Current Trends in
Microbiology
Vol. 12, 2018

Review

Emerging technologies and microbiological safety in the meat industry

Gale Brightwell[1,*] **and Andrea Donnison**[2]

[1]Food Assurance and Meat Quality, AgResearch Ltd, Hopkirk Research Institute,
CNR University Ave and Library Road, Massey University, Palmerston North 4442;
[2]Food Assurance and Meat Quality, AgResearch Ltd, Ruakura Research Centre,
Private Bag 3123, Hamilton, New Zealand.

ABSTRACT

Consumers require meat that is fresh and free from contamination. The challenge has been to design technologies that achieve maximum microbial safety while minimising effects on nutritional and quality attributes. This review specifically investigates the microbial inactivation processes of a number of different emerging technologies with the potential to improve meat microbiological safety and shelf life. Irradiation is probably the ultimate solution, but there is still widespread public opposition to its use. Mild to moderate technologies include ultrasound, ozone, UV irradiation, infra-red radiation and pulsed light at various wavelengths. Some technologies, principally applied to improve meat quality, may also increase microbial food safety including high pressure processing and pressure-assisted thermal sterilization, electrical treatments that include pulsed electric fields and thermal treatments including ohmic heating, microwave or radio-frequency heating and hydrodynamic shock wave treatment. Most of these technologies are at an experimental, or pilot-scale proof of concept stage. Therefore, in the short-term these technologies will generally be used as one component in a combination of treatments (i.e. as a hurdle) or as a minimum processing strategy, used in conjunction with conventional methods. Long-term success will depend on their cost-effectiveness, ease of implementation, customer acceptance and approval by regulatory authorities.

KEYWORDS: emerging technologies, food safety, microbiology, meat processing.

1. Introduction

In response to consumer demand there is ongoing development of technologies to improve quality, shelf life and microbiological safety of red meat. Meat is a favourable environment for a large range of microorganisms, many of which can grow at very low temperatures. Unlike chemical contaminants, microorganisms, including pathogenic and spoilage bacteria can enter the food chain at any stage [1] and multiply under the right conditions such as poor temperature control. Further challenges for inactivation occur through microbial contaminants being dispersed non-uniformly in raw meat, present in protective biofilms and present in a variety of physiological states ranging from active growth to stationery phase.

A variety of treatments are applied to food including fresh meat. Some, for example microwave or high-pressure processing treatments, are designed to improve quality but others such as irradiation or pulsed light are applied to inactivate any harmful microorganisms present to ensure

---

*Corresponding author
gale.brightwell@agresearch.co.nz

food safety. Sub-lethal injury has been reported for a range of technologies including irradiation, high pressure treatments and acid treatments. However, as these treatments may not inactivate all target microorganisms, monitoring is still required. It is also possible that treatments designed to eliminate harmful microorganisms will induce survival systems, or even virulence and could allow some microorganisms to adapt to the conditions in the food chain [1].

Designing technologies to eliminate or at least reduce microbial contaminants to low levels is a very active research field [2]. Some, such as ionising radiation, have been extensively studied, found effective and been approved by global authorities, but are only slowly gaining consumer acceptance. Others, including high-pressure processing, are being researched at "full scale"; while many others, including pulsed light, microwave-assisted thermal sterilization and cold plasma technology are promising but need more research and validation on products at the processing and consumer ends of the chain [2, 3].

Although many technologies are designed to be used alone an effective approach seems to be to use combinations of two or more microbiocidal treatments, commonly called "hurdle technology" [4]. For example, light-based treatments may be more effective when used in combination with "photosensitisers" [5]. This review investigates the microbial inactivation processes of a number of different emerging technologies (summarised in Table 1) with the potential to improve meat microbiological safety and shelf life.

2. Antimicrobial effectiveness of technologies applied to improve meat quality

Some technologies applied to improve meat quality may also increase microbial food safety. These include high pressure processing, hydrodynamic shock wave and electro-processing (e.g. ohmic heating, microwave and pulsed electric fields) amongst others.

2.1. High pressure processing (HPP)

High pressure processing (HPP) uses very high hydrostatic pressure to preserve and sterilize food including meat [6-8]. Unlike thermal degradation, HPP is not necessarily accompanied by changes in food quality. However, pressures ≥300 MPa appear to cause more rapid lipid oxidation in meat and can result in changes in the colour of fresh meat.

HPP inactivates pathogens including *Listeria monocytogenes*, *Salmonella* spp. and *Escherichia coli*, due to induced phospholipid crystallization on cell membranes causing increased permeability [9], deactivation of enzymes and gene expression. Gram-negative species are generally more susceptible than Gram-positives [10-12]. HPP can deactivate most microorganisms by up to 4 $\log_{10}$ and improve the safety and shelf life of meat products [8, 13-15]. For example, HPP treatment of ground beef has been shown to cause substantial reductions (>5 log units) of *Pseudomonas fluorescens* (at ≥200 MPa), *Citrobacter freundii* (at ≥280 MPa) and *L. innocua* (at ≥400 MPa) [16]. Also HPP slowed the development of spoilage organisms during subsequent storage of ground beef [17] and HPP treatment of ground beef at 400 MPa for 10 minutes reduced *E. coli* O157:H7 by 3 log cfu/g, and caused sub-lethal injury resulting in further reductions during frozen storage [18]. Lactic acid bacteria and bacterial spores are generally more resistant, although 15 minutes HPP application at 4 °C reduced *Clostridium estertheticum* endospores below the limit of detection [19].

2.2. Pressure-assisted thermal sterilisation (PATS)

Pressure-assisted thermal sterilisation (PATS) is a combination of moderate initial temperatures and pressures [20]. PATS gives better meat quality and food safety compared to conventional thermal treatments and is a technique of high promise for the meat industry [21]. Microbial inactivation depends on microbial type, food composition, pH and water activity.

