-temperature short-time (HTST) processing for liquid and packed food products. Microwave heating pasteurization and sterilization not only minimizes bacterial growth but also reduces the degradation of desired components in the food (Leonelli and Mason 2010, Shaheen et al. 2012). During baking applications, it helps to retain the distinctive flavor, color and texture and minimizes the cracking of the baked products (Chen et al. 2016, Valero, Cejudo, and García-Gimeno 2014). Microwave heating has been successfully combined in batch and continuous forms with RF heating to obtain the benefits of both dielectric and conduction forms of heating (Leonelli and Mason 2010, Valero, Cejudo, and García-Gimeno 2014, FDA 2015b). This technology has an advantage over conventional microwave heating because it utilizes longer wavelengths than microwave which can penetrate deeper into the food product without surface overheating or hot or colds spots (Shaheen et al. 2012). Though, the whole process needs an optimization prior to its application especially in the case of a composite food material, or a biphasic food system (Chen et al. 2016).

The microwave manufacturers are able to customize equipment to specific applications and food product types, and the technology is successfully utilized by food manufacturers across Asia, Europe and the USA (Maloney and Harrison 2016, Valero, Cejudo, and García-Gimeno 2014). However, the industrial adoption of microwave heating has been limited by its high initial capital cost. Microwave technology offers low energy efficiency compared to conventional drying techniques (Chua and Chou 2014). Fig. 2 shows a typical conveyor modular industrial microwave systems built by Thermex Thermatron (USA). The unit can apply up to 100 kW of power to the product being heated and can be operated at 915 MHz (Goullieux and Pain 2014). Though several type of commercial microwave instruments are currently in use in Europe (Belgium, Holland, and Italy), Japan and USA for multiple food sterilization applications, none of them are designed for high power (> 125 kW) operations (Leonelli and Mason 2010). In order for the microwave drying technique to be economically viable and adopted more widely by industry, energy conservation features must be incorporated (Chua and Chou 2014) and studies carried out to demonstrate its viability for large scale commercial adoption.

2.3 Ohmic Heating

Ohmic heating (OH), also referred as Joule heating, electro-heating or electro-conductive heating, is an advanced thermal processing method wherein electric current is passed through a food, which produces heat due to the electrical resistance of the food materials (Varghese et al. 2014, Wongsa-Ngasri and Sastry 2016). Ohmic treatment has no penetration depth limitation compared to microwave and radio frequency heating. However, the electrodes in ohmic heating should be in contact with the food containing liquid large enough to modulate energy. In contrast to conventional thermal processing, OH uniformly heats the entire mass of the product resulting in high quality product with almost no deterioration of its nutrients (Wongsa-Ngasri and Sastry 2016, Deeth and Datta 2011). OH helps to conserve almost all the nutrients by avoiding local overheating of food products (Wongsa-Ngasri and Sastry 2016). The technique also enables large particulates foods (up to 2.54 cm) to heat at similar rates, thus allowing it to be used as high temperature short time (HTST) and ultra-high temperature (UHT) technique on solids or suspended materials which cannot be achieved by conventional heat processing technologies (Deeth and Datta 2011, Kaur and Singh 2015, Darvishi et al. 2015, James and James 2014). Thus, heating liquid foods containing large particulates, such as soups, stews, and fruit slices in syrups and sauces, and heat sensitive liquids are considered to be the most promising applications of OH in the food industry (Wongsa-Ngasri and Sastry 2016, Kaur and Singh 2015, Saxena, Makroo, and Srivastava 2016, Cho, Yi, and Chung 2016).

OH is an emerging technology that provides the food industry with an opportunity to produce high quality, value-added, shelf-stable products along with large number of unexplored future applications. Other potential possibilities for OH include extraction, fermentation, thawing, sterilization, pasteurization, dehydration, blanching, peeling, evaporation, packaging, starch gelatinization detection and heating of foods to serving temperature (Table 1) (Varghese et al. 2014, Duygu and Ümit 2015, Fowler and Park 2015, Loypimai et al. 2015, Ito, Fukuoka, and Hamada-Sato 2014, Yildiz-Turp et al. 2013, Bastías et al. 2015, Ramaswamy et al. 2014). Additional to heating, recent research data strongly suggests that OH may present thermal and mild non-thermal cellular damage and cause microbial inactivation in food products. However, more knowledge regarding combined effect of temperature and electric field on the destruction kinetics of microorganisms is needed (Varghese et al. 2014, Duygu and Ümit 2015, Pan, Atungulu, and Li 2014).

The technology is economic, environmental friendly and is currently employed for commercial applications. The technology can easily be integrated into both new and existing equipment and processing systems (Varghese et al. 2014, Deeth and Datta 2011). SPX (formerly APV Ltd.) was the first company in the UK to sell commercial OH systems for fruit product processing. Emmepiemme, an Italian company, manufactures most of OH systems in Europe for fruits and vegetables processing (Pan, Venkitasamy, and Li 2016). Over twenty commercial systems are currently in use across Europe, Japan, and the United States supplied by UK, USA and Italian manufacturers. The widespread commercial adoption of OH in the United States was enabled by FDA regulatory approval (Bengtson et al. 2006). Although the economics and technology appear favorable, more research is needed to completely understand the impact of specific OH instrument designs and methods for confirming temperatures within individual solids (Varghese et al. 2014).

2.4 Infra-Red Heating

Infrared is a kind of electromagnetic radiation that lies between ultraviolet and microwave energy region. Based upon its spectral range, infrared radiations are normally categorized into near-infrared (700-1400 nm), mid-infrared (1400-3000 nm), and far-infrared (3000-10000 nm) regions (Maloney and Harrison 2016, Rastogi 2015). Far-infrared is the most suitable for food processing because most food constituents absorb radiation in the far-infrared region (Rastogi 2012, Wang et al. 2014). Infrared (or radiant) heating is an indirect mode of heating wherein electromagnetic energy penetrates the food, gets adsorbed on the surface and then converts to heat. The heat adsorbed on the food surface is mostly by radiation but to a lesser extent by convection and conduction mechanism. The magnitude of heating by radiant energy depends upon the food surface characteristics as well as food color, therefore, IR radiation is typically used to alter the food quality by modifying the flavor, aroma and surface color of the food products. IR rapidly and uniformly heats the product which not only reduces the processing time and energy costs but also prevents the product overheating because of rapid heating rates. The temperature of the air inside the instrument can be kept constant because the air is not heated by IR which helps to controls the product overheating during processing (Wang et al. 2014, Mao et al. 2011, Maloney and Harrison 2016).

Due to its compact design with high controllability and safety, IR heating has been widely adopted in the food industry for cooking, frying, drying, dehydration, roasting, baking, peeling, blanching, and pasteurization of agricultural and food products (Rastogi 2012, Moreirinha et al. 2016, Ramaswamy, Krishnamurthy, and Jun 2012). Recently, IR heating has been successfully employed to inactivate lipooxygenase, lipases, α amylases and other enzymes responsible for the development of off-flavors and deterioration of fruits and vegetables (Table 1). Additionally, it is effective to inactivate bacteria, spores, yeast, and mold in both liquid and solid foods (Huang et al. 2014, Bermúdez-Aguirre and Barbosa-Cánovas 2011).

The potential of this technology has only been exploited to a limited extent for heating purposes in the food industry. The technology can penetrate and supply heat to only a few millimeters below the surface of a sample which limits its application for heating a small number of food product (Rastogi 2015, Rastogi 2012). Additionally, this poor penetration capacity of IR slows down the temperature increase of solid foods as their thermal conductivity (k) is much lower than the liquid foods. To make the penetrative radiation energy more effective, IR heating may be used in combination with other conventional modes of heating for applications such as freeze drying, dehydration, cooking and baking (Wang et al. 2014, Mao et al. 2011).

