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Microwave-based sustainable in-container thermal pasteurization and sterilization technologies for foods

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Thermal processing is an important unit operation in the food industry for the production of prepackaged foods with extended shelf-life. Conventional thermal processes, such as canning, are widely employed in the food industry, but the energy efficiency of these processes is typically low. In addition, a significant amount of water is wasted during these processes. In recent years, advanced microwave-based pasteurization and sterilization systems have been developed for the production of extended shelf-life products at refrigeration and room temperatures, respectively. Microwave systems are relatively more water and energy efficient, can be directly powered by renewable electricity sources (*e.g.*, solar, wind, or hydropower), and have potential to reduce greenhouse gas emissions, and thus environmentally sustainable. The quality of microwave processed foods is often superior to that of foods processed using conventional thermal methods. Glass, metal, paper, and synthetic polymers continue to dominate as packaging materials for thermally processed food. However, sustainable packaging materials are being developed and investigated for thermally processed foods.

Sustainability spotlight

Thermal sterilization and pasteurization are widely recognized technologies for prolonging the shelf-life of food at ambient and refrigeration storage, respectively. Conventional thermal processing technologies rely on boilers to generate steam as the heating medium. During the process, a significant amount of water and energy is wasted. Additionally, fuels used in boilers generate a considerable amount of greenhouse gases. The advanced microwave-based thermal processing systems are relatively more water and energy-efficient, can be operated by renewable energy sources such as solar, wind, or hydropower, and can potentially reduce greenhouse gas emissions, thus making the technology environmentally sustainable. Advanced polymeric packaging made of synthetic polymers has succeeded in in-package thermal processing. However, they are derived from fossil fuels, creating environmental hazards and thus not sustainable. Thrusts is being given to develop green packaging material for food applications. However, developing sustainable packaging materials for in-package processing is challenging. Researchers are evaluating the performance of sustainable packaging for thermally processed food. This article discusses a broad knowledge of traditional and sustainable microwave-based thermal processing technologies, process-packaging, and packaging-food interactions. We also highlight recent developments in sustainable packaging materials, such as bio-based or biodegradable packaging material, for in-packaging thermal processing technologies.

1 Introduction

Thermal processing is one of the most widely used methods for prolonging the storage life of food products. Pasteurization and sterilization processes are commonly designed to inactivate targeted foodborne pathogens and reduce the level of spoilage microorganisms for the extension of shelf life of food. Thermal pasteurization and sterilization are distinguished from each other by the processing temperatures and times. In practice, thermal pasteurization and sterilization are done at temperatures in the range of 70–100 °C and 115–130 °C, respectively.[1] Boilers based on natural gas, coal and oil are used in food plants to generate pressurized steam as the heating medium in thermal processing operations. Worldwide, boilers use mostly biomass and byproduct fuels (54%) such as waste gas, still gas, and black liquor, followed by natural gas (34%) and coal (11%).[2] These fuels contribute significantly to the emission of greenhouse gases (GHGs). Typical thermal processing operations for pre-packaged foods have an overall thermal efficiency between 10 and 15% (a WSU project report to DoE Bonneville Power Administration). Thus, it is critical to develop the next generation of energy and water-efficient food manufacturing technologies that provide safe, high-quality foods with minimum or no adverse environmental impacts.

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2 Conventional thermal technologies

Conventional thermal processes continue to dominate in the food industry. However, current pasteurization and sterilization technologies have the following numerous drawbacks:

- Heat transfer is slow in solid or semi-solid foods due to their relatively low thermal diffusivities, as compared with metals and other solid non-food materials.[3]
- There are considerable losses of heat on the surfaces of the equipment and installations reducing energy efficiency.[4]
- The extended thermal exposures required to bring product interior temperature in packages to desired levels for pathogen inactivation often cause severe thermal degradation to the quality of heat-sensitive products (*e.g.*, canned green vegetables).
- The boilers in food plants burn coal and/or natural gas and generate large amounts of carbon dioxide (CO_2). Steam boilers in the food industry are now one of the largest consumers of natural gas.[5]

2.1 Thermal pasteurization

Thermal pasteurization is a successful commercial operation in the food industry to produce a variety of foods, including dairy, fruits and vegetables, egg, meat, seafood, poultry-based products, and ready-to-eat (RTE) meals. Pasteurization was first used as a mild thermal treatment (about 55 °C) to extend the shelf life of wine and beer, and later it was employed to improve the storage life of milk by reducing spoilage and pathogenic microorganisms. In commercial thermal pasteurization operations, foods are heated to a temperature <100 °C to inactivate non-spore forming pathogens of public health significance. The pasteurization process can also partially inactivate enzymes and spoilage microorganisms with minimal loss of food quality and extend the shelf life of food products under proper storage conditions (*i.e.*, cold storage for foods with pH > 4.6).[6] Pasteurization is defined as "any process, treatment, or combination thereof that is applied to food to reduce the most resistant microorganism(s) of public health significance to a level that is not likely to present a public health risk under normal conditions of distribution and storage".[7] Detailed discussions about the selection of the target bacterial and viral pathogens, the corresponding required thermal processing conditions, and the expected shelf-life of the pasteurized products at appropriate storage temperatures are provided elsewhere.[6]

2.1.1 Pasteurization systems. Pasteurization processes can be classified as (i) in-package pasteurization or (ii) pasteurization prior to aseptic packaging or the hot fill process.[8] During in-package pasteurization, a raw or partially cooked product is vacuum packed to minimize headspace oxygen and facilitate effective heat transfer.[8,9] Thermally treated containers are subjected to rapid chilling. In-package pasteurization reduces the chances of post-processing contamination that is often the case with hot-filled products. However, during in-package processing, the packaging material is also subjected to heating conditions, unlike with a hot-fill process. Therefore, the packaging material used for in-package pasteurization needs to be robust enough to withstand the processing conditions. In a hot filling process or pasteurization prior to packaging, the product is first cooked and pasteurized in a steam jacketed kettle, filled into containers while still hot, and then sealed (with a lid film in the case of trays), followed by rapid chilling.[10] There are possibilities of cross-contamination during hot-fill pasteurization and packaging operations. Hot water and steam are often used for in-container pasteurization of food in both batch and continuous versions of equipment.

2.1.1.1 Batch systems. The simplest batch equipment consists of a large tank filled with hot water maintained at a desired temperature at 100 °C or below.[8] A crate of pre-packaged food is immersed in the hot water tank and held for a pre-determined time.[8] The cooling may be carried out in the same tank after removing the hot water or the crate is transferred to another tank where cold water is pumped to cool the product.[8] The containers are generally cooled to 40 °C that also facilitates evaporation of water from the container surface.[8]

2.1.1.2 Continuous systems. A continuous commercial system consists of a long tunnel fitted with a conveyor belt to carry the packages through preheating, heating, holding, and cooling sections of the tunnel.[8] Water spray and steam at atmospheric pressure are used as the medium for heating of in-packaged foods.[8] The continuous system used for glass containers is divided into several heating and cooling sections with a smaller temperature difference (20–40 °C) to avoid thermal shock to the containers.[1,8] The belt speed is maintained to provide adequate time to achieve desired pasteurization and cooling. Most liquid foods such as juices and milk are pasteurized using a continuous system with high temperature and a short time process.[10,11] For pasteurization of unpackaged liquids, normally parallel plate heat exchangers, tubular heat exchangers, and scraped surface heat exchanges are used depending upon the viscosity of liquid food.[8,10] Steam and hot water are normally utilized as heating media.[8,10]

2.1.2 Energy efficiency. Indirect heating operation, *e.g.*, in-container pasteurization, is less energy efficient compared to direct heating with steam injection or through a heat exchanger with regenerative capacity.[8] Regenerative heat exchangers can be utilized to recover energy during heating and cooling processes to improve the thermal energy efficiency of a pasteurization system.[12] The addition of a regenerative system reduces the steam/hot water and refrigeration requirement, but it increases the electricity required for pumping and the cost of operation due to additional equipment.[8]

2.2 Sterilization systems

Sterilization is the most commonly used processing techniques to produce shelf-stable foods. Thermal sterilization involves heating of food to a temperature of 110 to 125 °C to ensure destruction of spore forming bacteria.[1,13] The slowest heating point within food geometry is heat treated for a duration which is equivalent of at least 121.1 °C for 3 minutes (an $F_0 = 3$ min) to achieve 12 decimal reduction of *Clostridium botulinum* spores.[1] In practice, the heat treatment takes much longer to achieve 3 to

5 decimal reduction of heat resistant spore forming spoilage type microorganisms. Retort systems are most common for sterilization of food.[13]

2.2.1 Sterilization systems. A wide range of sterilizing systems are utilized in the industry to produce self-stable foods. Like thermal pasteurization, thermal sterilization can be classified as (i) in-package sterilization or (ii) sterilization prior to aseptic packaging. The engineering principles involved in the thermal sterilization of foods remain the same for both methods.[8] Two types of retorts are batch retorts and continuous retorts.