A disadvantage of HPP and PATS is the inability to significantly inactivate spores resulting in injured or stressed cells. However, in combination with antimicrobial treatments i.e. "hurdle technology" this limitation may be overcome. Examples include HPP in combination with lytic enzymes [22], antimicrobial chitosans [23] or nisin [24], all of which reduced viable spores. Crawford *et al*. [25] combined HPP with irradiation and eliminated *C. sporogenes* from

Table 1. Summary of different emerging technologies with the potential to improve meat microbiological safety and shelf life.

Technology	Aim	Antimicrobial effectiveness	Hurdle treatment	Refs
Ionising radiation	Preservation and food safety	High	Bioactives (cinnemaldehye); increased food safety; decreased physical/chemical changes	[107] [24] [71]
High pressure processing (HPP) and Pressure-assisted sterilisation (PATS)	Preservation and sterilization	Deactivates most Gram negative; more susceptible. Lactic acid bacteria and spore-resistant – PATS may be more effective	Lytic enzymes Chitosans Irradiation Citral	[8] [11] [12] [22] [23] [25] [26]
Hydrodynamic shock wave (HSW)	Increased tenderness	Conflicting reports	Nisin	[30] [33]
Ohmic heating	Increased shelf life of packaged products	Good except for food high in fats and oils and less effective against spores than cells	High pressure (POT) – inactivated spores	[35] [34] [36] [38]
Microwave-assisted sterilization (MATS)	Packaged food treated without loss of flavour	Heating must be even to inactivate bacteria in internal locations	A two-stage heating process increased inactivation	[48] [46]
Pulsed electric fields (PEF)	Improve quality and extend shelf life and increase meat tenderness	Limited information for use as a hurdle technology	Changes in pH and ionic strength	[50] [51] [55]
Cold plasma	Inactivation of microorganisms on meat or applied to packages	Total bacteria and some species reduced if reactive oxygen and nitrogen high enough	Selection of gas: helium plasma more effective than argon plasma Nano-photocatalysis	[83] [91] [81]
Blue light-light emitting diodes (Blue light LEDs)	Inactivation of microorganisms without thermal degradation	Gram-positive bacteria generally more sensitive	Exogenous photosensitizers e.g. (aminolevulinic acid)	[5] [5]
Pulsed light (PL) Wavelengths (100 nm - 1 mm) applied in pulses	Disinfection with minimal effects on quality	Successful against low levels of contamination	Photosensitisers (e.g. hematoporphyin or sodium chlorophyllin)	[102] [103]

chicken breast. A hurdle approach may also reduce pathogenic bacteria as Chien *et al*. [26] reported that the combination of HPP and citral enhanced inactivation of *E. coli* O157:H7.

2.3. Hydrodynamic shock wave (HSW)

Hydrodynamic shock wave (HSW) involves a shock wave passing through vacuum-packaged raw muscle food [27, 28]. Concerns that HSW increases penetration of bacteria into the interior of intact meat may be unfounded [29]. Reports of microbial inactivation are conflicting [30]. Williams-Campbell *et al.* [31] observed a 1.5-2 $\log_{10}$ reduction in total plate count in ground beef with a 4.5 $\log_{10}$ lower total plate count after 14 days storage. In contrast no difference was found in coliform or aerobic plate counts in HSW-treated pork loin [32]. Patel *et al.* [33] investigated a combined treatment using nisin and HSW and showed a 2 $\log_{10}$ reduction in *L. monocytogenes* in frankfurters. The mechanism of bacterial inaction is probably generation of UV light during shock wave formation.

2.4. High pressure carbon dioxide decontamination (HPCD)

High pressure carbon dioxide decontamination treatment inactivates food microorganisms due to high pressure combined with mild heat in the presence of carbon dioxide which penetrates the food. Microbial inactivation is usually due to a decrease in cellular pH and the subsequent damage to the cell membrane together with disruption of cellular components.

3. Electro-processing techniques

Electro-processing technologies applied to food can be divided into thermal (ohmic heating, microwave and radio-frequency) and non-thermal (electrical stimulation and pulsed electric field).

3.1. Ohmic heating

With ohmic heating (OH) food placed in physical contact with electrodes is heated by an electric current [34]. Food high in fats or oils are less amenable to OH treatment [34]. For suitable food, e.g. stew type products, OH can produce safe, high-quality products with a shelf life of up to 3 years [35].

Antimicrobial effects are mainly due to thermal inactivation. At low frequency microbial cell walls build up charges with consequent formation of pores in the membrane. These changes do not occur in microwave heating because the electric field is reversed before sufficient charge builds up. Thermal inactivation curves are similar to those for other heating methods and there is also greater effectiveness against bacterial cells than spores [36]. OH treatment of whole beef muscle (500 g portions) successfully inactivated inoculated *L. monocytogenes* [37]. However, Varghese *et al.* [35] noted that ohmic heaters in current use are limited to treatment of processed food.

The combined use of OH and high pressure (i.e. POT) on fruit and vegetable juices was effective in activating spores [38]. POT is also effective for rapid thawing of frozen meat. Samples of frozen beef that received POT treatment (OH at 40 V cm^{-1} and pressure at 200 MPa) were completely thawed in 0.8 minutes compared to 23.3 minutes for conventional (air) thawing without adverse effects on quality [39].