3. NON-THERMAL TECHNOLOGIES

3.1 High Pressure Processing

High pressure processing (HPP), also termed as high hydrostatic pressure and ultra-high pressure, is a food processing method which is increasingly being exploited by the food industry since the first commercial HPP processed product was produced in 1990. The technology was initially invented in Japan and is now commercially implemented and accepted worldwide (Pingen et al. 2016, Tsevdou, Eleftheriou, and Taoukis 2013). The technology is basically a cold pasteurization method that has been employed for pathogen inactivation or reduction, protein denaturation, shelf life extension and preservation of all type of solid and liquid food products (Table 1) (Tribst et al. 2016, Zhou, Karwe, and Matthews 2016). The HPP works on isostatic and Le Chatelier's principle. The effect of HP on physical properties of food is governed by isostatic principle while food chemistry and microbiology is administered by Le Chatelier's principle. In HPP, the food is treated under ultra-high pressure which is instantaneously and uniformly transmitted throughout the food product regardless of the size or shape of the food. This high pressure stimulates the phase transition or changes the molecular configuration that are associated with a decrease in volume, but oppose reaction involving volume increase (Le Chatelier's principle) (Norton and Sun, 2008). Due to this fact, the chemical properties (especially covalent bond) of molecules are intact whereas the tertiary and quaternary structures (mainly maintained by hydrophobic and ionic interactions) of molecules are transformed by high pressure. Thus, the process inactivates microbial and enzymatic activities of food without exposing it to high heat or drying treatments, and hence facilitates retention of quality parameters (Tribst et al. 2016). HPP is safe, less time consuming, energy-efficient and waste free technology and works at room temperature. Furthermore, the technique does not depend on the size, shape or composition of products and meets the highest hygienic requirements, as the product can be treated post packaging and the overall processing cost (inclusive investment and operation costs) has been estimated to 10–15 Euro cent per kg of product (Tsevdou, Eleftheriou, and Taoukis 2013). In contrast to conventional processing methods, HPP retains the taste and freshness of the product to a higher level and does not result in cooking loss, thus resulting in a high product yield (Tsevdou, Eleftheriou, and Taoukis 2013).

High-pressure thermal sterilization (HPTS), wherein high pressure is applied at high temperatures as a tool for sterilization, has been used to improve food safety and food quality. The technique works on the synergistic effects of high temperatures (90 to 121°C) and high pressures (above or equal to 600 MPa) for a shorter time period which accelerates the inactivation of microbial endospores in low-acid media. Though the technology has been used for canned food products, it is not yet available at industrial scale (Sevenich et al. 2014, Barbosa-Cánovas and Juliano 2008). According to Sevenich et al. (2014), the absence of an indicator strain to demonstrate an acceptable inactivation of pathogenic and spoilage bacterial spores could be one of the mains reasons for limiting the adoption of HPTS in the food industry. Commercially, HPP has been investigated on a range of different foods, including juices and beverages, fruits, vegetables, ready to eat meals, meat-based products (raw and cooked sausages and dry ham), fish and seafood (Tribst et al. 2016, Georget et al. 2015, Khan et al. 2014, Evert-Arriagada et al. 2014). The technology has also been used to replace or assist in the cooking and preservation of meat products (Tribst et al. 2016, http://www.hiperbaric.com/). Furthermore, in dairy sector, the technology has been reported to significantly improve the shelf life of goat's cheese and yoghurt and reduce the allergenicity of milk and ripening time of cheese (Pingen et al. 2016, Zhou, Karwe, and Matthews 2016, Barba et al. 2015).

In the last decade, the installation of HPP equipment has increased by around 17% CAGR across the globe. Sales of HPP systems exceeded more than US$ 120 million in 2016 and are estimated to exceed US$ 430 million by the end of 2026 (FMI 2017). HPP manufacturers include Hiperbaric (Spain), Avure Technologies, Inc. (USA), Universal Pasteurization Co. (USA), Next HPP (USA), Engineered Pressure System, Inc. (USA), Chemac, Inc. (USA), Elmhurst Research, Inc. (USA), American Isostatic Pressure, Inc. (USA), Bao Tou Ke Fa High Pressure Technology Co., Ltd. (China), CHIC FresherTech (China), Kobe Steel Ltd. (Japan), Multivac Sepp Haggenmuller SE & Co. (Germany), Thyssenkrupp AG (Germany) and Stansted Fluid Power Ltd. (UK). Currently more than 352 commercial HPP units which can process 1.065 million metric tons/annum of HPP pasteurized foods are installed worldwide. Of these more than 200 industrial units are currently in operation in North America (Sevenich, Rauh, and Knorr 2016). Hiperbaric, one of the largest manufacturers of HPP units, has installed 150 industrial units, across 6 continents and over 30 countries. European companies presently employing this technology include UltiFruit, Cinq Degrés Ouest and Delpierre Adrimex in France, Espuña, MRM and Campofríoin Spain and Solofruita, Rovagnati and Ghezzi in Italy for juice, meat, fish, vegetables, sliced ham and fruit jams (Tsevdou, Eleftheriou, and Taoukis 2013, FDA 2015c).

Adoption of high pressure processing systems in the food and beverages industry has increased significantly in recent years. Consumer awareness and growing health concerns have significantly increased the demand for organic food and clean label food products. This has resulted in leading industry participants making significant investments in launching such products so as to penetrate the growing market; high pressure processing equipment manufacturers have therefore over the years increased their product variants in terms of capacity either by increasing vessel size or by increasing the number of intensifiers to cater to the technology adoption by the industry (FMI 2017).

3.2 Pulsed Electric Field Processing

Pulsed electric field (PEF) is an emerging technology that has been widely studied in recent years for non-thermal food processing. It utilizes short pulses of high electric fields for a short duration (micro- to milliseconds) which pass through the product placed between a set of electrodes inside a PEF chamber (Toepfl et al. 2014, Mohamed, Ayman, and Eissa 2012, Ma et al. 2016, Griffiths and Walkling-Ribeiro 2014, Ozkoc, Sumnu, and Sahin 2014). The electro-permeabilization mechanism of PEF has been used for a variety of purposes in food and bio-processing including the deactivation of microorganisms as well as permeabilization of the cells of the food without thermal effects. The technology is viable for the liquid or semi-solid food products and has successfully been applied for the processing and preservation of foods such as fruit juices, milk, yogurt, soups, cooked meats, liquid eggs and other pumpable food products (Toepfl et al. 2014, Mohamed, Ayman, and Eissa 2012, Ma et al. 2016, Agcam, Akyildiz, and Akdemir Evrendilek 2016, Lohani and Muthukumarappan 2016). However, PEF processing is not suitable for solid food products with no air bubbles which have very low electric conductivity (Griffiths and Walkling-Ribeiro 2014). Apart from food processing, the technology has been successfully utilized as a novel extraction technique in the area of bioprocessing (Table 1). It has enhanced the yield of potential bioactive compounds and other cellular components from various plants, fruits, vegetables, algae, oil seeds and other food matrices (Griffiths and Walkling-Ribeiro 2014, Toepfl et al. 2014, Shakhova et al. 2015, Amiali and Ngadi 2012). Furthermore, it has also demonstrated a positive influence in the texture of solid plant foods and has found a significant application in reducing the sludge of wastewater (Nasir et al. 2016).

Commercially, PEF has been successfully employed for a variety of fruit juices, studies have shown that it causes minimal detrimental effect on in the sensory and physical properties but improves the shelf life and functional and textural attributes of juices (Shakhova et al. 2015, Mohamed, Ayman, and Eissa 2012). Also, it is widely used to reduce the cutting force needed during the production of French fries'. The technique is considered advantageous over traditional thermal processing because it inactivates microorganisms while maintaining the sensory quality and nutritive value of food. The technology is cost effective, energy-efficient, waste free and can easily be implemented into the existing processing lines (Ma et al. 2016, Griffiths and Walkling-Ribeiro 2014, Niemira 2014). While the technology has been successfully commercialized, it still needs more refinement for large scale industrial operations. Currently only a few commercial PEF manufacturers (PurePulse Technologies (Netherlands), KEA-Tec GmbH (Germany), Elea GmbH (Germany), Energy Pulse Systems (Portugal), Montena Technology (Switzerland), Diversified Technologies, Inc. (USA), Pulsemaster (USA) and Thomson-CSF (USA) sell commercial PEF systems. More suppliers are needed to design and construct reliable PEF units (Mohamed, Ayman, and Eissa 2012). Industrial PEF equipment is expensive and has limited treatment capacity. Unavailability of dependable and affordable industrial size equipment and a lack of innovation have limited the industrial adoption of the technology. Successful exploitation of the technique will require the identification of a cost or quality benefit to justify the costs of investment, as well as efforts to reduce the cost and most importantly to increase the equipment capacity (Toepfl and Heinz 2007).