2.2.1.1 Batch systems. In batch systems, the retort vessel is filled with food packaged in metal, glass, or polymeric containers, and then heated with different heating media and cooled with cold water. The batch retorts are manufactured in two different configurations: (i) static and (ii) agitating retorts.[3,14] Saturated steam, a steam and air mixture, and hot water under high pressure are used as the heating media.[1,3,15] The static retorts are usually arranged either vertically or horizontally.[16] In the steam retorts, containers filled with food are loaded in the retort, and the retort vessel is brought to operating temperature by allowing steam to pass through the vessel to the atmosphere for sufficient time, so that air in the vessel is vented.[17] The steam venting removes air from the retort vessel and enhances the rate of heat transfer from the heating medium to food containers.[14] At the end of heating, the containers are held at operating temperature to achieve targeted lethality.[1] Then steam is turned off, and a mixture of cooling water and air is introduced into the retort to cool the containers. Other heating methods are also used in different retort systems, such as steam/air mixture (for flexible containers), steam-spray, water spray, falling water and water immersion.[3,17] The batch retorts are also designed to provide product agitation to improve the rate of heat transfer in viscous liquid foods and liquid/solid mixtures.[3] The containers can be agitated in different ways, *e.g.*, axial rotation, end-over-end rotation, oscillating motion, or linear motion.[14,17]

2.2.1.2 Continuous systems. Three different types of continuous systems are used in the food industry, namely, rotary hydrolock, and hydrostatic.[16] A rotary system consists of one heating shell and one cooling shell, and designed to process 600 cans per min.[16] After sealing, the cans enter the shell using a rotary valve. Each shell contains spiral assembly on the surface of the reel to guide the continuous movement of cans through heating and cooling processes.[14,16] As the shell/reel turns, the cans follow the path of the spiral through the shell. The cans transferred from the heating shell to the cooling shell through a rotary transfer valve.[14] The retorts are also equipped with multiple vent lines for removal of air from the system and uniform distribution of steam.[15] Though not very common, hydrolock and hydrostatic pressure sterilizers are two other continuous systems for manufacturing of shelf-stable foods.[10,16]

2.2.2 Energy efficiency. In food plants, boilers are most commonly used to generate steam, which is then transported through steam pipes to different heating devices.[14] These boilers normally use natural gas, coal, and oil as the main energy source. The energy used to supply steam is one of the biggest contributors to the costs in food and beverage manufacture operations.[15] Basic boiler control can be inefficient if the steam is not required constantly. During thermal processing of foods, steam is frequently vented to the environment to increase heat transfer at the surface of food containers and improve steam distribution within fully packed retorts, creating a humid work environment that requires energy intensive air conditioning.[14,15] Condensation water can be partially circulated back to the buildings, but the rest is lost.[16] Most retort manufacturing companies specify useful life of a retort to a minimum of twenty years. However, there are many batch retorts that are still in operation after more than fifty years of use, and the energy savings could be significant over the life of the retort if equipped with heat recovery systems.[15,16]

Retort equipment companies have developed innovative ways to reuse and recover the large amounts of water and heat expended in commercial retorting operations.[15] Increasing efficiency involves optimizing retort designs and processes while reducing resource usage, while producing safer and higher quality products.[15] For example, Allpax, a retort company (Covington, LA, USA), has developed heat energy recovery systems for different retort systems to improve the sustainability of thermal processing operations.[15] For saturated steam retorts, the equipment manufacturing companies have developed a method of recapturing the vented steam vapor, which is normally exhausted to the atmosphere, and condensing it to be able to re-use the entrained thermal energy.[15]

All batch retorts utilize steps for cooling the food containers down to near room temperature after sterilization.[14] A significant amount of low temperature water is used to remove the heat from the products as quickly as possible. Allpax has developed different types of water recovery systems to capture and re-use the cooler (*i.e.*: <60 to 65.5 °C) discharged water for successive cooling cycles, and/or to remove the heat energy out of the hotter (*i.e.*: >65.5 °C) water outflow from the cooling system for other usage in the food plant, such as cleaning water, heating product, or heating boiler feedwater.[15] In a steam retort with direct cooling, up to 50% water savings can be achieved by reusing cooling water from a previous retort cycle.[15] For a water immersion retort, at the very beginning of the cooling step (pressure cool) the superheated water in the process vessel is recovered by pumping it back into the preheat storage vessel.[15] That hot water is then reused in the next retort process cycle, thus saving a significant amount of water and thermal energy in each batch.[15] For the remainder of the cooling cycle, the cooler (and clean) discharged water can be stored or recirculated through a cooling tower and/or chiller and can be re-used for a subsequent retort cooling cycle.[15]

2.2.3 Disadvantages of the conventional thermal technologies. Conventional pasteurization and sterilization result in food with poor organoleptic properties.[18,19] Longer processing time at high temperature (70–90 °C for pasteurization and 121 °C for sterilization) significantly deteriorates the quality of food including loss in color, nutrients (vitamins, ascorbic acids, and chlorophyll), aroma and texture.[8,20] This is due to conduction and convection heating (outside-to-inside) of packaged food. Slow heat transfer from the heating medium to the cold spot frequently leads to overprocessing (*i.e.*, treating the material at the container's edge more severely than is necessary to ensure commercial sterility).[1] Creating agitation is an alternative way to improve traditional retorting which is applicable to certain groups of containers, like cans. This method works well for foods that include liquids or semi-liquids since convection heating accelerates the heating process.[3,20] The product's viscosity, headspace, container geometry, arrangement of containers inside the chamber, and the type of retort motion all influence the convection process.[20] Agitation-based retorts are available, including end-over-end processing, hydrostatic cookers, and continuous and semi-continuous agitating retorts.[3,20] They are severely criticized since there are few opportunities for thermal processing optimization and they are only utilized for a restricted variety of containers, most of which have some symmetry, such cans and jars.[20] Advanced retorting systems have shorter processing times and better heat transfer characteristics that lead to more uniform heating, and as a result, produce products with better physicochemical and sensory qualities, including texture, color, aroma, and appearance, while the nutritional value is significantly higher than with conventional retorting.[20]

3. Microwave-assisted thermal processing technologies

Consumer demand for food with superior sensory qualities has stimulated the development of thermal processing technologies based on electromagnetic energy. Electromagnetic heating in food processing has gained significant interest in the food industry and has potential to replace the conventional well-established thermal processes.[4] Ohmic heating and dielectric heating including radio frequency (RF) and microwave (MW) heating are promising alternatives to conventional thermal processes. These novel thermal processes are regarded as volumetric forms of heating in which thermal energy is generated directly inside the food. Microwaves volumetrically heat the food through absorption of electromagnetic energy by food components within food packages.[19] A limited number of frequency bands are assigned by the U.S. Federal Communications Commission (FCC) for industrial, scientific, and medical (ISM) applications.[19] Two commonly used frequencies for MW heating applications are 2450 ± 50 MHz (0.122 m wavelength in air) for domestic ovens and industrial systems and 915 ± 13 MHz (0.327 m wavelength in air) primarily in industrial heating systems.[13,19] Compared to 2450 MHz, 915 MHz has deeper penetration in food. To ensure microbial safety of processed food, it is critical that an industrial MW sterilization or pasteurization system heats food packages with a stable heating pattern so that the cold spot stays at a predictable location inside food packages.[13,19] Only a single-mode heating cavity can satisfy this requirement.[13] A 915 MHz single-mode cavity is about 3 times the size for 2450 MHz MW and is able to accommodate common food packages for MW sterilization or pasteurization.[13] All the domestic ovens using 2450 MHz are multi-mode cavities, since 2450 MHz single-mode cavities are too small for heating foods in single-meal-sized packages.