3.2. Microwave (MW) and radio frequencies (RF)

MW and RF use electromagnetic waves to generate heat in a material [40-42]. Both MW and RF inactivate microorganisms due to the rapid increase in temperature. Bacterial cells are more resistant than yeasts and moulds with spores more resistant than vegetative cells. Microbes that have been successfully inactivated include *Bacillus cereus*, *Campylobacter jejuni*, *Clostridium perfringens*, pathogenic *E. coli*, *Enterococcus* spp., *Listeria monocytogenes*, *Staphylococcus aureus* and *Salmonella* spp. [43-45]. A two-stage microwave process applicable to raw meat inactivated bacteria including *E. coli* O157:H7, principally in the second heating phase [46]. A log reduction in total bacterial count was reported for frozen sheep carcasses exposed to MW for 25 seconds [47] but there are also reports of survival of some bacteria including *Salmonella* spp. and *L. monocytogenes* in internal locations [48]. However, to date there have been no reports of microwave-resistant bacteria.

3.3. Microwave-assisted thermal sterilization (MATS)

MATS is a thermal process involving pressurized hot water and microwave energy that is applied to packaged products. Inactivation has been reported in a range of food types including poultry, fish, beef, pork, milk and eggs. It gives a shelf life of more than 2 years for sterilized products and 3-4 months for pasteurized products. Antimicrobial inactivation is due to the rapid increase in either pasteurization or sterilization temperature. There have been concerns around survival due to uneven heating [48] but the immersion of packaged food in pressurized water largely overcomes this. Bacterial cells are more resistant to MATS than moulds and yeasts with spores the most resistant. It is fundamentally a thermal process, which means that the regulatory hurdles (while still important considerations) are lower than for non-thermal approaches.

3.4. Pulsed electric fields (PEF)

Pulsed electric field technology is energy efficient compared to thermal processes [49, 50] but is best suited to food of small particle size, low salt content and low electrical conductivity. Recent results suggest that it significantly increased meat tenderness [51]. It is not currently optimised for controlling microbial contamination on meat and meat products. Microbial inactivation is due to a build-up of electrical charges and the subsequent disruption of cell membranes [52-54]. There are some concerns over PEF promoting microbial growth in meat products due to increased availability of precursor metabolites for microbial spoilage. Unpublished results have shown increased microbial growth after PEF treatment. The level of inactivation has been shown to be dependent on processing conditions as well as product properties and works poorly on spores. Inactivation of *E. coli* has been demonstrated for PEF applied as one of a series of “hurdles” including pH and ionic strength [55]. PEF is currently not optimised for controlling microbial contamination on meat and meat products.

Overall there is little data on the effectiveness of OH, radiofrequency and PEF against foodborne pathogens or spores.

4. Highly effective “Disinfection” technologies

4.1. Ionising radiation

Ionising radiation of meat (or other foodstuffs) increases preservation and reduces the risk of foodborne illness. Overall, consumer perception of irradiated food remains negative despite a large amount of research confirming safety and effectiveness [56, 57] and widespread approval from authorities (e.g. [58-60]). In 2003 the Codex Alimentarius Commission (FAO and WHO) removed any upper dose limits declaring all food can be safely irradiated. However, most countries currently only give approval on a case-by-case basis [61] e.g. food that has been USA-approved includes uncooked meat and by-products [62]. New Zealand and Australia permit irradiation of herbs and spices and some fruit and vegetables [63]. Health Canada has recently authorized irradiation of raw fresh and frozen ground beef [64].

Ionizing radiation damages DNA and generates reactive oxygen species that damage microbial cell membranes [65] causing cell death [66]. Gram-negative bacteria, including meat spoilage organisms, are more sensitive to irradiation than viruses and bacterial spores [56]. Cells in stationary phase and stress-adapted bacteria may have greater resistance [67]. Meat proteins can protect microorganisms against damage caused by free radicals [68] while carbon monoxide (in modified atmosphere packaging), osmotic and heat stress [69] can enhance survival. The addition of antimicrobials (e.g. sodium lactate) can enhance bacterial cell death [70]. A hurdle technique combination of irradiation and bioactive compounds (cinnamaldehyde, with or without ascorbic acid) significantly reduced microorganisms on meat without causing physical or chemical changes [71].

Irradiation, applied as Gamma-ray (Cobalt-60), controls microbial contamination in meat [72, 73] including shiga toxin producing *E. coli* [74, 75]. X-ray irradiation [76] (Mitchell, 1994) increased ground beef shelf life by 14 days [77, 78] and Electron-beam (e-beam) irradiation, which does not expose food to electromagnetic radiation but has poor penetration depth (limited to about 2.5 cm), is effective in combination with acetic acid [79]. E-beam plus lactic acid is approved for beef in the US and Canada. Irradiation combined with bioactive compounds can decrease microbial load (in ground beef) without significant change to physical or chemical properties [71].

5. Mild to moderate disinfection technologies

Techniques of a mild to moderate in nature that are reasonably effective against microorganisms of concern include cold plasma and the spectral technologies of UV irradiation, infra-red radiation and pulsed light at various wavelengths produced by LED light sources.

5.1. Cold plasma

Cold plasma is a non-thermal technology that can inactivate microorganisms on meat and poultry and also sealed packages [80]. For packaged meat it has been suggested that effectiveness would be increased if a bacteriostatic nano-photocatalyst (e.g. $ZnO + Fe_2O_3$) was deposited onto packaging film [81]. Cold plasma is generated by applying an electric charge to selected gases [82, 83]. Antimicrobial inactivation is mainly due to direct oxidative effects between plasma ions and cellular components. Many factors including plasma source, nature of the product/substrate and target microbial species influence the effectiveness of microbial inactivation [83].