3.3 Cold Plasma Treatment

Cold plasma technology (CPT) is a novel and emerging non-thermal processing technology that uses energetic, reactive gases to inactivate pathogenic and spoilage microorganisms pertinent to food. Plasma is an ionized gas that consists of a large number of different charged species (such as electron, ions, photons and free radicals as well as gas atoms and molecules in their fundamental or excited states) which are produced by providing energy to a neutral gas causing the production of these charged carriers (Misra et al., 2011). Plasma flows around the treated product, causing no shadow effect, ensuring all parts of the product are treated completely. It offers many potential applications for surface decontamination of both food products and food packaging materials. During surface decontamination, microorganisms are exposed to heavily bombard charged species that create surface lesions on the bacterial cell wall causing it to rupture. The technology was initially developed to enhance the surface energy of polymer and sterilization of medical equipment in hospitals (Pankaj et al. 2014, Bahrami et al. 2016, Jayasena et al. 2015). However, it has recently emerged as a powerful disinfection tool for food industry for in-package and post-packaging decontamination of food products including the dry disinfection of solid and liquid food surfaces like dried milk, meat, poultry, fish, herbs, sprouted seeds, grains, spices and fresh produces (Jayasena et al. 2015, Korachi et al. 2015, Misra et al. 2011, Lee et al. 2015, Scholtz et al. 2015). Although different plasma systems are being studied in food packaging and processing, capacity coupled plasma (CCP) sources have gained more attention because of their recent application for enhancing the shelf life and nutritional quality of food products (Table 1) (Schlüter and Fröhling 2014, Mason, Chemat, and Ashokkumar 2015, Bahrami et al. 2016).

While cold plasma technology is gradually gaining acceptance among food processors, the long lasting effect of generated reactive species and their actual mechanism is still unclear. In some cases, reactive species change the morphology of biological cells and cause hindrance in their regular functions (Jayasena et al. 2015), and the role of these active species on some sensitive food constituents such as lipids and vitamins is still ambiguous (Scholtz et al. 2015). Some of the reactive species trigger the oxidation of high lipid containing food products which produce off flavor compounds that cause rancidity. Therefore, meat products are not considered an ideal substrate for plasma treatment (Awad et al. 2012). Nevertheless, cold plasma treatment is an emerging food processing technology which is rapid and does not leave any toxic residuals or exhaust gases post-processing. However, issues regarding the nutritional content, color, texture, chemical changes and overall food quality need to be considered (Mason, Chemat, and Ashokkumar 2015, Korachi et al. 2015).

Although, CPT is not fully adopted by the food industry for large scale industrial setting due to the lack of knowledge on some critical parameters, the equipment is readily scalable and has potential for wide-scale applications. Research efforts around the globe are underway to understand the safety of the gases used before bringing it for commercial usage (Awad et al. 2012).

3.4 Ultrasound Processing

Ultrasonication has been widely researched and is increasingly employed in the food industry. Ultrasound technology is based on a series of compression and rarefaction cycles induced by sound waves, on the molecules of the medium they pass through, at a frequency above the threshold of human hearing (>16 kHz). These mechanical waves travels through the material or on its surface which leads to the formation of cavitation bubbles. At a high ultrasound power, these bubbles distribute throughout the liquid and at high acoustic pressure they grow to a critical size over a period of a few cycles and violently collapse. This phenomenon leads to energy accumulations in hot spots, generates extremely high pressure (up to 100 MPa) and temperature (up to 5000 K) which subsequently produce shear energy shock waves and turbulence in the cavitation zone. Combination of these micro events can induce various physical and chemical properties (such as breakdown the water molecules, disruption of cell wall of biological tissue or polymeric chain of biomolecules) which can be harnessed in food processing (Cheng et al. 2015, Soria and Villamiel 2010). Ultrasound processing is widely employed in the food processing and preservation applications including drying, homogenization, crystallization, defoaming, dispersing, emulsification, solubility and texture enhancement, plant sanitation, viscosity alteration, fermentations, as well as most recently ultrasonication assisted extraction (UAE) of biochemicals from plant tissue and foods (Table 1) (Guamán-Balcázar et al. 2016, Soria and Villamiel 2010, FDA 2015d, Zinoviadou et al. 2015, Ozkoc, Sumnu, and Sahin 2014). The technology has now been adopted for commercial operations across Europe and the USA (Minjares-Fuentes et al. 2016, Guamán-Balcázar et al. 2016). The US food and drug administration (US-FDA) approved the technology as a potential alternative to traditional thermal preservation approach which is capable of achieving a desired 5 log for food borne pathogens and fulfils the requirements for microbial safety in fruit juices (Alarcon-Rojo et al. 2015, Pingret, Fabiano-Tixier, and Chemat 2013). Similarly, ultrasonication assisted extraction of organic compounds from plants, foods or seeds have significantly improved the yield of (heat labile) bioactive compounds (Soria and Villamiel 2010, FDA 2015d).

Though, ultrasonic assisted processing, preservation and extraction offers many advantages including suitability for commercial scale-up, studies have reported degradation of food properties including flavor, color, or nutritional value at high amplitude ultrasound treatment (Farkas and Mohácsi-Farkas 2011, Harder, Arthur, and Arthur 2016). Therefore, a better understanding of the complex mechanism of ultrasound and its effect on functional food properties would advance industry adoption of this technology. In addition, significant improvement in high power process design, improved energy efficiency, easy installation, competitive energy consumption and low maintenance cost need to be considered to make it feasible for large industrial scale-up with worthwhile economic gains (Zinoviadou et al. 2015, Alarcon-Rojo et al. 2015, Pingret, Fabiano-Tixier, and Chemat 2013).

3.5 Irradiation

Radiation is a non-thermal food preservation process that reduces or eliminates microorganisms without causing harmful changes to the food. The process is considered to be safe under certain conditions and has been approved and adopted by more than 55 countries including USA, European countries, Japan and China (FDA 2012, Urbain 2012). Foods can be considered safe if they are irradiated by one of the following three processes approved by FDA. Gamma rays emitted from radioactive forms of the element cobalt 60 or cesium 137; X-rays produced by reflecting a high-energy stream of electrons off a heavy metals substance or electron beam wherein the high-energy electrons are propelled from an electron accelerator into food (Morehouse and Komolprasert 2004). Gamma or X-rays are high frequency and more powerful than the rays emitted by a microwave oven. They rapidly penetrate the food, inactivate microorganisms, generate no heat hence the nature of the food remain intact. The radiation dose applied to a food material is based upon its composition as well as the potential to harbor microorganisms, however no radioactive waste is produced at the food processing facility.

During processing, the food is exposed to radiation for a precise time period and never comes in contact with the radiation source. The process takes very less energy to inactivate microorganisms without increasing the temperature of food product, thus no modification in food quality occurs (Kumar et al. 2016, Marathe et al. 2016, Maloney and Harrison 2016). The process cause minimal modification in the color, flavor, nutrients level, taste, and other quality attributes of food. However, this change in food quality is associated with raw material used and the type of radiation source and its dose level applied (Urbain 2012, Gautam, Nagar, and Shashidhar 2015). Nonetheless, in all instances food remains uncooked and none of these energy sources induce radioactivity or leave any residues in the food or its packaging (FDA 2012, Kumar et al. 2016, Rawson et al. 2011).