The WSU team, in collaboration with industrial partners and the U.S. Amy Natick Soldier Center, has pioneered the development of 915 MHz microwave-assisted heating technologies for pasteurization[19] and sterilization of packaged foods.[13] These systems utilize specially designed 915 MHz single-model cavities with power supplied by microwave generators. Specially designed microwave cavities provide predictable stable volumetric heating in food in polymer packages and drastically shortens the time for the product to reach lethal temperatures for pathogen control. The new processes result in ∼80% reduction of heating time compared with conventional canning and ∼60–70% reduction of overall energy use based on our premilitary studies.[19]

3.1 Microwave-assisted thermal pasteurization

Microwave heating has shown advantages in reduced heating time and improved heating uniformity when compared with conventional hot water and steam heating.[19,21] The microwaves penetrate the food and generate heat throughout the whole volume of food reducing the temperature gradient during heating. The direct conversion of electromagnetic radiation into heat within foods sharply improves energy efficiency. These advantages over hot water heating shortens the exposure time of food to elevated temperature, resulting in an increased production rate and reduced food quality degradation.[19] The pilot-scale 915 MHz semi-continuous microwave-assisted pasteurization system (MAPS) developed at Washington State University is illustrated in Fig. 1.[19] It consists of four sections: preheating, microwave heating, holding, and cooling.[19] Each section has a separate water circulation system to control the water temperature and flow rate. The microwave section has four single-mode cavities connected to microwave generators. A power of approximately 5 kW is applied to each of the first two cavities, and the other two cavities equally split 8.7 kW.[19] Polymeric trays or pouches containing food are placed in transport carriers and heated in the preheating section to about 50 °C.[19] They are then moved through the microwave heating section where they are heated simultaneously with microwave energy and hot circulating water before moving to the holding section. The temperature of the circulation water in the microwave heating and holding sections is set at 70 to 90 °C, depending on the desired shelf-life of the processed products.[9,19] The speed of the belt in the microwave heating section and the holding time of the food package are adjusted to achieve the desired pasteurization values.[22] It typically takes 2.5–4 min for microwave heating, depending on package thickness, for the cold spots of food packages to reach desired pasteurization temperature for thermal inactivation of target bacterial and viral pathogens.[19] The cooling is carried out by circulating cold water. For all the sections, water is circulated in close loops, resulting in zero water lose in the operation.[19] An example of microwave pasteurized RTE food is given in Fig. 2.[19]

3.2 Microwave-assisted thermal sterilization

Similar to MAPS, a microwave-assisted thermal sterilization (MATS) system also consists of four sections, namely,

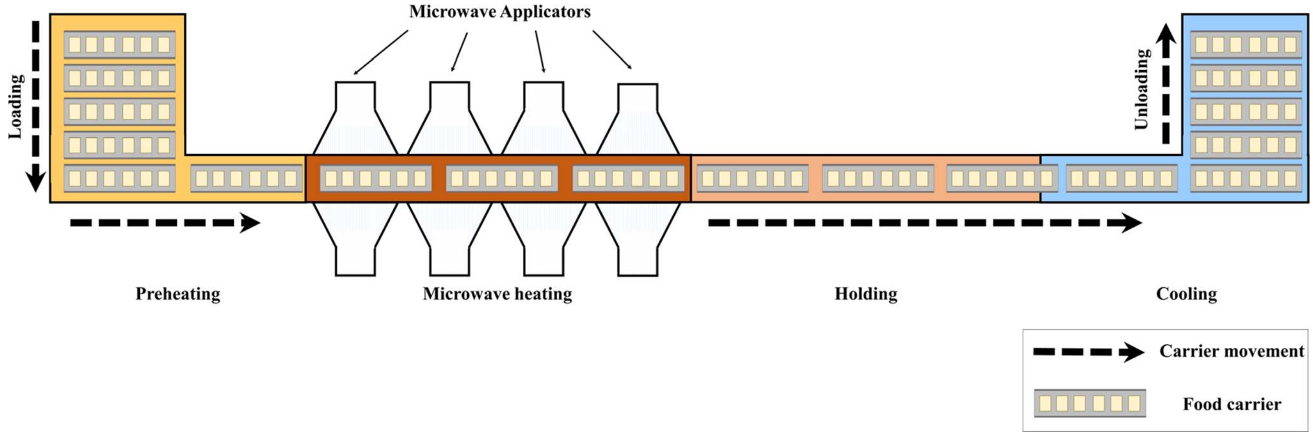

Fig. 1 Schematic diagram of the microwave assisted pasteurization system (MAPS) at Washington State University.[19]

Fig. 2 Example of products after 90 °C-10 min processes using the MAPS at Washington State University.

preheating (using circulating water), microwave heating (by microwave and hot circulating water), holding (by hot circulating water) and cooling (using cold circulating water).[13] The microwave heating section consists of multiple connected single-mode 915 MHz microwave cavities similar to those illustrated in Fig. 1.[13,23] In operation, food packages are heated in the preheating section to about 90 °C, and then move through pressurized circulating water at above 121 °C while being heated by microwave energy.[13] The immersion water reduces microwave edge heating and improve heating uniformity. Deionized water is used to minimize the absorption of microwave energy in the circulating water and improves the overall energy efficiency of the system.[24] It typically takes 2–4 min, depending on package thickness, for the food packages to travel through the microwave heating section.[13,25] Food packages then travel through the holding section filled with circulation water at above 121 °C to achieve the desired commercial sterility before moving to the cooling section. Specially designed pressure-locks allow a continuous movement of the food packages from the ambient environment into and out of the pressurized MATS systems.[13] No steam venting and water drainage are needed in commercial operation with MATS, thus minimizing energy and water loses.[13] Protocols for regulatory acceptance (*i.e.*, FDA and USDA FSIS) of novel thermal processes based on MATS have been developed by engineers at Washington State University in collaboration with industrial partners.[13]

Both MATS and MAPS are licensed to 915 Labs (Denver, CO, USA) for global commercialization. Several continuous MATS systems with throughputs between 30 and 45 meals per min are currently in operation in India for commercial production of shelf-stable meals (Fig. 3).[26] The shortened exposure time of food to high temperatures in MATS and MAPS systems greatly improves the quality of thermal processed ready-to-eat meals.[13,19] Our studies have also reported a 50% salt reduction in a MATS-processed chicken pasta meal when adding herbs.[27]

Industrial scale MAPS and MATS systems are powered by microwave generators with a total electric power requirement of 40 to 150 kW.[13,28] Such a level of electrical power can be easily supplied by locally generated electricity from solar, wind, and hydro energy. There is no need for boilers, which eliminates the use of fossil fuels. MAPS and MATS systems provide opportunity for rural communities to use local agricultural products in the production of high quality ready-to-eat meals with desired shelf-life for transportation to markets in urban centers. This will enhance the resilience of food supply chains, reduce agricultural and food wastes, and bring high quality jobs to rural communities, ultimately contributing to a sustainable bio-circular economy.

Fig. 3 Continuous MATS system in a TATA affiliated food processing plant (left, courtesy of 915 Labs) and shelf-stable meals produced by the company (right).[26]

4 Impact of thermal processing on food quality and packaging

Traditional retort sterilization and hot-water based pasteurization techniques heat the food from outside to inside due to conduction-convection mode heating, which affects the food quality to a greater extent. To ensure microbial food safety, the cold spot (slowest heating region) of the packaged food must achieve desired lethality for the target pathogen. The degree of lethality highly depends on the product type (solid, semi-solid, and particulate system), thermophysical properties of food (thermal diffusivity, specific heat capacity, density, and viscosity), package size and shape, thermal properties of the container, and headspace within the package.[1,3,14] For a given type of food, high headspace, a bigger container and high material thickness slow down the rate of heat penetration, affecting the overall processing to reach the desired sterilization value (F_0-value) or pasteurization value (P-value).[29] These factors result in a longer processing time at high temperature and yield food with poor organoleptic qualities. Biochemical reactions in food proceed at a significantly lower rate compared to microbial destruction because of a higher z-value (for example, 25–30 °C for vitamins, 15–37 °C for proteins, and 25–47 °C for color) than the microorganisms (7–12 °C for bacterial species).[1] Therefore, thermally processed foods usually have a very high cook value.

Advanced MW-based thermal processing technologies involve a dielectric heating process that heats the food volumetrically and have a shorter processing time, resulting in superior quality food.[13] Dielectric heating relies on the dielectric properties of food materials, particularly the dielectric constant (ε') and dielectric loss (ε'').[24,30,31] Dielectric properties depend on several factors including moisture content, temperature, and other food components particularly fat and salt content.[30,31] In food, free polar molecules (free water) and ions (salt) have the strongest interaction with microwaves as the loss factor is contributed by dipolar polarization of water molecules and ionic conduction of dissolved salt.[30] Foods with low moisture content have less ability to convert microwave energy into thermal energy due to the reduced loss factor at low moisture content.[30] Oils are often considered unsuitable for MW heating due to their poor dielectric loss which is almost 1/100th that of water.[32] However, a study revealed that, at 2450 MHz, vegetable oil heats faster (1.4–2.0 times) than water due to 10 times stronger electric field in oil than that of water.[33] The dielectric loss of vegetable oil is 30 times higher ($\varepsilon'' = 0.15$) than that of mineral oil ($\varepsilon'' = 0.005$) because of the presence of the glycerol component in vegetable oil, resulting in rapid heating of vegetable oil.[32] MW heating can alter the structure and crystallinity of starch by molecular vibration and therefore influence the starch characteristics including viscosity and gelatinization properties.[34] MW heating can cause reduced granule swelling and formation of soft gel in starch–water systems.[35] Enzyme activity can also be inhibited using MW heating.[36] Other parameters including nonuniform heating with an unstable heating pattern and edge-heating of packaged food can significantly affect the quality of packaged food.[36] A 915 MHz MW system with a single mode cavity can provide a stable and predictable heating pattern within the packaged food for ensuring food safety and quality control of the processed food.[13] A study revealed that MATS processing results in a cook value 3–7 times lower than that of retort sterilization to achieve the same lethality ($F_0 = 6$ min).[13]

In conventional in-package thermal processing technologies, metal cans, glass or polymeric packaging (films, pouches and trays) is used. However, thick metals as packaging material block MWs and therefore are not used in MW cavities.[37] Polymeric packaging usually has a low loss factor and therefore is transparent to microwaves and suitable for in-package MW-assisted thermal processing. High temperature and longer processing time affect the gas barrier properties of packaging films, which in turn influences the food quality during storage. In MW-assisted thermal processing, hydrophilic polymers such as ethylene vinyl alcohol may absorb water, resulting in increasing loss factor.[38,39] Increase in the loss factor may generate heat and affect the packaging properties. Therefore, multilayer packaging is preferred for its high gas and moisture barrier properties and suitable thermal and mechanical properties. Following sections discuss the packaging considerations and food quality and shelf-life studies for MW-assisted thermal processing technologies.