Cold plasma has been applied to pork [84], chicken [85, 86] and beef [87, 88] with mixed success. The concentration of ROS (reactive oxygen species) and RNS (reactive nitrogen species) needs to be high enough for effective bacteriocidal effects [83). Noriega *et al.* [89], reported effective reduction of the total bacterial count (TBC) in chicken skin but Dirks *et al.* [85], using the same generation system found <1 $\log_{10}$ TBC reduction. In contrast 2.5 $\log_{10}$ TBC reduction was reported by Ulbin-Figlewicz *et al.* [90] for pork treated with either helium or argon low pressure plasma. In a further study Ulbin-Figlewicz *et al.* [91] reported a 2 $\log_{10}$ reduction in TBC in beef for helium plasma (but only 0.5 $\log_{10}$ for argon plasma) and noted that prolonged treatment (10 min) was required for psychrotrophs. There are also reports of inactivation of spores [92] and Hepatitis A virus [93] in meat and of *Aeromonas hydrophila* in biofilm on lettuce [94]. After evaluating published data Misra *et al.* [83] reported that although cold plasma at ambient pressure is effective in inactivating *L. monocytogenes* (average reduction of 2.5 $\log_{10}$) its effectiveness against *E. coli* is relatively low. Results to date for *Campylobacter* are similarly disappointing. Zhang *et al.* [81] reported that a combination of high voltage plasma and nano-photocatalysis may increase effectiveness.

6. Radiation or electromagnetic radiation technologies

Electromagnetic radiation has many applications to food safety including direct treatment with infrared and ultraviolet technologies.

6.1. Infrared radiation

Infrared radiation is accompanied by heat and hence applications to the meat industry are usually indirect. A range of instruments operate at different wavelengths along the IR spectrum. Near infrared (NIR) spectroscopy and imaging techniques detect microbiological hazards and have promise for in-line/real time applications [95]. He *et al.* [96] reviewed applications of visible/infrared, Raman and fluorescence spectroscopy and concluded that despite promise for microbial evaluation further development is needed for optimal spectral pre-processing, model calibration and instrumentation. Kumaravelu *et al.* [97] also favour a new statistical approach for all NIR applications. As these technologies are non-destructive in nature research is ongoing to overcome present limitations.

Fourier-transform infrared spectroscopy was used to obtain information on meat spoilage from the surface of beef samples under aerobic storage at various temperatures ranging from chill to abuse. By plotting spectral data against aerobic plate counts Alshejari *et al.* [98] constructed a model for the rapid prediction of spoilage. This technique is an efficient and accurate method for assessing meat spoilage [99].

In a practical demonstration for meat processors, a visible/near infrared hand-held fluorescence imaging device (HFID) was used to detect faecal contamination on beef meat surfaces under visible light providing a useful device to assist identification of contamination on food and food contact surfaces [100].

7. Light-emitting-diode (LED) technologies

Light-emitting-diodes (LED) emit light over a narrow bandwidth [5]. There is interest in the application of LED technologies for food safety across the agro-industries, including meat.

7.1. Blue light LEDs

Blue light or near UV (400-495 nm) can induce microbial cell damage, injury and death through damage to DNA, photodynamic inactivation (PDI) due to formation of damaging “reactive oxygen” species (ROS). Blue light has peak effectiveness at 405 nm, peak adsorption spectrum of meat porphyrins, suggesting porphyrins are responsible for the ROS production that damages cellular constituents: DNA, lipids, some enzymes and other proteins, and most damaging of all, cell membranes. As cells cannot repair this damage they are unable to develop antimicrobial resistance to blue light treatment. Gram-positive bacteria are generally more sensitive than Gram-negative but there are also species differences and blue light at 405 nm can inactivate bacterial spores without severe damage to animal cells. Microbial sensitivity can be increased by adding exogenous photosensitisers such as 5-aminolevulinic acid (ALA), a metabolic precursor to various cellular photosensitising porphyrins. For example, ALA treatment with LED at 400 nm for 15 minutes successfully inactivated *Listeria monocytogenes* and *Bacillus cereus* spores on packaging surfaces [5]. As little heat is emitted, LED application is unlikely to cause thermal degradation of the product. However, each food-type will need to be evaluated individually for suitability for PDI treatment [5].

7.2. UV light LEDs

UV LEDs (100-400 nm) can be operated to create rapid pulses which may enhance the effectiveness of conventional UV treatment. Although usually applied to water treatment, using pulsed UV in the UV-C range (100-280 nm), pulsed UV-A (315-400 nm) effectively reduced biofilm populations of *E. coli* [101]. Several problems need to be solved before the technology can be applied to meat due to low LED penetration into food like meat with uneven surfaces. Bacterial contamination of meat occurs on the surface and hence incorporation of photosensitisers into packaging materials that are then exposed to blue light could be a promising approach. However, realistically, blue light application may be a “hurdle” technology i.e. one of a series of procedures required for effective reduction of pathogens and spoilage organisms.

7.3. Pulsed light technology

Pulsed light (PL) technology involves the application of intense light pulses of a broad spectral range comprising ultraviolet, visible and near infrared (100 nm^{-1} mm). It has higher efficiency than conventional UV and it has successfully been used for disinfection of packaging for several years. PL has been applied to chicken skin and meat with reductions of at least a log reported for common pathogens with minimal adverse effects on quality. Pulsed light has also been successfully used to disinfect transparent packaging. There may be several steps in a processing chain where the application of PL would be useful as there are minimal adverse effects. One suggestion is to apply PL to carcasses in conjunction with refrigeration to reduce the microbial burden. It can also be used in processing lines to prevent cross-contamination between equipment and the final product. The greatest success has been reported when treatment is given immediately after possible contamination (e.g. when meat is cut), before there is an increase in the endogenous microflora [102]. Hurdle technology suggestions include combining PL with sub-lethal stress treatments such as an acid or salt wash, or after addition of food-grade compounds called photosensitizers. Photosensitizing agents that have been trialled experimentally include hematoporphyrin and sodium chlorophyllin [103].