Irradiation processes may be employed in many applications in the food industry. The technology minimizes the post-harvest loss, retains the color of fresh meat, inhibits sprout formation in products such as potatoes and control post-packaging contamination in a range of food products including cereals, legumes, spices, poultry, fish, seafood, meat, fruits vegetables, tubers and dried vegetable seasonings (Table 1) (Rawson et al. 2011, Urbain 2012, Kumar et al. 2016, Rogers 2010). However irradiation is not suitable for all food types; for instance, milk and high lipid and vitamin content food are unsuitable for irradiation. This is because peroxidation of unsaturated bonds present in the polyunsaturated fatty acids (especially omega 3, C22.5, and C22.6 fatty acids) increases the onset of oxidative rancidity in milk and high lipid foods (Caulfeld, Cassidy, and Kelly 2008). There is conflicting evidence regarding the effect of irradiation on packaging materials. Some reports argue that radiation may react with packaging polymer, printing ink labels or adhesive and can produce low molecular harmful radiolytic hydrocarbons which can transfer into the food product (FDA 2012, Marathe et al. 2016). On the other hand some reports suggest that ionizing radiation process has a potential to overcoming quarantine barriers for international trade in fresh fruits and vegetables (Urbain 2012, Vieites and Calvo 2011). Despite its limited use to date, industrial adoption of the technique is increasing as consumers are beginning to appreciate the benefits of irradiated food. Interest in the use of food irradiation increased when the US Food and Drug Administration (FDA) approved the irradiation of unprocessed red meat and meat products for pathogen control in 1997 (Morehouse and Komolprasert 2004). To ensure the safety of product, food authorities have introduced a number of detection methods which focus on selected chemical, physical or biological changes that could occur in treated foods (Kumar et al. 2016). The consensus of opinion is that, within the prescribed dose limit, the process is safe and causes no significant damage to nutritional quality (FDA 2012, Marathe et al. 2016).

3.6 UV and Pulsed Light

Techniques like ultraviolet (UV) and pulsed light (PL) light are innovative minimal food processing technologies that improve the safety of food products, maintain their appearance and nutrient content while extending their shelf life. (Cheigh et al. 2012, Abida, Rayees, and Masoodi 2014, Koutchma et al. 2016). UV technology utilizes shorter wavelength light of (100-380 nm) while pulsed light works on broad spectrum of light (180-1100 nm). However, the lethal effect of both UV and pulsed light is attributed to the UV part of the spectrum and its photochemical, photothermal and physical mechanism. The damage of microbial cell wall after the treatment is so severe that its DNA repair system is affected and enzymatic functions are affected which leads to a collapse of cell structure due to increased cell membrane permeability and depolarization of cell membrane (Elmnasser et al. 2007).

UV technology was originally used in Europe to disinfect municipal drinking water as an alternative to chlorination but now it is applied globally for the treatment of drinking water, wastewater, process water and industrial affluent (Forney and Moraru 2009, Demirci and Ngadi 2012, Koutchma 2014). The use of UV light as an alternative treatment to thermal pasteurization of fresh juices has been approved by the USFDA (IFT 2000). UV systems are low maintenance, environmentally friendly and can be installed at any point along a process system, with minimum disruption to the plant. Commercially, UV is already a well-established disinfection method in pharmaceutical manufacturing and now is rapidly gaining acceptance across food and beverage industries. It is demonstrated to be effective against bacterial pathogens in liquid foods, and it neither increases the temperature of the product not produces undesirable organoleptic changes (Oteiza, Giannuzzi, and Zaritzky 2010, Gabriel 2012). The technology (UV-C, λ=254 nm) achieves microbial inactivation by radiant exposure of at least 400 J/m^2 in all parts of the product (IFT 2000). Besides, its new industrial applications and innovative treatments are being studied and developed continuously (Forney and Moraru 2009, Hamanaka et al. 2011, Koutchma 2014).

Similarly, pulsed light (PL) technology is an emerging non-thermal technology and appears to be one of the best alternatives to conventional thermal heating for decontamination of food surfaces and food packages. The technology can be described as a sterilization or decontamination technique used mainly to inactivate surface micro-organisms on foods, packaging material and equipment (Abida, Rayees, and Masoodi 2014). It exposes the substrate to intense short time high-peak pulses of broad spectrum white light in concentrated form and is considered an alternative to continuous ultraviolet light treatments for solid and liquid foods. While this technology inactivates bacteria, fungi, and viruses more rapidly and effectively than continuous UV treatment (Elmnasser et al. 2007, Cheigh et al. 2012) and has better sterilization properties than UV light, pulsed light sterilization has a relatively low penetration depth in comparison to continuous ultraviolet light (UV). This limits its use to the surface decontamination of foods, packaging materials, and food contact surfaces, and the sterilization of certain liquids (Hierro et al. 2009, Oms-Oliu, Martín-Belloso, and Soliva-Fortuny 2010, Abida, Rayees, and Masoodi 2014). The mechanism by which pulsed light induces cell death has yet to be fully explained, but the general consensus is that the UV region of the broad spectrum of pulsed light can inactivate microorganisms by chemical modification and cleavage of its DNA (Oms-Oliu, Martín-Belloso, and Soliva-Fortuny 2010, Dhineshkumar, Ramasamy, and Kumar 2015). In most cases, the technology doesn’t alter the treated material thus legal approval is easier, however a detailed analytical study is required for each new PL treated food and that needs to follow the legal framework designed by FDA for radiation-treated foods for its commercial usage (Forney and Moraru 2009).

The effect of thermal and non-thermal processing on nutritional quality, physico-chemical properties and sensorial characteristic may further validate the use of emerging processing techniques as an upcoming tool for food processing industry. Although, all different food processing techniques have their own benefits and limitations, more research is required to facilitate food equipment manufacturers realize their potential for successful applications in the food industry. Advantages, limitations and commercial applications of emerging thermal and non-thermal technologies are described in Table 1.

4. ADOPTION OF NOVEL TECHNOLOGIES BY INDUSTRY

The adoption and incorporation of newly developed technologies by industry is a key measure of successful technology development. Rogers (2010) outlined key factors that influence novel technology adoption by industry. These include the relative advantage of the new technology; ease of adoption compared to alternative options; level of technology complexity and perception of the technology. The adoption of novel technologies can be viewed as a process of organizational change that impacts the technical and social systems of an organization (Vieites and Calvo 2011). It is consisting of two main stages: initiation and implementation (Fig. 3), with the initiation stage can be further categorized as three sub-stages: awareness of a novel technique; formation of an attitude towards it; and its evaluation from an organizational standpoint (Novoselova, Meuwissen, and Huirne 2007). Rollin et al. (2011) suggest that the decision to adopt a novel technology marks the beginning of the implementation stage, which can also be categorized into two sub stages: trial implementation and sustained implementation. Trial implementation is the limited application of the technology to determine its suitability to organizational needs while sustained implementation, the final stage of the adoption process, involves the complete assimilation of the technology into the organization. The series of decision making involved, often includes a comparative analysis of the uncertain benefits of the novel technique and of the uncertain costs of adopting it. While the benefits from adopting a new technology are ongoing and are exploited throughout the life of the acquired novel technology, costs including the fixed costs of adoption or costs associated with technical know-how, are primarily incurred at the time of adoption and cannot be recovered (Rivas 2010).

Industrial usage of the new technology may require initial investment, modification of manufacturing processes and specialized staff training. Consequently, unless new technologies can provide cost and/or performance advantages relative to existing technologies in use, their adoption by industry is unlikely (Suri 2011). When considering the possible adoption of new technologies companies evaluate potential benefits and associated risks, uncertainty of usage, and the cost of any management and production changes necessitated by the adoption (Long, Blok, and Coninx 2016). The success of the adoption of a novel technology is therefore estimated by the degree of likely integration of the technology into an organization and its potential contribution to key business objectives.

The technology, organization and environment framework describing the technology context, influence technology adoption by an enterprise. The technology context includes the internal practices and equipment of a company as well as the external technologies available to the company (Tornatzky, Fleischer, and Chakrabarti 1990). The organizational context refers to the managerial structures, scope and size of the company while the environmental context includes the industry, competitors and policy frameworks (Oliveira and Martins 2010). Furthermore, the investigation of psychological, social, political and historical issues is an essential element of commercialization of novel technologies (Frewer et al. 2011). Patist & Bates (2008) and Suri (2011) outlined that industrial adoption of any technology is often guided by the following commercial considerations :

a) The monetary and intellectual property appeal of the technology.

b) The economical need or the payback schedule of the industry. For instance in many industries the maximum payback time is shorter when the risk is higher.

c) The scalability and reliability of the novel technology and its implementations elsewhere.

d) A complete road map to technology adoption (including cost, time and resources required). This helps manage expectations and ensures a good understanding of what the technology adoption involves both in terms of investment and returns.

e) Usually the adoption of a new technology in an existing production facility means a provisional shutdown or production slow down. It is therefore important that managers understand the benefits of the implementation and maximize the adoption value during the implementation or overlap period.

f) The cultural appropriateness of integrating a novel technology also guides its adoption.