5 Packaging

5.1 Packaging requirements

For in-package processes, polymeric packages must maintain their physical shape and seal integrity during and after thermal processing.[40,41] The visual appearance/integrity of the package is also important for consumer acceptance in addition to maintaining desired shelf life. Any kind of damage such as pinholes, a broken seal, shrinkage, or delamination will compromise the safety and quality of the product.[22,40] The thermal and mechanical properties of polymers used in the package usually determine the performance of package under processing conditions. The thermal properties (melting temperature, T_m, and glass transition temperature, T_g) of the packaging polymer can determine whether the package can withstand thermal processing conditions.[22,39] The T_m of the packaging polymer should be significantly higher than the processing temperature to prevent the melting of the polymers used as the packaging material and any shrinkage or seal damage, while T_g should be low enough to provide flexibility to the packaging film.[22,39] The mechanical properties of packages should be balanced (not very stiff/brittle or elastic) to prevent any damages during heating and cooling cycles of the thermal process.

Food products are a multi-component system containing lipids, proteins, nutrients, and color pigments, and these components are prone to oxidative degradation. Pasteurized and sterilized products are also rich in water content, and a small change of moisture content could influence the sensory quality of the processed products. The gas (mainly oxygen and water vapor) barrier properties of packaging materials influence the shelf life of the pasteurized and sterilized products. Specifically, the oxygen transmission rate (OTR) of the packaging material determines quality losses due to oxidation, while the water vapor transmission rate (WVTR) controls moisture losses during storage.[42,43] Hence, the gas barrier properties, OTR and WVTR, of packages are crucial for maintaining the desired shelf life of products. The barrier properties of packaging films may change following in-package thermal pasteurization and sterilization processes,[22,39,44–46] which may influence product shelf stability.[47–50] The extent of barrier property deterioration after processing depends on the type of film structure and the severity of the thermal process. Therefore, to maintain product shelf life, the deterioration of the film barrier should be minimal.

5.2 Packaging for in-package thermal pasteurization

Multilayer films with various ranges of OTR and WVTR are used in the in-package thermal pasteurization process.[22,47,51] For pasteurization, the selection of packaging with an appropriate OTR and WVTR largely depends on the nature of the food. Foods (chicken, fish, and oils) that contain oxygen sensitive nutritional compounds (*e.g.* lipids and vitamins) would require medium barrier (medium OTR and WVTR) packaging.[52] Nevertheless, pasteurized products, unlike sterilized products, require comparatively low-barrier packaging materials since the products have shorter shelf life (a few days to weeks) at refrigerated temperature.[9] For instance, the OTR of packaging films for pasteurized meat products is 3–5 cc/m^2-day which is much lower compared to the OTR of 85 cc/m^2-day for commercially available pasteurized mashed potatoes (Table 2).[9]

5.2.1 Changes in package properties after thermal pasteurization. The barrier qualities of the polymer packaging are impacted by in-package pasteurization.[44,47] The packaged product is submerged into hot water (temperature ≈70–90 °C) during in-package pasteurization. It reduces the barrier properties of the packaging material due to water absorption by the hydrophilic layer. The phenomena rely on both time and temperature. MAPS and conventional hot-water pasteurization both affect the gas barrier properties of packaging films. For example, the OTR of the packages increased by 2 to 3 times after in-package pasteurization processes.[44,47,53] We observed that the oxygen barrier properties of the packaging material after MAPS were not significantly different from the one conventionally pasteurized. However, MAPS retained the water vapor properties of packaging better than the conventional one.[47]

During in-package thermal pasteurization, the lid film of a tray containing high moisture food bulges. Inside the packages, vapor forms at high temperature causing thermo-mechanical stress on the packaging film. High temperatures and humidity during in-package pasteurization may affect the orientation of the crystal structure, which in turn may affect the morphology, gas barrier, and thermal characteristics.[22,44] The changes in gas barrier properties and the morphological changes in packaging films are closely connected.[9,53] The moisture absorption by hygroscopic layers in multilayer films leads to an increase in the dielectric loss factor following microwave pasteurization.[44] Plasticization due to moisture uptake affects the gas barrier performance of the packaging film. Increase in fractional free volume, crystal fragmentation, and other morphological changes in polymers causes increase in oxygen and water vapor transmission in thermally treated polymeric structures.[44]

5.3 Packaging for in-package sterilization processes

Packaging for the in-package thermal sterilization process is divided mainly in two broad groups: flexible polymeric films and semi-rigid type.[40,41] Flexible films are high gas barrier multilayer structures (thickness 110–130 micron) and consist of several layers.[40,54,55] These films are used to form pouches and as a lid material for cups, bowls, and semi-rigid trays.[40] The high barrier structure is often achieved by coextrusion, lamination, metal oxide coating, organic coating, and active barrier coating.[41] Semi-rigid trays and cups are made by thermoforming, in which a barrier layer of ethylene-vinyl alcohol copolymer (EVOH) is sandwiched between polypropylene (PP) layers.[38,56]

Table 1 Structure and gas barrier performance of multilayer films after the in-package sterilization process

		OTR, cm^{-2} per days		WVTR, g m^{-2} per days		
Film structure	Sterilization method	Before	After	Before	After	References
PET[a] (12 μm)//EVOH[b] (12 μm)//PP[c] (75 μm)	Retort, 125 °C, 28 min	0.16	1.75	—	—	25
PET//PP (50 μm)/tie/Nylon 6(10 μm)/EVOH/Nylon 6(10 μm)/tie/PP (50 μm)	Retort, 125 °C, 28 min	0.096	4.57	—	—	
Metal oxide-coated PET (12 μm)//ONy[d] (15 μm)//CPP[e] (50 μm)	Retort, 121 °C, 30 min	0.04	1.02	0.11	0.33	39
Overlayer/SiO$_x$[f]-coated PET (12 μm)//ONy (15 μm)//CPP (60 μm)	Retort, 121 °C, 30 min	0.01	0.06	0.11	0.41	
Metal oxide-coated PET (12 μm)//ONy (15 μm)//CPP (50 μm)	MATS[g], preheating: 61 °C for 25 min; MW[h] heating: 123 °C for 9 min	0.04	0.33	0.11	0.67	
Overlayer/SiO$_x$-coated PET (12 μm)//ONy (15 μm)//CPP (60 μm)	MATS, preheating: 61 °C for 25 min; MW heating: 123 °C for 9 min	0.01	0.07	0.11	0.45	
PET (15 μm)/tie/nylon (15 μm)6/tie/PP (50 μm)	Retort, 123 °C, 28 min	0.04	0.48	0.38	1.85	45
Coated-PET-coated (12 μm)/tie/oriented-nylon 6(15 μm)/tie/PP (50 μm)	Retort, 123 °C, 28 min	0.03	1.25	4.31	3.72	
PET (15 μm)/tie/nylon (15 μm)6/tie/PP (50 μm)	MATS, 123 °C, 9 min	0.04	0.24	0.38	1.44	
Coated-PET-coated (12 μm)/tie/oriented-nylon 6(15 μm)/tie/PP (50 μm)	MATS, 123 °C, 9 min	0.03	0.60	4.31	3.72	

[a] PET: polyethylene terephthalate. [b] EVOH: ethylene vinyl alcohol. [c] PP: polypropylene. [d] Ony: oriented nylon. [e] CPP: cast polypropylene. [f] SiO$_x$: silicon oxide. [g] MATS: microwave assisted thermal sterilization. [h] MW: microwave.