8. Packaging

Traditional food packaging is used for protection, convenience and containment using inert materials that do not react with food. In contrast, active and intelligent (smart) packaging systems are based on a useful interaction between the packaging environment and the food, with the intention of enhancing presentation, ensuring food safety and/or prolonging shelf life [104]. However, overall technological improvements and new design may be more applicable to case-ready meat at the retail level than bulk meat at the processing level [105].

8.1. Active packaging

As oxygen accelerates deterioration both vacuum packaging (that aims to exclude oxygen) and modified atmosphere packaging (MAP) (which involves the use of specific gas mixtures e.g. nitrogen/oxygen/carbon dioxide mixtures) are commonly used for raw red meat. As neither of these two systems removes oxygen completely “oxygen scavengers” may be added. Scavenging materials can be included in layers coated onto the inner walls of packaging or blended with high permeability films like polyethylene [104]. Secondary gases can also be used, and those that are permitted for MAP packaging in Europe include argon, nitrous oxide and helium. There is on-going debate about adding small quantities of carbon monoxide and hydrogen. Carbon dioxide has a complex bacteriocidal effect that increases as the gas increases in solubility with decreased temperature [106]. However, vacuum packaging continues to be the most cost-effective strategy [107] particularly for bulk meat. Active packaging is likely to continue to be widely used as it can deliver cost-effective spoilage prevention and safety control [108].

8.2. Antimicrobial packaging

The aim of antimicrobial packaging is to improve food safety while at the same time maintaining shelf life and consumer appeal. There are two types of antimicrobial packaging materials: those that contain antimicrobial agents that migrate to the surface of the packaging material and those that are effective against surface microbes without migration into the food. Direct application of antibacterial substances onto food has limited application because most are neutralised on contact or (i.e. become diluted) into the food [109]. Consumer preference for natural products has led to interest in natural antimicrobial agents, for example, extracts from spices such as cinnamon or cloves or from plants such as onion, garlic and horseradish. However, due to their usually strong odour and high cost of production they are not considered a viable option to synthetic antimicrobial substances [110]. Other substances that are classed as natural are antimicrobials derived from fungi or bacteria such as natamycin, nisin and various bacteriocins. Ultraviolet light-assisted titanium dioxide photocatalysis is a non-thermal technology that efficiently inactivates foodborne pathogens and has been explored; however more work is needed to develop this technology for antimicrobial food packaging [111]. Consumer concerns over health issues have led to interest in probiotics. Antimicrobial packaging with incorporation of probiotics has been reported to control pathogens and could be a technology that has favourable consumer acceptance [112].

8.3. Intelligent packaging

Intelligent packaging systems include sensors that are strategically placed on or within packages to continuously measure characteristics such as integrity, freshness and time-temperature [113]. Intelligent packaging employs sensors to detect marker compounds associated with poor quality and microbial contamination. For example, the level of volatile basic nitrogen that is a good indicator of beef quality, and pH changes that will detect an increase in lactic acid bacteria. As information is available in real time food quality and safety or necessary remediation is maintained [114]. Intelligent food contact materials (FCMs) are the next generation of packaging with active research world-wide [105].

Packaging that includes nanotechnology promises benefits that include prolonged shelf life, allowing wide geographical distribution and reduction of waste. A wide variety of polymers has been tested for use with nanoparticles. Research has concentrated on ensuring nanoparticle size and concentration are optimal for the required timed release. There is currently a blanket ban on development of packaging materials incorporating nanoparticles under European Legislation due to concerns over biocidal properties of the particles themselves (intended to inhibit microbial growth) and their ultimate effects on human health or the environment. However, given the advantages of nanotechnology for packaging research effort is likely to continue and public concerns be addressed [105].

9. Conclusions

Fresh chilled meat is traded between different countries with large amounts of product travelling long distances, but irrespective of its source consumers increasingly demand that their food, including meat, is fresh and free from contamination. A number of novel thermal and non-thermal technologies have been designed to achieve microbial safety while minimising effects on nutritional and quality attributes. Although many of these technologies are not yet officially accepted by all markets, an exception is high pressure processing (HPP) that has approval from the USDA Food Safety and Inspection Service for removal of *Listeria monocytogenes* on processed meat and as a consequence several US meat and poultry manufacturers have applied this technology to seafood, ham, chicken and ready-to-eat products. The need to supply markets with meat that meets both maximum quality and food safety standards is likely to lead to increasing use of "hurdles" in which two or more technologies are applied to increase microbial safety without compromising quality or shelf life. In practice, the long-term success and uptake of emerging technologies depends on their cost-effectiveness, ease of implementation, customer acceptance and approval by regulatory authorities.

ACKNOWLEDGEMENTS

This work was supported by New Zealand Meat Industry Association Innovation Funding Contract Number A22628.

CONFLICT OF INTEREST STATEMENT

There are no conflicts of interest.