Thus the adoption a new technology by the industry, as depicted in the Fig. 4, can be seen as the collection or aggregate outcome of a range of individual calculations that estimate the incremental benefits of a new technology adoption verses the expense of changes it involves. The analysis consists an uncertain environment with limited information; ambiguous environment with regard to the future evolution of the technology and its benefits and minimal information about both the benefits and costs of the technology (Biagini et al. 2014, Gatignon and Robertson 1989). An understanding of the industrial adoption of new technologies is therefore an important aspect in achieving commercial success.

5. FACTORS IMPACTING ADOPTION OF NOVEL TECHNOLOGIES BY INDUSTRY

The costs of adoption and benefits received by the users are the most observable determinants of new technology adoption. These benefits in the case of companies are generally the difference in profits when a company shifts from an existing to a new technology. As consumer acceptance is one of the vital considerations for industry when adopting a new technology, companies need to evaluate the perceived benefits and risks (health, economic, social, and environmental) as perceived by consumers. Ethical concerns, regulatory frameworks, differential accruement of risks and benefits and socio-cultural differences are other points of consideration (Frewer et al. 2011). For instance, while the application of irradiation for food preservation has been approved by the US Food and Agriculture Organization, its usage is limited due to lack of consumer awareness and public perception. Factors other than public acceptance, that influence the adoption of new technologies by industry have been explored in previous research (Milliou and Petrakis 2011, Genius et al. 2013). These factors include availability of resources and technical skills, customer relations, company size, market share and regulatory issues. Additionally, factors pertaining to the competitive environment of the industry and its information processing characteristics also play a role in the adoption of novel technologies (Siegrist 2008, Rivas 2010). Thus overarchingly these factors can be categorized as social, environmental, economic and technological factors.

5.1 Economic and Technological Factors

5.1.1 Availability of Resources and Complementary Skills

Capital goods and skilled work force are critical in successful adoption and implementation of a new technology. Important complementarities between adoption of novel technologies and training for skill development specific to the technology are essential (Boothby, Dufour, and

Tang 2010). Technology that is expensive to implement and requires complex new skills or if acquiring the skills is time-consuming or costly then the adoption of the technology tends to be slow (Novoselova, Meuwissen, and Huirne 2007, Long, Blok, and Coninx 2016). Thus technical know-how, availability of the necessary skills and the manner in which the required skills can be developed are important determinants of adoption of new technologies by industry. For instance, while RF is widely employed in industrial applications, it is still not considered an indispensable heating technology due to its high operational cost and other technical challenges including dielectric breakdown and thermal runaway heating (FDA 2015a). Furthermore, the dielectric property information of many food products is not available for the RF region which has limited the full commercialization of this technology in food processing (Maloney and Harrison 2016).

Nemoto, Vasconcellos, & Nelson (2010) emphasized that industrial adoption of a novel technology also depends on the technical capacity of an industry. If the proposed technology is too advanced relative to the technical capacity of the industry then implementing the technology would be a much longer and complex process. Often high fixed costs and infrastructural requirements restrict adoption of novel technologies (Suri 2011).

5.1.2 Company Size and Market Share

It has been argued that company size and market share have a positive role in determining the adoption of novel technologies by industries (Cullen, Forbes, and Grout 2013). Companies with larger market share are more likely to adopt a new technology because of the availability of funds and enhanced ability to generate profits from the adoption. Larger and more profitable companies are better equipped with the financial resources required for purchase and installation of new technology. Companies with sufficient market power are more likely to find it profitable to adopt a new technology. Also, these companies may be more likely to attract the required human capital and other important resources that may be required. Many new technologies that are scale-enhancing are quickly adopted by larger companies so as to capture economies of scale from production and spread the associated fixed costs across a larger number of units.

However, there are alternative arguments that large size and market power may also impede the adoption of new technologies by industries. Firstly, multiple levels of bureaucracy in larger companies may obstruct the decision making processes about new concepts, and skills and resources required. Secondly, the argument that older and larger companies may find it relatively more expensive to adopt a new technology due to large sunk costs in their current resources and human capital (Vieites and Calvo 2011).

5.1.3 Competitive Environment of the Industry

Companies are always impacted by technology adoption decisions of their competitors (Doraszelski 2004, Kapoor and Lee 2013). For example, the Irish marine biotechnology company, Little Samphire Island company outperforms the competition by using an unique bio refinery/ integrated manufacturing process to manufacture a range of high value products derived from marine algae (Teagasc 2016). Novel technology adoption therefore is significantly influenced by strategic interactions with competitors in manners like (i) Industry concentration; (ii) Competitive price intensity, (iii) Demand uncertainty and (iv) Supplier – customer co-ordination.

5.2 Environmental Factors

5.2.1 Regulatory Compliance

New technology adoption is often impacted by the regulatory environment. Food safety issues including inactivation of pathogenic microorganisms, processing induced chemicals, as well as interaction effects between the process, packaging and product need to be evaluated. For instance reactive species responsible for providing microbial safety of cold plasma processed food can change the morphology and regulatory function of biological cells and therefore this must be examined (Jayasena et al. 2015). Similarly some studies have reported food safety risks of irradiation that it reacts with packaging material, printing ink and labels producing harmful radiolytic compounds that can contaminate food products (Marathe et al. 2016). Independent data is therefore primarily required to endorse, with a high degree of certainty, that the safety requirements of the regulatory agencies are met by the products. However, the precision and consistency demanded for confirming safety and regulatory compliance, together with the high accompanying cost, often slowdown or discourage commercialization and therefore the application of the novel processing technologies (Koutchma and Keener 2015).

Golembiewski et al. (2015) suggest that the rate of new technology adoption is contingent on development of new industry standards. In Europe, the Novel Food Regulation (EC 258/97) may be regarded as a significant example of laws being framed to meet the demand of legislative tools arising from technological innovations (Van Der Meulen 2011). Government policies to encourage new technology adoption are often designed as tax incentives to encourage industry investments in machinery and equipment pertaining to the novel technology. Another way by which government policies encourage new technology adoption is by state's investment in related infrastructure to support the industries (Boothby, Dufour, and Tang 2010). Optimal policy measures towards technology adoption also impacts the speed of its adoption e.g., by way of academic–industry research joint undertakings, where costs of bringing the new technology to market is reduced by contribution from public research labs, speeding up of the new technology adoption is achieved (Milliou and Petrakis 2011).

5.3 Social Factors

5.3.1 Consumer Acceptability

While a range of new technologies are continuously being developed with a promise of more efficient production and better quality for consumers, their industrial adoption and implementation is strongly impacted by consumers' acceptability (Fig. 5). Limited acceptance of a technology by consumers in turn affects its adoption at industry level (Golembiewski, Sick, and Bröring 2015). Previous research on consumer attitudes towards novel technologies highlights that consumer acceptance depends on whether consumers perceive benefits associated with the product and largely define the success/survival of the product on retail shelves and consequently an adoption by industries (Frewer et al. 2011, Olsen, Grunert, and Sonne 2010, Rollin, Kennedy, and Wills 2011). Many risk-benefit perceptions influence consumers' acceptance of new technologies related to their food (Golembiewski, Sick, and Bröring 2015). Research also suggest that while perceived benefits drive technology acceptance by consumers, lack of these result in accentuating concerns and perceived risks about the novel technology (Frewer et al. 2011, Rollin, Kennedy, and Wills 2011, Siegrist 2008). Other factors that impact new technology acceptance by consumers' range from socio-demographic attributes to knowledge and information about the technology, as well as trust in the source of the information (Rollin, Kennedy, and Wills 2011, Long, Blok, and Coninx 2016, Johnson 2010).