Coextruded multilayer films are produced by combining different polymers of interest using several extruders without producing individual layers. The process allows manufacturers to produce two-to-twenty-one-layer films made of one or more layers of gas barrier material, including EVOH, nylon 6, and MXD6. The typical structures of coextruded multilayer films are (Table 1):[41,57]

Table 2 Structure and gas barrier performance of multilayer films after the in-package pasteurization process

		OTR, cm^{-2} per days		WVTR, g m^{-2} per days		
Film structure	Processing conditions	Before	After	Before	After	References
Synthetic film						
PET[a]/LLDPE[b]/LDPE[c]/tie/nylon66/tie/LLDPE/LDPE	Conventional hot water (60 min at 92 °C)	1.00	1.77	3.93	5.00	22 and 47
Nylon/nylon/tie/LLDPE		10.3	8.97	3.92	5.16	
LDPE/tie/nylon/tie/LDPE		29.9	28.4	4.11	2.84	
PET-PE based		80.9	119	6.60	11.7	
PET/LLDPE/LDPE/tie/nylon66/Tie/LLDPE/LDPE	Microwave assisted (30 min holding at 51 °C, 3.2 min microwave heating at 91 °C, 10 min holding at 91 °C)	1.00	1.77	3.93	5.00	
Nylon/nylon/tie/LLDPE		10.3	8.97	3.92	5.16	
LDPE/tie/nylon/tie/LDPE		29.9	28.4	4.11	2.84	
PET-PE based		80.9	119	6.60	11.7	
PET/barrier PET/tie/PE	Conventional hot water (36 min at 93 °C)	0.7	1.5	2.4	2.9	44
PET/tie/nylon-6/PP		0.1	1.1	1.1	1.6	
PET/LLDPE/LDPE/tie/nylon66/tie/LLDPE/LDPE		2.3	6.0	2.3	2.6	
PET/barrier PET/tie/PE	Microwave-assisted (30 min holding at 61 °C, 2 min microwave heating at 93 °C, 20 min holding at 93 °C	0.7	1.2	2.4	2.8	
PET/tie/nylon-6/PP		0.1	1.7	1.1	1.5	
PET/LLDPE/LDPE/tie/nylon66/Tie/LLDPE/LDPE		2.3	7.9	2.3	2.7	
Biobased film						
Chemically modified PLA-PBAT blend	Conventional hot water (15 min at 72 °C)	330	358	37.7	217	53
Heat-sealable PLA layer/PLA core/heat-sealable PLA-layer		541	>1000	47.6	254	
Heat-sealable PLA layer/PLA core/heat-sealable PLA-layer		619	>1000	48.8	288	

[a] PET: polyethylene terephthalate. [b] LLDPE: linear low-density polyethylene. [c] LDPE: low-density polyethylene.

PP/tie/barrier/tie/PP (5-layer symmetric structure).

PP/tie/barrier/tie/Regrind/PP (6-layer asymmetrical structure with 1 regrind layer).

PP/tie/barrier II/barrier I/barrier II/tie/PP (7-layer with 3 barrier layers where barrier I and II are different polymers but compatible with each other and do not require a tie layer in between).

When coextrusion of two or more packaging materials is not feasible, lamination methods are typically utilized.[41,54] It is often done when different polymers are combined with either metal foil or metal oxide-coated PA or PET into a single film.[41] Adhesive laminations use adhesive materials, as opposed to extrusion laminations, which assemble the components using molten polymers (LDPE copolymers).[41] A conventional laminated structure might have an inner layer of PP and an exterior layer of bare or metal oxide-coated polyester. To create a more complex structure, such as PET//PP/tie/Nylon 6/EVOH/Nylon 6/tie/PP (Kuraray America Inc., Houston, Texas, USA), a hybrid method called "coextrusion-lamination" is used.[41] In this film, a PET layer is laminated (denoted by//) with coextruded structured (denoted by/) PP, Nylon, and EVOH.[38,39]

Metal oxide coating is used to improve the barrier qualities of polymer layers to produce extremely high-barrier films.[55] Superior barrier coatings of silicon oxide (SiO_x) and aluminum oxide (AlO_x) can be created by layer-by-layer deposition of thin inorganic coatings on a polymeric film using the atomic layer deposition (ALD) technique.[40,41] An example of metal oxide-coated multilayer films used for in-package sterilization is AlO_x-coated PET (12 μm)//ONy (15 μm)//CPP (70 μm) (developed by DNP, Fig. 4).[50]

Organic coating has also been used by Toppan to develop high barrier films. A laminated structure of organic coated PET (1 μm thick coating of modified polyacrylic acid, Besela™), oriented nylon, and cast polypropylene (CPP) provides a high barrier multilayer film.[41] After thermal processing, the oxygen barrier performance of the Besela™ film improves due to the formation of a cross-linked network within the polymer matrix, which restricts the diffusion of gas molecules.[41]

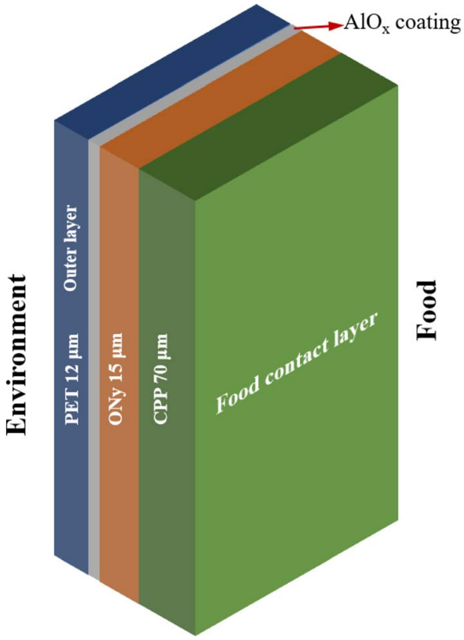

Fig. 4 Schematic of a single metal oxide coated film used in the sterilization process.

5.3.1 Effect of thermal sterilization on package properties. Thermal sterilization can influence the gas barrier properties of multilayer films.[39,41,45,58] The oxygen transmission rate (OTR) and water vapor transmission rate (WVTR) of packaging films significantly increase after thermal processing (Table 1).[25,38,39,45,58] The oxygen barrier properties of EVOH-based multilayer films are affected largely (OTR increased by a factor of 12) compared to metal oxide-coated PET-based multilayer films (increased by a factor of 2)[45] after microwave sterilization. During the process, packages are subjected to high temperature (121 °C) and high moisture environment, causing water to penetrate through the protective layers of multilayer films. This results in plasticization of the hydrophilic EVOH layer and lowers the gas barrier properties. The phenomenon is time dependent; the longer the processing time, the higher the water absorption by the EVOH layer and the higher the permeation of gases through the film. However, a single layer of metal oxide coated film is more susceptible to cracks and pinholes compared to the one with a double layer of metal oxide-coating.[23,50]

Morphological and structural changes in polymers are often correlated with the changes in the gas barrier performances of the film. Changes in the crystallinity, crystal structure, free volume properties, plasticization of barrier polymers, and formation of crack and pinholes in the structure determine the gas barrier performance of the multilayer film.[39,45] The characterization of such changes in polymers has been done using several analytical techniques, such as differential scanning calorimetry (DSC), X-ray diffraction (XRD), scanning electron microscopy (SEM), and positron annihilation lifetime spectroscopy (PALS). Multilayer films containing a barrier EVOH layer absorb water that imparts the plasticization effect. The water uptake by hydrophilic polymers increases the dielectric loss factor that can be measured by the split post dielectric resonance (SPDR) technique. A PALS study showed that thermal processing increases localized free volume between polymer chains of polymeric films, which allows the gas molecules to permeate more easily through the polymer matrix.[39]

5.4 Sustainable packaging materials

Commonly used synthetic polymer packaging materials including PA, PET, PP, PE, and EVOH are suitable for in-package thermal processing.[53] Synthetic packaging materials, derived from non-renewable petroleum-based sources, are not biodegradable.[59] Therefore, there is a need for development of eco-friendly packaging that is suitable for in-package thermal processing. Biobased materials are derived from renewable sources and can be compostable or biodegradable. Biobased and/or biodegradable polymers like polylactic acid (PLA), polybutylene adipate terephthalate (PBAT), polyhydroxy alkanoates

(PHAs), polybutylene succinate (PBS), and thermoplastic starch (TPS)[59] are not suitable for in-package sterilization as the process involves a high temperature and high moisture environment.[53] Nevertheless, the biobased packaging can be used for the in-package pasteurization process.

A study indicated that PLA and PBAT-based pouches are suitable for in-package hot-water based thermal pasteurization.[13] The packaging films made of PLA or PBAT do not have a high gas barrier (OTR 330–619 cm^{-2} per days and WVTR 38–49 $\mathrm{g\ m}^{-2}$ per days).[53] The gas barrier performance of such films is affected by the thermal pasteurization process. Increase in the OTR of the PLA/PBAT packaging film is correlated to the quality loss of pasteurized food (*e.g.*, increase in lipid oxidation in salmon and loss in vitamin C content in mashed potato).[53] Our findings revealed that PLA and PBAT-based films can be used as an alternative to polyethylene films for a shelf life of 10 days at 4 °C.[13] Unlike sterilization, the processing temperatures are low during the pasteurization process, and hence there is potential to utilize PLA, PBAT, and PHA-based packaging for in-package pasteurization of high moisture and short shelf life food products.[53] A lot of research efforts will be needed to develop sustainable packaging for in-container food sterilization and pasteurization processes.