REFERENCES

1. Havelaar, A., Brul, S., De Jong, A., Zwietering, M. H. and Ter Kuile, B. H. 2010, International Journal of Food Microbiology, 139(Suppl. 1), S79-S94.
2. Cummins, E. J. and Lyng, J. G. 2017, Editors, Emerging technologies in meat processing: production, processing and technology. John Wiley & Sons Ltd., UK.
3. Midgley, J. and Small, A. 2006, Review of new and emerging technologies for red meat safety. Meat & Livestock Australia. PRMS 083. 73p.
4. Khan, I., Tango, N. C., Miskeen, S., Lee, B. H. and Oh, D.-H. 2017, Food Control, 73, 1426-1444.
5. D'Souza, C., Hyun-Gyun, Y., Khoo, G. H., and Zhou, W. 2015, Comprehensive Reviews in Food Science and Food Safety, MS 20150772, 22 p.
6. Hugas, M., Garriga, M. and Monfort, J. M. 2002, Meat Science, 62(3), 359-371.
7. Campus, M. 2010, Food Engineering Reviews, 2, 256-273.
8. Rendueles, E., Omer, M. K., Alvseike, O., Alonso-Calleja, C., Capita, R. and Prieto, M. 2011, LWT-Food Science & Technology, 44(5), 1251-1260.
9. Sikes, A., Tornberg, E. and Tume, R. 2010, Meat Science, 84, 390-399.
10. Hoover, D. G, Metrick, C., Papineau, A. M., Farkas, D. F. and Knorr, D. 1989, Food Technology, 47, 99-107.
11. Marcos, B., Aymerich, T., Monfort, J. M. and Garriga, M. 2008, Food Microbiology, 25(1), 171-182.
12. Liu, G., Wang, Y., Gui, M., Zheng, H., Dai, R. and Li, P. 2012, Food Control, 24, 64-71.
13. Hereu, A., Dalgaard, P., Garriga, M., Aymerich, T. and Bover-Cid, S. 2014, International Journal of Food Microbiology, 186, 84-94.
14. Ahmadi, H., Anany, H., Walkling-Ribeiro, M. and Griffiths, M. W. 2015, Food and Bioprocess Technology, 8, 1160-1167.
15. Hygreeva, D. and Pandey, M. C. 2016, Food Science, 65(S8), 93-95.
16. Carlez, A., Rosec, J., Richard, N. and Cheftel, J. 1993, Lebensmittel-Wissenschaft und Technologie, 26, 357-363.
17. Carlez, A., Rosec, J. P., Richard, N. and Cheftel, J. C. 1994, Lebensmittel-Wissenschaft und Technologie, 27, 48-54.
18. Black, E. P., Hirneisen, K. A., Hoover, D. G. and Kniel, K. E. 2010, Journal of Applied Microbiology, 108, 1352-1360.
19. Ho. 2013, https://iafp.confex.com/iafp/2013/webprogram/Paper4345.html
20. Sizer, C. E., Balsubramaniam, V. M. and Ting, E. 2002, Food Technology, 56(2), 36-42.
21. Barbosa-Cánovas, G. V. and Juliano, P. 2008, In G. F. Gutiérrez-Lope, G. V. Barbosa-Cánovas, J. Welti-Chanes and E. Parada-Arias (Eds.), Food Engineering: Integrated Approaches, (pp. 9-46). Springer, NY.
22. Popper, L. and Knorr, D. 1990, Food Technology, 44, 84-89.
23. Papineau, A. M., Hoover, D. G., Knorr, D. and Farkas, D. F. 1991, Food Biotechnology, 5, 45-47.
24. Roberts, C. M. and Hoover, D. G. 1996, Journal of Applied Microbiology, 81(4), 363-368.
25. Crawford, Y. J., Murano, E. A., Olson, D. G. and Shenoy, K. 1996, Journal of Food Protection, 59, 711-715.

26. Chien, S.-Y., Sheen, S., Sommers, C. and Sheen, L. Y. 2017, Food Control, 73, 672-680.
27. Kolsky, H. 1963, Stress waves in solids. Dover Publications, New York.
28. Zuckerman, H. and Solomon, M. B. 1998, Journal of Muscle Foods, 9, 419-426.
29. Gill, C. and Penney, N. 1977, Applied & Environmental Microbiology, 33, 1284-1286.
30. Solomon, M. B., Liu, M. N., Patel, J. R., Bowker, B. C. and Sharma, M. 2006, In L. M. L. Nollet and F. Toldra (Eds.), Advanced Technologies for meat processing (pp. 219-24). CRC Taylor & Francis.
31. Williams-Campbell, A. M. and Solomon, M. B. 2002, Journal of Food Protection, 65(3), 571-574.
32. Moeller, S., Wulf, D., Meeker, D., Ndife, M., Sundararajan, N. and Solomon, M. 1999, Journal of Animal Science, 77, 2119-2123.
33. Patel, J. R., Sanglay, G. C. and Solomon, M. B. 2009, Journal of Muscle Foods, 20(2), 227-241.
34. Kaur, N. and Singh, A. K. 2016, Critical Reviews in Food Science and Nutrition, 56(14), 2338-2351.
35. Varghese, K. S., Pandey, M. C., Radhakrishna, K. and Bawa, A. S. 2014, Journal of Food Science and Technology, 51(10), 2304-2317.
36. Sastry, K. S. and Barach, J. T. 2000, Journal of Food Science, 65(S8), 42-45.
37. Zell, M., Lyng, J. G., Cronin, D. A. and Morgan, D. J. 2010, Meat Science, 86, 258-263.
38. Park, S. H., Balasubramaniam, V. M., Sastry, S. K. and Lee, J. 2013, Innovative Food Science & Emerging Technologies, 19, 115-123.
39. Min, S.-G., Hong, G.-P., Chun, J.-Y. and Park, S. H. 2015, Food Bioprocessing Technology, doi:10.1007/s11947-015-1652-3.
40. Metaxas, R. and Meredith, R. J. 1988, Industrial microwave heating. Peter Peregrinus, London, UK.
41. Roussy, G. and Pearce, J. A. 1995, Foundations and Industrial Applications of Microwaves and Radio Frequency Fields. Wiley, New York.
42. Datta, A. K. and Davidson, P. M. 2000, Journal of Food Science, 65(S8), 32-41.
43. Heddleson, R. A., Doores, S. and Anantheswaran, R. C. 1994, Journal of Food Science, 59(2), 447-451.
44. Rosenberg, U. and Bögl, W. 1987, Food Technology, 41(6), 92-99.
45. Knutson, K. M., Marth, E. H. and Wagner, M. K. 1987, Lebensm Wiss Technologie, 20, 101-110.
46. Huang, L. and Sites, J. 2010, Journal of Food Science, 75(2), E110-E115.
47. Abdul Aali, N. I. and Ali Alobaidi, D. A. 2017, International Journal of Science and Research, 6(1), 1426-1428.
48. Schnepf, M. and Barbeau, W. E. 1989, Journal of Food Safety, 9, 245-252.
49. Quass, D. W. 1997, Pulsed electric field processing in the food industry. A status report on PEF. Electric Power Research Institute, Palo Alto CA, USA. CR-109742.
50. Barbosa-Canovas, G. V., Pierson, M. D., Zhang, Q. H. and Schaffner, D. W. 2000, In: Report of the Institute of Food Technologist for the Food & Drug Administration of the US Department of Health & Human Sciences. Journal of Food Science, 65(S8), 65-78.
51. Faridnia, F., Bremer, P., Burritt, D. J. and Oey, I. 2015, Effects of pulsed electric fields on selected quality attributes of beef outside flap (Biceps femoris). 1st World Congress on Electroporation and Pulsed Electric Fields in Biology, Medicine and Food and Environmental Technologies, pp. 51-54. https://rd.springer.com/chapter/10.1007/978-981-287-817-5_12
52. Zimmerman, U. 1986, Reviews in Physiological Biochemical Pharmacology, 105, 175-256.
53. Castro, A. J., Barbosa-Canovas, G. V. and Swanson, B. G. 1993, Journal of Food Processing and Preservation, 17, 47-73.
54. Vega-Mercado, H., Martin-Belloso, O., Chang, F.-J., Barbosa-Canovas, G. V. and Swanson, B. G. 1996, Journal of Food Processing & Preservation, 20(6), 501-510.
55. Vega-Mercado, H., Pothakamury, U. R., Chang, F.-J., Barbosa-Canovas, G. V. and Swanson, B. G. 1996, Food Research International, 29(2), 117-121.