Nowadays consumers are more health cautious and focused on what they eat and how it is produced compared to a few decades ago. For example because of consumer attitudes, many processing technologies are either delayed (e.g. genetically engineered foods) or limited (e.g. ionizing radiation) (Frewer et al. 2011, Olsen, Grunert, and Sonne 2010). A survey conducted on 609 consumers across Norway, Denmark, Hungary, and Slovakia showed that European consumers have a positive view on HPP and PEF treated juice alternatives to pasteurized juice if the price is right (Olsen et al. 2011). Similarly, potential consumers from Australia and US were interested in new food processing technologies and willing to pay for new food products treated by these technologies. However, their primary willingness was to have safety and benefits statement on to the product and the risks associated with the technology applied. Among the consumers, female participants were more concerned about the safety of technology and their expected liking ratings were positively influenced by visual exposure to the product (Cardello, Schutz, and Lesher 2007, Cox and Evans 2008, Frewer et al. 2011). Thus consumer awareness and consequently their demands have forced the legislators, retailers and food and technology manufacturers to value their opinion and take it into consideration even when it is not based on a sound technical understanding of the concept.

5.3.2 Customer Relations of Industry

Having a stable and secure customer base is another important factor impacting the adoption of novel technologies by industries. As a way of reducing the risk inherent in adoption, companies' decision is impacted by the stability of its customer bases which is seen as a way to recover high expenditure incurred in the adoption new technologies (Rollin, Kennedy, and Wills 2011). In some cases, even if a technology has the potential of improving productivity or product quality, companies might not adopt due to potential cost of production shut down for new installations and the uncertainty of recovering adoption costs in presence of uncertain market scenarios (Long, Blok, and Coninx 2016, Sonne et al. 2012, Olsen, Grunert, and Sonne 2010). However, having a committed customer base can impact this decision in a favorable manner.

6. CONCLUDING REMARKS

This review of trends in food processing technologies discusses the emerging innovative food processing technologies and highlights various factors influencing adoption of such novel innovative technologies. New technologies are needed by the food industry to meet the challenges of increased competition, globalization and the growing dynamic and varied consumer demands. Emerging food processing technologies are offering sophisticated solutions to some of these challenges and meeting the consumer preferences. In contrast to traditional technologies, these novel technologies are not well accepted by industry or consumers. It is attributed that the consumers' attitude towards novel food technologies are uncertain, unknown or unfamiliar which is associated with the risk perception. Especially when some processing technologies are connected to adverse perceptions associated with the radiations. These lead to unacceptability by consumers and consequently by industry. Additionally, as detailed above, some technologies require high initial investments, expensive equipment and/or other constraints and limitations. The development of food processing technologies appears to be a long-term trend with important market potential, where research and innovations are needed to be supported by industrial investments, adoption decisions and government regulations. These innovative technologies not only present an opportunity for the development of new foods but by way of milder processing these can also improve the safety and quality of conventional foods. Additionally the different physical phenomena that these technologies utilize can potentially reduce energy and water consumption, which in turn can aid in decreasing the carbon and water footprint of food processing, thereby working towards toward environmental sustainability and global food security.

While this review details the various innovative thermal and non-thermal food processing technologies in terms of their mechanisms, applications and commercial aspects, it also outlines that at industry level, the technological capabilities of individual companies, their size, market share as well as their absorptive capacity can impact adoption. Characteristics of the technology itself such as costs involved in its development and commercialization, associated risks and relative advantage, its level of complexity and compatibility are also important.

Previous research has also outlined that adoption of novel technologies is marred by challenges both on the demand and supply side; therefore a detailed exploration and understanding of the development and application of innovative technologies along with that of factors influencing their adoption are crucial for their technological and commercial success.

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Figure captions

Fig. 1. Conveyor based modular industrial microwave systems (Photo curtesy: Thermex Thermatron, USA).

Fig. 2. Industrial RF conveyor based drying system (Photo curtesy: Thermex Thermatron, USA).

Fig. 3. The stages of technology adoption by the industry (Rollin, Kennedy, and Wills 2011, Novoselova, Meuwissen, and Huirne 2007).

Fig. 4. Conceptual model of factors impacting adoption of novel technologies (Biagini et al. 2014, Gatignon and Robertson 1989).

Fig. 5. Theoretical basis of adoption of technology by consumers (Fischer et al. 2013).

Fig. 1.

Fig. 2.

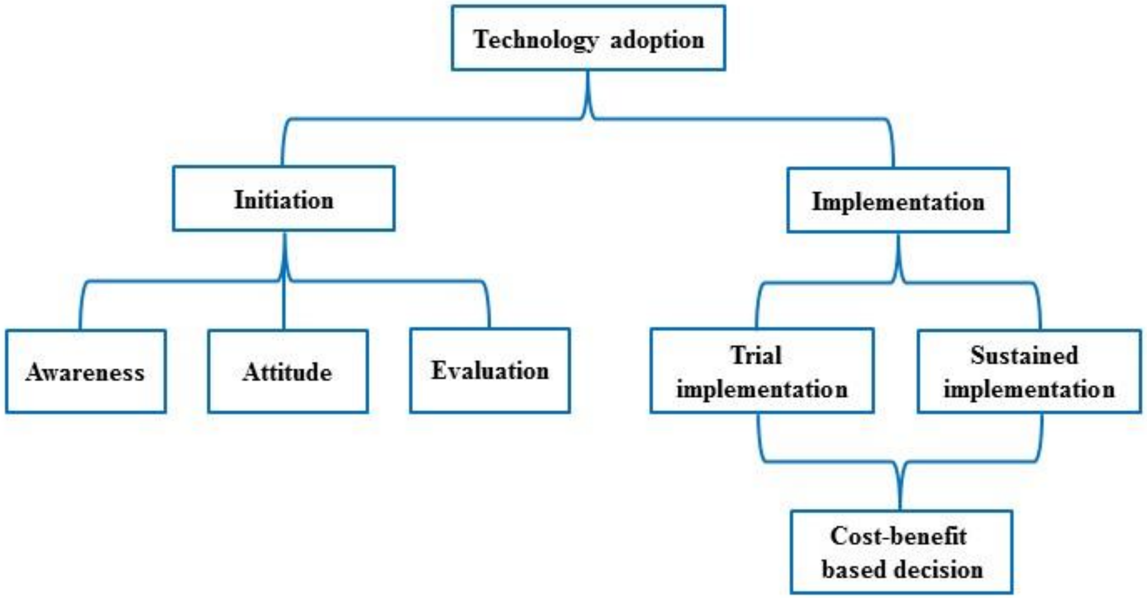

Technology adoption
Initiation
Implementation
Awareness
Attitude
Evaluation
Trial implementation
Sustained implementation
Cost-benefit based decision

Fig. 3.