6 Food quality

6.1 Thermal pasteurization

Thermal pasteurization inactivates pathogenic microorganisms of concern and destroys endogenous enzymes to hinder the quality deterioration of vegetable products during post-processing and storage.[6] The absence of oxygen within the package of a pasteurized food (low acid, pH > 4.6)[51–53] may create a local anaerobic environment and may promote the growth of anaerobic *Clostridium botulinum*, which must be avoided. Therefore, transfer of oxygen through packaging with an appropriate OTR and/or by the adjusting vacuum level during sealing prior to processing is necessary. However, high heat of pasteurization and oxygen present in package headspace determines the quality of pasteurized food. During storage, the shelf life of pasteurized food depends on the oxygen and water vapor available in the package headspace and the amount of each gas permeates through the package over the storage period. Foods contain lipids, vitamins, and pigments that are susceptible to oxidation, which significantly affects the nutritional and sensory attributes of the food.[47,51,52] The weight loss of high moisture pasteurized food products is influenced by the WVTR of packaging films.[22,47]

Thermal pasteurization causes increase in lipid oxidation in food (*e.g.* blue mussels in sauce), which further increases with increase in the OTR of packaging films.[51] It also results in increased hardness of mussels. A better stability after pasteurization and higher retention of encapsulated oxygen sensitive compounds (*e.g.* vitamin C) against oxygen (varied using varying OTR of packaging films) were observed.[47] A high barrier film (OTR = 1 $\mathrm{cc/m^2}$-day) retains the food quality better than the one packaged in a lower barrier film (OTR = 81 $\mathrm{cc/m^2}$-day)[43] for foods containing oxygen sensitive compounds.[47,51] Nevertheless, a medium-barrier film (OTR of 30 $\mathrm{cc/m^2}$-day) is sufficient to retain the quality attributes of in-packaged pasteurized vegetables (*e.g.* carrot puree).[43]

Microwave pasteurization can provide products with better color quality and comparable nutrient retention when compared to conventional pasteurization (Table 3).[47] Studies indicated that carrots processed with microwaves experienced less colour changes than the conventional hot water-based pasteurization process. MAPS also reduced the cook values and improved the quality of carrots compared, indicating less thermal deterioration of MAPS processed carrots.[6] It was reported that MAPS-treated mashed potatoes and green peas had the least colour change.[21] Microwave pasteurized green beans also showed better retention in chlorophyll a, colour, and ascorbic acid compared to one hot-water pasteurization.[60,61] A comparative study on the effects of high-pressure (HPP) and microwave-assisted (MAPS) thermal pasteurization on the inactivation of *Listeria innocua* of green beans showed that the MAPS (70 °C for 2 min) resulted in a 9 log CFU g^{-1} reduction of *L. innocua*, while HPP (600 MPa at 25 °C for 10 min) resulted in a 3.7 log CFU g^{-1} reduction, indicating more efficacy of MAPS in reducing the target pathogen than HPP. However, HPP and MAPS processed green beans showed similar quality attributes.[62] MAPS-processed green beans had a significantly higher microbial shelf life compared to hot water pasteurization (Table 3).[60] In a study, the physio-chemical and microbial quality of microwave pasteurized RTE fried rice was evaluated.[63] During storage at 7 °C for 6 weeks, MAPS treated RTE fried rice did not show any change in sensory qualities attributed to microbial spoilage and extended the 5 day shelf life of regular chilled meal to 6 weeks. The effect of MAPS on the textural properties of Pacific whiting surimi was investigated.[64] The heating rate greatly influenced the thermal gelation of Surimi samples, with higher heating rates (23 °C min^{-1} at the geometric centre of Surimi) resulting in stronger gels. MAPS was found to be effective in producing strong Surimi gels compared to conventional water bath heating. In another study, the feasibility of MAPS was investigated to produce pasta having similar textural attributes to conventionally cooked pasta. The authors found that microwave treatment produced pasta with weaker pasta strands, indicating that microwave processing can amplify the reactions of product-aging. However, researchers concluded that microwave heating provided more efficient and uniform heat distribution, ensuring better pasteurization and overall pasta quality.[65]

An attempt has been made to pasteurize human milk[66] and cow milk[67,68] using microwaves. For human milk, microwaves reduced the processing time by roughly 15 to 16 minutes as compared to holder pasteurization (62 °C for 30 min).[66] MW can inactivate the microflora in human milk microflora at 62.5 °C or 66 °C for 5 or 3 minutes, respectively.[66] Cow milk was pasteurized in a domestic microwave oven (900 W) converted into a continuous type.[67] The authors reported that microwave heating did not alter the protein and fat composition of the milk. However, MW-treated samples had a different color compared to the one conventionally pasteurized. In another study, milk, pasteurized using microwaves (2450 MHz and 540

Table 3 Effect of the MAPS process and storage on food quality

Product	Packaging and storage conditions	Processing conditions	Food quality changes	References
Mashed potatoes	Film F-1 (control film): OTR value – 0.99 cm^3 m^{-2} per days; WVTR – 3.93 g m^{-2} per days Film F-10 (nylon-based film): OTR value – 10.3 cm^3 m^{-2} per days; WVTR-3.92 g m^{-2} per days	The total heating time for MAPS was around 43.2 minutes, which included a pre-heating time of 30 minutes at 51 °C, microwave heating time of 3.2 minutes at 91 °C, and holding time of 10 minutes at 91 °C. The product was then cooled at 23 °C for 5 minutes in the cooling section followed by further cooling in a chilled water bath at 4 °C for 20 minutes. The obtained cumulative lethality at the cold spot was 15.8 minutes	MAPS did not significantly affect the vitamin A and E contents of the mashed potatoes Both MAPS and CP (conventional thermal pasteurization) had a significant effect on the color parameters of the mashed potatoes. There was a significant increase in lightness, redness, and yellowness values in both processes, with larger changes observed in CP due to longer processing times. The overall color difference was higher in CP compared to MAPS.	47
	Film F-30 (LDPE-based film): OTR value – 29.9 cm^3 m^{-2} per days; WVTR – 4.11 g m^{-2} per days Film F-81(PET-PE based film): OTR value – 80.9 cm^3 m^{-2} per days; WVTR – 6.60 g m^{-2} per days		The mashed potatoes packed in the F-81 film showed browning at the end of the storage period, possibly due to non-enzymatic browning reactions and oxidation. The other three types of films showed changes in color due to starch retrogradation	
RTE green beans	Multilayer laminate pouches (hyper-branched polyester (HBPET) 12 μm/biaxially oriented nylon (BON) 15 μm/cast polypropylene (CPP) 70 μm) OTR = 0.02 cm^{-2} per days	MAPS: Preheating at 31 °C for 25 minutes using circulating water; MW heating section: 19.5 mm s^{-1} with hot water circulation at 91 °C; holding section: 91 °C for 11 min	The effects of both pasteurization techniques on the color values and chlorophyll contents of green beans were comparable Green bean, treated with HPP, has higher firmness than the MAPS one	61
	WVTR = 0.44 g m^{-2} per days		Swelling and a sharp pH drop in pouches treated with MAPS and high pressure after three and five weeks of storage at 7 °C, respectively	
	Storage: 2 °C and 7 °C for 14 weeks and 7 weeks respectively	High pressure processing (HPP): preheating to 45 °C followed by HPP at 600 MPa for 20 min	The shelf life of treated green beans was found to be 6 weeks for HPP and 12 weeks for MAPS when kept at 2 °C or lower, and 2 and 3 weeks, respectively, when kept at 7 °C	

Table 3 (*Contd.*)