56. O'Bryan, C. A., Crandall, P. G., Ricke, S. C. and Olson, D. G. 2008, Critical Reviews in Food Science & Nutrition, 48, 442-457.
57. Roberts, P. B. 2014, Radiation Physics & Chemistry, 105, 78-82.
58. FDA. 1986, Irradiation in the production, processing and handling of food. US Department of Health and Human Services, Food & Drug Administration. Federal Register 51, 13376-13399.
59. WHO. 1994, Safety and nutritional adequacy of irradiated food. World Health Organisation, Geneva Switzerland.
60. WHO. 1999, High-dose irradiation: wholesomeness of food irradiated with doses above 10 lGy. Report of a joint FAO/IAEA/WHO study Group. WHO Technical Report Series No. 890. World Health Organisation, Geneva, Switzerland.
61. Farkas. J. and Mohacsi-Farkas, C. 2011, Trends in Food Science & Technology, 22, 121126.
62. US Federal Register. 2012, Irradiation of food including unrefrigerated and refrigerated meat and meat products. Rules and Regulations. Volume 77, Issue 23, Document 2012-28967, 71312-71316.
63. Food Standards Australia New Zealand 2017, Food Irradiation (April 2017), 2p. www.foodstandards.govt.nz/consumer/foodtech/irradiation
64. Health Canada 2017, Government of Canada announces changes to the Food & Drug Regulations to permit the irradiation of ground beef. News Release, February 22nd 2017. www.canada.ca/en/healthcanada/news/2017/02/government_of_canadaannounceschangestothefoodanddrugregulations.html
65. Mishra, K. P. 2004, Journal of Environmental Pathology, Toxicology & Oncology, 23, 61-66.
66. Verma, N. C. and Singh, R. K. 2001, Journal of Environmental Pathology, Toxicology & Oncology, 20, 1-7.
67. Mendonca, A. F., Romero, M. G., Lihono, M. A., Nannapaneni, R. and Johnson, M. G. 2004, Journal of Food Protection, 67, 470-474.
68. Diehl, J. F. 1995, Safety of irradiated foods. 2nd Ed. Marcel Dekker Inc. New York, NY.
69. Lacroix, M. and Ouattara, B. 2000, Food Research International, 33(9), 719-724.
70. Ahn, D. U., Kim, I. S. and Lee, E. J. 2013, Poultry Science, 92(2), 534-545.
71. Ayari, S., Han, J., Vu, K. D. and Lacroix, M. 2016, Food Control, 64, 173-180.
72. Lee, N. Y., Jo, C., Shin, D. H. and Kim, W. G. 2006, Food Microbiology, 23, 649-656.
73. Konteles, S., Sinanoglou, V. J., Batinrou, A. and Sflomos, K. 2009, Food Microbiology, 26, 157-165.
74. Fu, A.-H., Sebranek, J. G. and Murano, E. A. 1995, Journal of Food Science, 60, 972-977.
75. Sommers, C., Rajkowski, K. T., Scullen, O. J., Cassidy, J., Fratamico, P. and Sheen, S. 2015, Food Microbiology, 49, 231-234.
76. Mitchell, G. E. 1994, Irradiation preservation of meats. Food Australia, 46, 512-516.
77. Long, J. 1994, Apparatus for tenderizing meat. US Patent 5,273,766.
78. Gamage, S. D., Faith, N. G., Luchansky, J. B., Buege, D. R. and Ingham, S. C. 1997, International Journal of Food Microbiology, 37(2-3), 175-182.
79. Fielding, L. M., Cook, P. E. and Grandison, A. S. 1997, International Journal of Food Control, 35, 259-265.
80. Misra, N. N., Ziuina, D., Cullen, P. J. and Keener, K. M. 2013, Transactions of the ASABE, 56, 1011-1016.
81. Zhang, J., Jiamei, W. and Zhuang, H. 2014, Synergistic sterilizing and preserving method for fresh meat with high voltage electric field plasma and nano photocatalysis 15/305 China: Nanjing Agricultural University 727.
82. Scholz, V., Pazlarvoa, J., Souskova, H., Khum, J. and Julak, J. 2015, Biotechnology Advances, 33, 1108-1119.
83. Misra, N. N. and Jo, C. 2017, Trends in Food Science & Technology, 64, 74-86.
84. Frohling, A., Durek, J., Schnabel, U., Ehlebeck, J., Bolling, J. and Schluter, O. 2012, Innovative Food Science and Emerging Technologies, 16, 381-390.