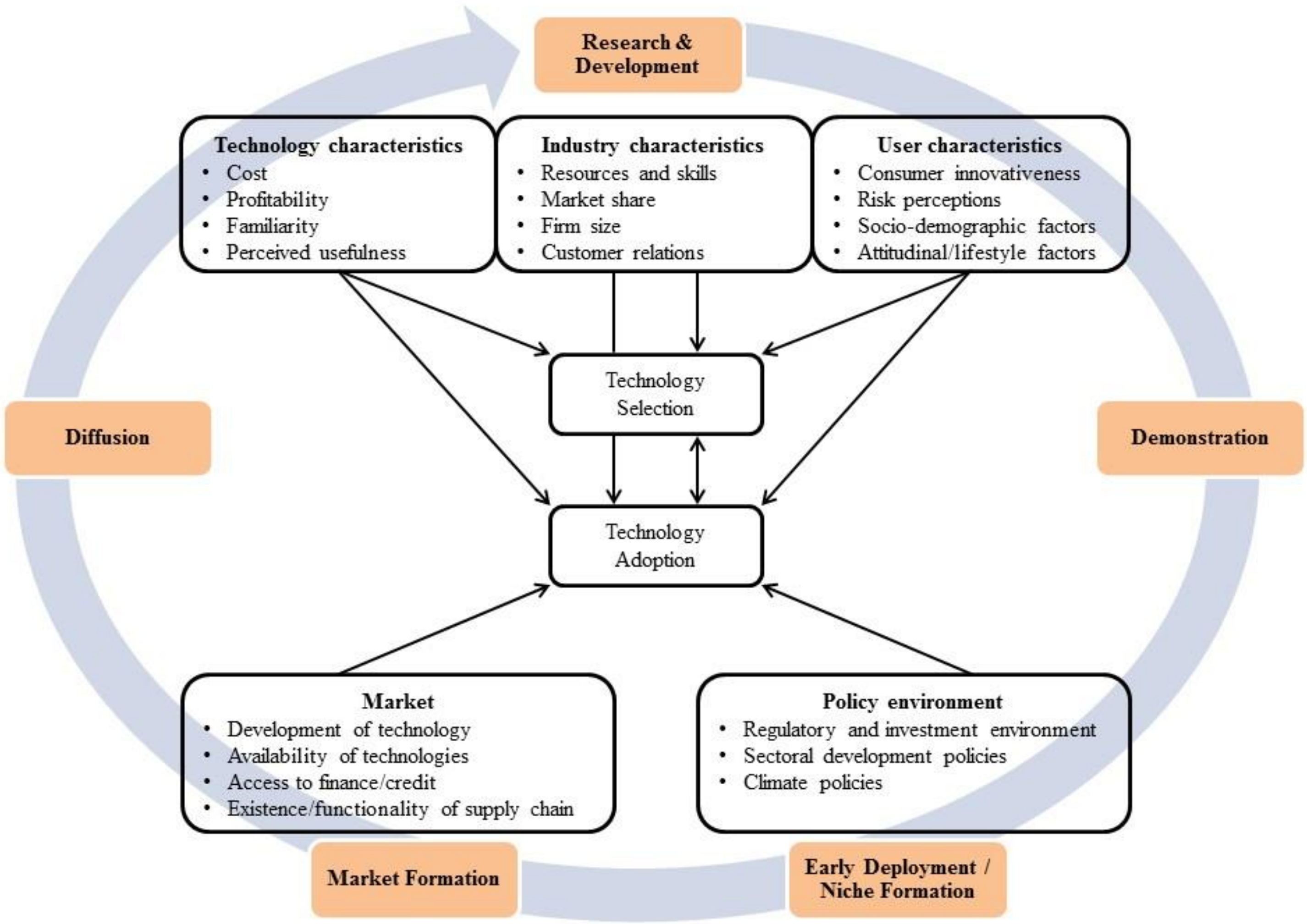
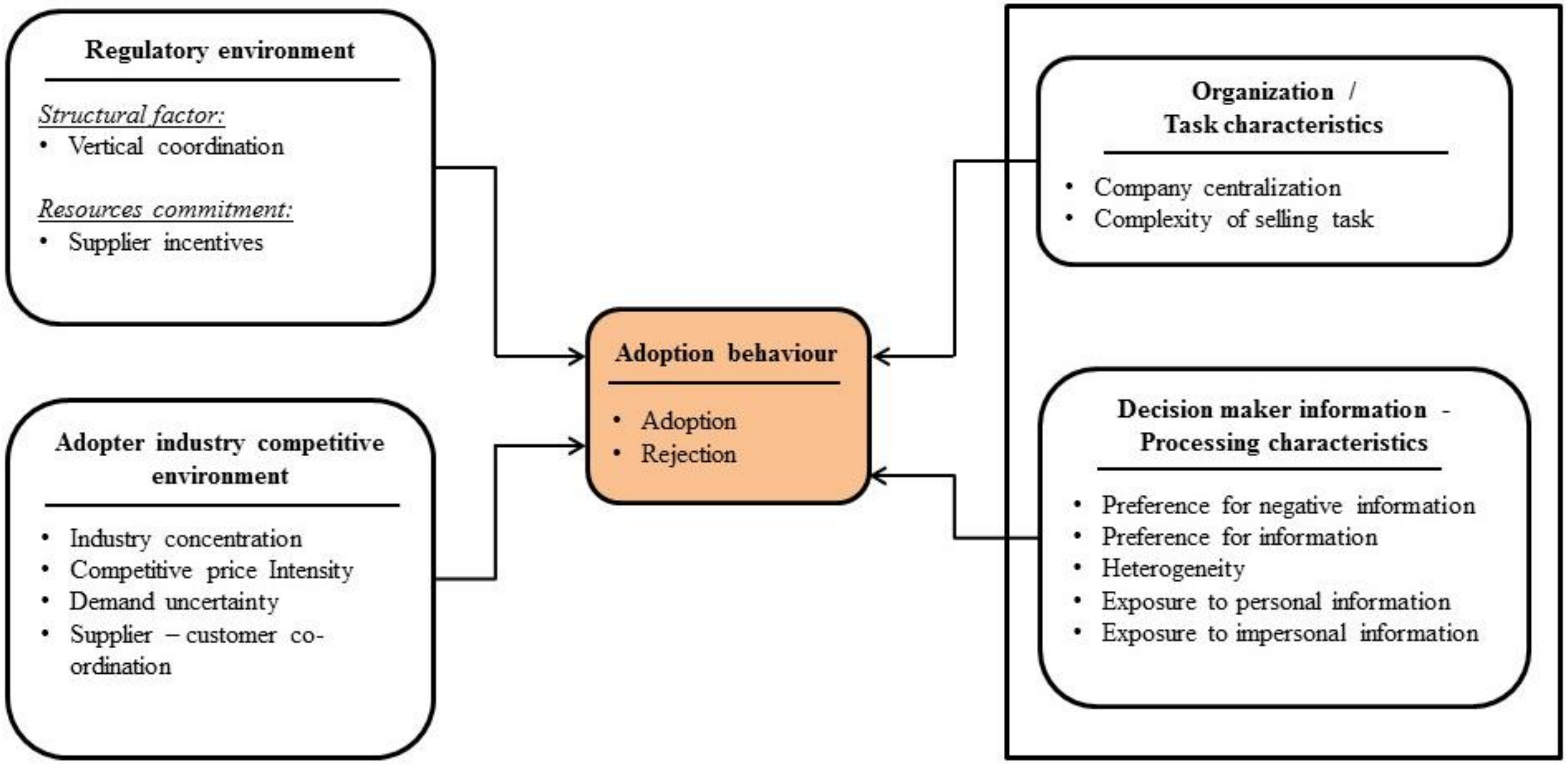

Research & Development
Technology characteristics
• Cost
• Profitability
• Familiarity
• Perceived usefulness
Industry characteristics
• Resources and skills
• Market share
• Firm size
• Customer relations
User characteristics
• Consumer innovativeness
• Risk perceptions
• Socio-demographic factors
• Attitudinal/lifestyle factors
Technology Selection
Diffusion
Demonstration
Technology Adoption
Market
• Development of technology
• Availability of technologies
• Access to finance/credit
• Existence/functionality of supply chain
Policy environment
• Regulatory and investment environment
• Sectoral development policies
• Climate policies
Market Formation
Early Deployment / Niche Formation

Fig. 4.