Product	Packaging and storage conditions	Processing conditions	Food quality changes	References
Green beans	Multilayer laminated polymeric pouches (hyper-branched polyester (HBPET) 12 μm/biaxially oriented nylon (BON) 15 μm/cast polypropylene (CPP) 70 μm)	MAPS: preheating at 31 °C for 25 minutes using circulating water; MW heating section: 116.8 cm min^{-1} with hot water circulation at 72 °C; holding section: 72 °C for 3 min	The green beans treated with MAPS were significantly greener than those treated with HPP (high-pressure processing) after pasteurization High-pressure treatment resulted in a 3.7-log CFU g^{-1} reduction in *L. innocua* ATCC 51742, whereas MAPS processing showed a 9.0-log CFU g^{-1} reduction	62
	Storage: 2 °C and 10 °C for 36 and 20 days, respectively	HPP: 600 MPa for 10 min	The vitamin C content in the untreated green beans was 8.6 mg/100 g wet basis (wb), but after MAPS treatment, it decreased to 3.3 mg/100 g wb. This indicated a significant loss of vitamin C due to the MAPS treatment. The higher vitamin C loss in the MAPS-treated samples could be attributed to the longer treatment time compared to high pressure processing	
Fried rice	The MAPS-based fried rice samples were stored at a temperature of 7.3 ± 2 °C during the 6 week storage period. The storage temperature was chosen based on research that showed approximately 10% microbial growth at this temperature	The MAPS processing conditions for the rice involved weighing 250 g of the rice into polypropylene and EVOH trays and sealing them with a lid film. The processing was done at 200 °C for 4 seconds under a 65 mbar vacuum with a 400 mbar nitrogen flush. The aim of these processing conditions was to achieve a minimum temperature of 90 °C for 10 minutes at the cold spot in the food trays, which would result in a significant reduction of nonproteolytic *Clostridium botulinum*	After 6 weeks of storage at a temperature of 7.3 ± 2 °C, the APC (aerobic plate count) for the MAPS-rice ranged from 10^5 to 10^6 CFU g^{-1}, resulting in the acceptable range for bacterial contamination (the APC should not exceed values of 10^7 CFU g^{-1}) Storage time had a significant effect on all sensory modalities, including aroma, appearance, taste/flavor, and texture for both the control and MAPS based fried rice. The ΔE mean values of the MAPS-fried rice significantly increased ($P < 0.0001$) from 1.84 ± 0.72 at 1 week of storage to 3.08 ± 1.17 after 6 weeks of storage The pH values of the fried rice samples significantly differ (<0.0001) due to MAPS. The pH values of the fried rice samples decreased significantly ($P < 0.0001$) after 6 weeks of storage. There is no significant change of moisture, fat, and salt content of the MAPS-fried rice	63

Table 3 (*Contd.*)

Product	Packaging and storage conditions	Processing conditions	Food quality changes	References
Pacific whiting surimi	226.8 g in 8 oz pouches	MAPS: preheating at 30 °C for 15 min; MW heating at a rate of 3 °C $\min^{-1}$, 12 °C $\min^{-1}$, and 24 °C $\min^{-1}$ up to 90 °C followed by cooling for 10 min Hot water pasteurization: 90 °C for 10 min	Surimi samples processed in MAPS formed stronger gels compared to those heated in a water bath. The heating rate in MAPS influenced the thermal gelation of surimi, with faster heating rates resulting in stronger gels	64
Pasta	MAPS cooked pasta was stored at 4 °C for 1 week. After 1 week, the pasta samples were allowed to equilibrate to room temperature (22 ± 2 °C)	MAPS: preheating the sealed trays for 40 minutes at 60 °C followed by microwave heating up to 86 °C at a rate of 76.2 cm $\min^{-1}$ and holding at 90 °C for 10 minutes Conventional cooking: boiling water up to 12 min	Microwave-cooked pasta had a more compact gluten network and higher degrees of amylose solubility and gelatinization compared to conventionally cooked pasta. However, microwave cooking also increased starch damage, gelatinization rates, and retrogradation rates, which negatively affected pasta quality	65

W), showed stable protein content and fat and fatty acid profiles compared to the one using high temperature short time (HTST) methods.[68] It indicates that MW pasteurization of milk has greater potential for industrial applications due to its shorter pasteurization time and reduced energy requirement. Studies also showed that microwave pasteurization of fruit juices and beverages also retains significantly a higher amount of bioactive compounds.[69,70] Orange juice-milk beverage, pasteurized using microwave, showed a reduced browning index, higher amounts of ascorbic acid, total phenolics, and carotenoids, and increased antioxidant activity and greater α-amylase and α-glucosidase compared to the conventionally pasteurized one.[69] In another study, the effect of MW pasteurization on the quality of tamarind and mixed fruit beverages was studied.[70] Following MW-pasteurization, there was a 100% reduction in enzymatic activity and a decrease in microbial load. When comparing the tamarind beverage to the untreated one, there were no discernible differences in pH, titratable acidity, or total soluble solids. However, the green beverage's color and sensory characteristics were impacted by MW-pasteurization ($p < 0.05$).

MAPS, offering mild thermal treatments, presents a valuable trade-off for food companies seeking to manufacture a diverse array of ready-to-eat (RTE) meals in response to increasing consumer demands for convenient and healthy foods with clean labels.[19] However, the propensity for large food corporations to adopt novel food processing technologies remains sluggish, primarily due to potential disruptions to existing production and distribution systems. Consequently, it is likely that smaller and medium-sized enterprises or emerging start-ups can capitalize on flexible MAPS-based RTE meals, emphasizing health benefits and devoid of bacterial and viral pathogens. These innovative meals are dignified for applications in diverse sectors such as airline catering, educational institutions, healthcare facilities (including nursing homes and hospitals), home delivery through e-commerce platforms, and retail distribution *via* refrigerated vending machines.[19]

6.2 Thermal sterilization

Thermal sterilization involves heating of in-package food to a very high temperature (121 °C) for 12 log reductions in the most heat resistant *Clostridium botulinum* spores. MATS processing involves a shorter processing time (2.5–4 min in the microwave heating section) to achieve a process value, F_0 = 3 min or higher, compared to conventional sterilization and therefore, a retort processed food has very poor quality in terms of texture, color and other nutritional attributes compared to the one treated with MATS.[13] For in-package processing, foods are often vacuum-packed for better quality retention and to facilitate the heat transfer process.[1] Nevertheless, sterilization affects the gas barrier performance of packaging films and allows oxygen and water vapor to permeate at a higher rate results in faster degradation in food quality.[23,47]

MATS and conventional retort processing alter the physicochemical attributes of food significantly and it changes further during storage.[23,25,71–77] Retort sterilization severely impacts the quality of foods including deterioration in the texture, color, and antioxidant activity of asparagus,[72] softening of RTE pork meat,[71] decreasing hardness and discoloration of vegetables with increasing temperature and holding time,[74] cook loss, browning, shrinkage, and thiamine degradation in salmon

Table 4 Effect of the MATS process and storage on food quality

Product	Packaging and storage conditions	Processing conditions	Food quality changes	References
Ready to eat macaroni and cheese	High barrier and oxygen scavenger-based polymeric packaging OTR = 0.01 to 0.04 cm^{-2} per days WVTR = 0.13 to 0.35 g m^{-2} per days (values shown above are before processing) Stored at 37.8 °C for 6 months	MATS: 25 min of preheating at 60 °C, 3.7 min of microwave heating, and then 3.8 min of holding at 121 °C, with a final step of 5 min cooling in tap water (around 20 °C) $F_0 = 11.1$ min Retort: a pilot-scale Allpax retort in water spray mode. Come-up time of 11 min, cooking time of 19 min at 121 °C, and cooling time of 38 min at 25 °C $F_0 = 6$ min	The color parameters of were not affected, while vitamin A and vitamin E increased after MATS and retort processing. The retort process resulted in a higher shear force of cutting macaroni compared with MATS processing. The vitamin A and vitamin E decreased by 49% and 9%, respectively, during 6 month storage at 37.8 °C. The color change was significant, while the shear force of macaroni and cheese did not change during storage, except in oxygen scavenger packaging. The OTR of MATS-processed packages in the range of 0.03 to 0.34 cc m^{-2} days did not impact physicochemical and vitamin stability in macaroni and cheese throughout the accelerated shelf life. However, WVTR influenced the shear force of macaroni at the end of storage in oxygen scavenger packaging. Sensory analysis also confirmed that the shelf life of macaroni and cheese is at least 3 years at 23 °C. The high-barrier packaging used in this study has a similar shelf life to aluminum pouches offering a suitable alternative in the packaging and transportation of food for the US Army and NASA space programs	23
Purple mashed potatoes	Ultra-high barrier triple layer of metal oxide (TLMO) coated PET-based polymeric packaging OTR= <0.01 to 0.21 cc m^{-2} per days; WVTR = 0.13 to 5.92 g m^{-2} per days (values shown above are before processing) Stored at 37.8 °C for 7 months without and with light (700 lumens and 5000 K daylight correlated color temperature)	MATS: 25 min of preheating at 61 °C, 3.9 min of microwave heating, and then 4.0 min of holding at 121 °C, with a final step of 5 min cooling in tap water (around 20 °C) $F_0 = 12.7$ min	MATS processed samples showed a higher concentration of anthocyanins, a lower retention in the phenolic compounds than the unprocessed samples. MATS did not result in any significant vitamin C loss. This could be attributed to the lower thermal exposure time and volumetric heating conditions of the MATS process. The TLMO films with three MO-coated PET layers did not have any detectable OTRs before and after MATS processing. The OTR of the poly acrylic acid (PAA) barrier coated film	25

Table 4 (*Contd.*)