1304

1305 **Fig. 5.**

Table 1 Advantages and limitations of some novel food processing technologies and their commercial applications

Process technology	Advantages	Limitations	Commercial applications
Thermal technologies			
Radio Frequency Heating	• Increased throughput and reduced footprint • Shorter process lines with instant start up • Contactless heating • Increased penetration power • Improved moisture levelling • More opportunity for new product development • May be used alone or combined with conventional heating • Sensory, nutritional and functional values of food are less affected • More energy efficient than surface heating techniques	• Equipment and operating cost • Reduced power density • Not good for fresh produce and protein (Meat) • Probiotic food cannot be treated	• Vacuum drying of temperature sensitive products • Post baking drying of biscuits and bakery products • Defrosting of fish and meats • Cooking of bacon and vegetable blanching • Tempering of frozen foods, such as beef, butter blocks prior to ongoing processing • Energy efficient processing of nuts, seeds, spices, dry foods, pet foods • Broad application range including food safety, agriculture, wood and waste water treatment • Disinfect, disinfest, and pasteurize food products without chemicals • Controls germination in grains and seeds and enhanced storage quality
Microwave Heating	• Reduced carbon footprint • May be used alone or combined with conventional heating • Heat generates within the products • Reachable acceleration and time savings	• Need a high input of engineering intelligence • High energy costs • Need a lot of knowledge or experience to understand uneven heating or the thermal runaway	• Thawing and tempering meals • Reheating of previously cooked or prepared food • Cooking, baking and pasteurizing • Vacuum drying of thermo-labile products

	• Safe food products for consumers		• Defrosting of fish, meats and frozen food products • Puffing of snack foods, cooking of bacon and vegetable blanching • Tempering of frozen foods • Waste treatment • Blanching, microwave assisted pasteurization and sterilization
Ohmic Heating	• Allows the use of High Temperature Short Time (HTST) and Ultrahigh Temperature (UHT) techniques on solids or suspended materials • Generates heat within the product • Energy efficient processing • Volumetric and uniform heating • Applicable equally in batch and flow-through systems • High throughput and reduced process time	• More knowledge on the effects of applied electric field, current and frequency on different microorganisms and foods (at molecular and cellular level) are required • Cold-spots identification and measurement during complex foods processing • Detailed studies on modelling and heating pattern of complex foods are required • Electroporation mechanism decreases the productivity of fermentation • Not suitable for solid food products • Materials to be treated should contain sufficient water and electrolytes	• Blanching, evaporation, extraction, dehydration, fermentation, sterilization, pasteurization and heating of foods to serving temperature • Reduces the lag phase of the fermentation • Causes a thermal and non-thermal lethal effect on the microorganisms • Used in military or in long-duration space missions • Most promising for aseptic processing of fluids containing particulates and fluids of high viscosity • Appropriate for both liquid and solid particulates • Highly effective for yeast cell destruction

Infra-Red Heating	• Fast heating rate and shorter response time • Uniform drying temperature • High degree of process control • Possibility of selective heating • Reduction in drying time • Increased energy efficiency • Better-quality finished products • Clean working environment • Can be combined with conventional convective heating	• Low penetration power • Prolonged exposure of biological materials may cause fracturing • Modelling of infrared heat transfer inside food is critical • Radiation energy may be absorbed at the surface of a food system due to water content	• Drying and dehydration of fruit and vegetable products • Drying of seaweed, vegetables, fish flakes, and pasta • Inactivates bacteria, spores, yeast and mold in both liquid and solid foods • Other applications include roasting, frying, broiling, heating, and cooking meat and meat products, soybeans, cereal grains, cocoa beans and nuts.
Non-thermal technologies			
High Pressure Processing	• No evidence of toxicity • Colors, flavors and nutrients are preserved • Reduced processing times • Uniformity of treatment throughout food • Desirable texture changes possible • In-package processing possible	• Little effect on food enzyme activity • Some microbes may survive • Expensive equipment • Foods should have approx. 40% free water for anti-microbial effect • Limited packaging options • Regulatory issues to be resolved	• Kills vegetative bacteria (and spores at higher temperatures) • Pasteurization and sterilization of fruits, vegetables, meats, sauces, pickles, yoghurts and salad dressings • Potential for reduction or elimination of chemical preservatives • Decontamination of high risk or high value heat sensitive ingredients

Pulsed Electric Field Processing	• Colors, flavors & nutrients are preserved • No evidence of toxicity • Relatively short treatment time	• No effect on enzymes and spores • Difficult to use with conductive materials • Only suitable for liquids or particles in liquids • Only effective in combination with heat • By products of electrolysis may adversely affect foods • Safety concerns in local processing environment • Energy efficiency not yet certain • Regulatory issues remain to be resolved • Presence of bubbles may lead to non-uniform treatment • Operational and safety issues	• For liquid foods • Pasteurization of fruit juices, soups, liquid egg and milk • Accelerated thawing • Decontamination of heat sensitive foods • Inactivates vegetative cells
Cold Plasma Treatment	• Effective with temperature sensitive products • Reduce cross-contamination and the establishment of biofilms on equipment. • Minimal effects on food quality and appearance of the product • No shadowing effect ensuring all parts of a product are treated	• No commercial instrument available for disinfection of both food product and packaging materials • Used by various universities and research organization but not by industry • No potential scale up to pilot plant level for food industry yet • Spores inactivation mechanism is unknown • Interaction of electronically excited molecules with the food or packaging materials needs to be identified	• Inactivates surface microflora and spores on packaging materials/ food surfaces • Decontamination technology for mild surface such as cut vegetables and fresh meat • Shelf-life extension or online disinfection of processing equipment • Food packaging, preservation, food contact surfaces and food processing equipment • Irregularly shaped packages such as bottles can be effectively treated,

		• Stability for large-scale commercial operations is not clear • Modification of food packaging polymers is expected • Regulatory issues	contrary to technologies such as UV or pulsed light where shadowing occurs
Ultrasound Processing	• Reduction of process times and temperatures • Little adaptation required of existing processing plant • Increased heat transfer • Batch or continuous operation • Can be used alone or in combination with heat and/or pressure • Higher throughput, and lower energy consumption • Achieves a desired 5 log for food borne pathogens in fruit juices	• Complex mode of action • Depth of penetration affected by solids and air in the product • Possible damage by free radicals • Unwanted modification of food structure and texture • Needs to be used in combination with another process (e.g. heating) • Potential problems with scaling-up plant • Negatively modify some food properties including flavor, color, or nutritional value • Possible modification of food structure and texture	• Effective against vegetative cells, spores and enzymes • Effective tool for microbial inactivation • Minimal effect on the ascorbic acid content during processing • Enhances extraction yield • Fruit juices preservation
Irradiation	• Excellent penetration into foods • Reliable and energy efficient • Little loss of food quality • Suitable for large-scale production • Improvement in flavor in some foods	• High capital cost • Localized risks from radiation • Poor consumer understanding • Changes in flavor due to oxidation • Difficult to detect • Higher doses may produce radiation-induced degradation products	• Suitable for sterilization • Insecticidal • Suitable for non-microbial applications (e.g. sprout inhibition) • Appropriate for fruits, vegetables, herbs, spices, meat and fish preservation • Packaging

	• Minimal modification in the flavor, color, nutrients, taste, and other quality attributes of food • Negligible or subtle losses of bioactive compounds • No increase in food temperature during processing	• Formation of free radicals	• Suitable for Raw, dry foods, or processed food
UV and Pulsed Light (PL) Treatment	• No thermal effect, so quality and nutrient content are retained • Maintains food texture and nutrients • Can be applied with other non-thermal processing technologies • Neither increases the temperature of the product nor produces undesirable organoleptic changes • Unlike chemical biocides, UV does not alter the chemical composition, taste, odor or pH of the product and leave no toxins or residues into the process	• PL-Mostly suitable for liquid foods and surface of solid foods and hence limiting its application • PL-The mechanism by which pulsed light induces cell death is yet to be fully explained • PL-Packaging materials for irradiation should be chemically stable • PL- The material should be transparent in order to allow the light to pass into the food • UV- More kinetic inactivation data for pathogen and spoilage microorganisms is required to predict UV disinfection rates on food surfaces • UV- Dose response behavior of food pathogens in viscous liquid foods needs to be developed	• Shelf-life extension of ready to eat cooked meat products • Surface decontamination of eggs and chicken • Alternative treatment to thermal pasteurization of fresh juices • Bacterial inactivation in fruit juices and milk • Decontamination of food processing equipment • Decontamination of food powders • Water sterilization and wastewater disinfection • Decontamination of air and surfaces • Mitigation of allergen from food

Source: Adapted from (Fellows 2009); updated from (Shaheen et al. 2012, Rastogi 2012, Abida, Rayees, and Masoodi 2014, Koutchma 2014, Pankaj et al. 2014, Patist and Bates 2008, Farkas and Mohácsi-Farkas 2011, Rawson et al. 2011, Kaur and Singh 2015, Hussein, Yetenayet, and Hosahalli 2014, Norton and Sun 2008)