Product	Packaging and storage conditions	Processing conditions	Food quality changes	References
			didn't change significantly ($P > 0.05$) after MATS, reconfirming the gentle effect of MATS processing on the flexible barrier films. Exposure to light resulted in a higher deterioration in the overall color, pigment content and vitamin C during storage	
Mashed potatoes	Multilayer polymeric packaging OTR = 0.07 to 2.1 cm^{-2} per days WVTR = 0.70 to 8.7 g m^{-2} per days (values shown above are before processing) Stored at 50 °C, 37 °C, and 23 °C for 12 weeks (2.8 months), 6 months, and 12 months, respectively	MATS: 26 min of preheating at 61 °C, 7.4 min of microwave heating, and then 4 min of holding at 124 °C, with a final step of 4 min cooling in tap water (around 2 °C) $F_0 = 9$ min	The total color change, ΔE, of mashed potatoes in four types of pouches stored at different temperatures followed zero-order reactions, with an activation energy ranging from 74 to 85 kJ mol^{-1}. Findings show that temperature and packaging barrier properties had a significant ($p < 0.001$) impact on color change. The Q_{10} values were 2.85–3.15 using $\Delta E = 12$ as the endpoint	42
Sweet potato puree	High barrier polymeric packaging OTR = 0.02 to 1.4 cm^{-2} per days WVTR = 0.13 to 3.57 g m^{-2} per days (values shown above are before processing) Stored at 35 °C, 23 °C, and 4 °C for 9 months, 18 months, and 18 months, respectively	MATS: 25 min of preheating at 61 °C, 3.7 min of microwave heating, and then 3.8 min of holding at 124 °C, with a final step of 5 min cooling in tap water (around 20 °C) $F_0 = 7.6$ min	Microwave-assisted thermal sterilization had limited impact on the color, vitamin C and total β-carotene content of vitamin C-fortified sweet potato puree. During the following storage, significant degradation of color and vitamin C was observed that are dependent on storage temperature and package barrier properties. Packaging also influenced the flavor liking and overall acceptance of the food samples. Reaction rates of color and vitamin C loss remained comparable to the foil pouch when the OTRs of pouches were under 0.3 cc m^{-2} per days at 35 °C or 0.1 cm^{-2} per days at 23 °C. Consumers considered the SPP as qualified baby food until the end of 18 months. Extremely high oxygen barrier packaging can provide similar shelf-life lengths to foil packaging for MATS processed SPP.	48

Table 4 (*Contd.*)

Product	Packaging and storage conditions	Processing conditions	Food quality changes	References
Garlic mashed potatoes	High barrier and oxygen scavenger-based polymeric packaging OTR = 0.01 to 0.04 cm^{-2} per days WVTR = 0.05 to 0.12 g m^{-2} per days (values shown above are before processing) Stored at 37.8 °C for 6 months	MATS: 25 min of preheating at 60 °C, 3.7 min of microwave heating, and then 3.8 min of holding at 121 °C, with a final step of 5 min cooling in tap water (around 20 °C) F_0 = 11.1 min Retort: a pilot-scale Allpax retort in water spray mode. Come-up time of 11 min, cooking time of 50 min at 116.6 °C, and cooling time of 42 min at 20.4 °C F_0 = 10.5 min	Thermal processing resulted in a 13% (MATS) and 18% (retort) loss in vitamin C and more than 50% loss in the garlic volatile compound, diallyl sulphide (DAS). The higher OTR and WVTR resulted in higher color change. The total color change in high barrier pouches during storage was similar to that of the foil based pouches. The shelf life of garlic mashed potatoes based on a 50% loss of processed vitamin C at 25 °C was similar for the foil based and high barrier multilayer polymeric pouches with initial OTR <0.1 cm^{-2} per days and WVTR <1.0 g m^{-2} per days	49
Chicken pasta	Ultra-high barrier (double layer of metal oxide coated PET) polymeric packaging OTR = <0.01 to 0.25 cm^{-2} per days WVTR = 0.11 to 1.67 g m^{-2} per days (values shown above are before processing) Stored at 37.8 °C for 6 months	MATS: 25 min of preheating at 61 °C, 3.9 min of microwave heating, and then 4.0 min of holding at 121 °C, with a final step of 5 min cooling in tap water (around 20 °C) F_0 = 12.7 min	The OTR of the double-layer pouch was below the detection limit of the instrument before MATS processing, and it remained very low (below detection limit) after MATS processing. Similarly, the WVTR of this pouch did not change after MATS processing. The package permeability to oxygen and water vapor greatly affected the color, lipid oxidation and sensory quality of the chicken pasta meal during the storage. Overall, the double-layer pouches showed similar performance to the foil-based pouches in terms of retention of physical, chemical, and sensory quality of chicken pasta during the storage. The MATS-processed chicken pasta in double-layer pouches could be stored up to 3–5 years at room temperature. Therefore, this recipe and packaging material selection may be suitable for U.S. Army rations and NASA extended duration space missions	50

Table 4 *(Contd.)*

Product	Packaging and storage conditions	Processing conditions	Food quality changes	References
Mashed potatoes	Multilayer polymeric packaging OTR = 0.02 to 1.12 cm^{-2} per days WVTR = 0.44 to 5.2 g m^{-2} per days (values shown above are before processing) Stored at 50 °C for 12 weeks (2.8 months)	MATS: 26 min of preheating at 61 °C, 7.4 min of microwave heating, and then 4 min of holding at 124 °C, with a final step of 4 min cooling in tap water (around 20 °C) $F_0 = 9$ min	The original hexanal content was higher than other volatiles since it is naturally present in potatoes. The increased content of volatiles after processing mainly resulted from the thermal effect of MATS. The weight loss, oxygen content in pouches, color change, and oxidation indicators (TBARS, volatile compounds) of mashed potatoes were associated with the barrier properties. The pouches with lower transmission rates maintained better quality, *e.g.*, such as with an OTR of 0.07 cm^{-2} per days and a WVTR of 0.29 g m^{-2} per days was found to be similar to the control pouch consisting of high barrier Al foil. The higher barrier pouches were slightly lower in volatiles during storage	58

fish.[77] MATS treated foods such as mashed potatoes,[29,58] purple mashed potatoes,[25] garlic mashed potatoes,[49] chicken pasta,[50] sweet potato puree,[48] RTE macaroni and cheese[23] and duck meat[73] have shown lower degradation in quality parameters and retain superior quality. The overall quality changes in MATS processed RTE macaroni and cheese were lower compared to the retort processed one.[23] MATS did not result in any significant vitamin C loss. This could be attributed to the lower thermal exposure time and volumetric heating conditions of the MATS process.[25,49] The results of several MATS studies are summarized in Table 4. The OTR and WVTR of packaging material also influence the quality of the stored product at ambient temperature. Product dryness due to moisture loss in packaged food (*e.g.* macaroni and cheese) correlated with increase in the packaging WVTR after thermal processing.[23] However, nutrients such as vitamins were stable during storage irrespective of packaging.[23] A high barrier packaging with an oxygen scavenger (OTR ~ 0.03–0.34 cm^2 per day and WVTR ~0.62–7.19 g m^{-2} per days) can be suitable for RTE meals for extended shelf life for soldiers and astronauts.[23,49] Better retention of quality of sterilized food in high barrier packaging during long term storage has been demonstrated in several studies.[23,25,42,48] During the last fifteen years at the bootcamps held at Washington State University, several food companies investigated the feasibility of MATS and MAPS processes for shelf life extension of several ready to eat (RTE) meals based on animal, plant and dairy products. These investigations showed great promise for manufacturing of high quality RTE meals with extended shelf life.

The effect of MW heating on the quality of PUFA-rich milk[78] and infant milk formula[79] has also been studied. Microwave heating did not affect the concentration of total saturated fatty acid (SFA), monounsaturated fatty acid (MUFA) and PUFA[78] as compared to UHT treated milk. In a study, the formation of Maillard reaction products and vitamin C degradation in infant formula food during MW (2450 MHz; power range 0–1860 W) sterilization were determined.[79] The authors concluded that high specific power with shorter MW treatment could be beneficial to minimize the formation of Maillard reaction products and vit-C degradation.[79]

7 Conclusions

Thermal sterilization and pasteurization are utilized to improve the safety and extend the shelf life of food products at ambient storage and refrigeration temperature, respectively. Regulatory guidelines are available for the design of thermal pasteurization processes for specific products. These guidelines are based on the thermal sensitivity of target pathogens relevant to different food categories. A variety of batch and continuous systems are developed for sterilization and pasteurization of food. Increasing industry and consumer interests in superior sensory quality food has led to the development of microwave assisted thermal processing systems. Compared to the traditional thermal processing, MATS and MAPS are energy and water efficient. Consumers' and industry interest in high performance polymer and laminated paper-based packaging for pasteurized food is growing. The current development in bio-based packaging materials may be suitable for an in-package hot-water based thermal pasteurization process. Further research is needed for the development of sustainable packaging materials for in-package conventional and microwave-based thermal processing.

Conflicts of interest

There are no conflicts of interest.

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