85. Dirks, B. P., Dobrynin, D., Fridman, G., Mukhin, Y., Fridman, A. and Quinlan, J. J. 2012, Journal of Food Protection, 75, 22-28.
86. Lee, H., Yong, H. I., Kim, H.-J., Choe, W., Yoo, S. J., Jang E. L. and Jo, C. 2016, Food Science & Biotechnology, 25, 1189-1195.
87. Kim, J.-S., Lee, E.-J., Choi, E. H. and Kim, Y.-J. 2014, Innovative Food Science & Emerging Technologies, 22, 124-130.
88. Jayasena, D. D., Kim, H. J., Yong, H. L., Park, S., Kim, K., Choe, W. and Jo, C. 2015, Food Microbiology, 46, 51-57.
89. Noriega, E., Shama, G., Laca, A., Diaz, M. and Kong, M. G. 2011, Food Microbiology, 28, 1293-1300.
90. Ulbin-Figlewicz, N., Brychcy, E. and Jarmoluk, A. 2015, Journal of Food Science & Technology, 52, 1228-1212.
91. Ulbin-Figlewicz, N., Jarmoluk, A. and Marycz, K. 2015, Annals of Microbiology, 65, 1537-1546.
92. Patil, S., Moiseev, T., Misra, N. N., Cullen, P. J., Mosnier, J. P., Keener, K. and Bourke, P. 2014, The Journal of Hospital Infections, 88, 162-169.
93. Bae, S.-C., Park, S. Y., Choe, W. and Ha, S.-D. 2015, Food Research International, 76, 342-347.
94. Jahid, I. K., Han, N. and Ha, S.-D. 2014, Food Research International, 55, 181-189.
95. Fu, X. and Ying, Y. 2016, Critical Reviews in Food Science and Nutrition, 56(11), 1913-1924.
96. He, H. J. and Sun, D. W. 2015, Trends in Food Science and Technology, 46(2), 199-210.
97. Kumaravelu, C. and Gopal, A. 2015, A review on applications of Near-infrared spectrometer and Chemometrics for the agro-food processing industries. 2015 Proceedings IEEE International Conference on Technological Innovations in ICT for Agriculture and Rural Development, TIAR 2015. (Pp. 8-12) Institute of Electrical and Electronics Engineers Inc.
98. Alshejari, A., Kodogiannis, V. and Petrounias, I. 2015, A rapid detection of meat spoilage using FTIR and neuro-fuzzy systems. IntelliSys 2015 – Proceedings of SAI Intelligent Systems Conference. Institute of Electrical and Electronics Engineers Inc., pp. 576-578.
99. Kodogiannis, V. S., Petrounias, I. and Lygouras, J. 2015, An intelligent based decision support system for the detection of meat spoilage. In D. Filev (Ed.), Intelligent Systems 2014. Advances in Intelligent Systems and Computing, 323, 302-310, Springer.
100. Oh, M., Lee, H., Cho, H., Moon, S. H., Kim, E. K. and Kim, M. S. 2016, Detection of faecal contamination on beef meat surfaces using handheld fluorescence imaging device (HFID). In M. Z. Kim, B. A. Chin and K. Chao (Eds.), Proceedings of SPIE – The International Society for Optical Engineering. SPIE Article No 986411.
101. Li, S., Kundu, D. and Holley, R. A. 2015, Food Microbiology, 46, 34-39.
102. Kramer, B., Wunderlich, J. and Muranyi, P. 2017, Recent findings in Pulsed light disinfection Journal of Applied Microbiology, 122(4), 830-856.
103. Heinrich, V., Zunabovic, M., Varzakas, T., Bergmair, J. and Kneifel, W. 2016, Critical Reviews in Food Science and Nutrition, 56(4), 591-613.
104. Biji, K. D., Ravishankar, C. N., Mohan, C. O. and Srinivasa Gopal, T. K. 2015, Journal of Food Science & Technology, 52(10), 6125-6135.
105. Cushen, M. and Cummins, E. J. 2017, Smart packaging solutions encompassing nanotechnology In E. J. Cummins and J. G. Lyng (Eds.), Emerging Technologies in Meat Processing: Production, Processing and Technology (pp. 265-284), J Wiley & Sons Ltd, UK.
106. Gill, C. O. and Tan, K. H. 1980, Applied & Environmental Microbiology, 39, 317-319.
107. Eilert, S. J. 2005, Meat Science, 71, 122-127.
108. Cruz-Romero, M. and Kerry, J. P. 2017, Packaging systems and materials used for meat products with particular emphasis on

the use of oxygen scavenging systems. In E. J. Cummins and J. G. Lyng (Eds.), Emerging Technologies in Meat Processing: Production, Processing and Technology (pp. 233-263), JC Wiley & Sons, UK.

109. Quintavalla, S. and Vicini, L. 2002, Meat Science, 62(3), 373-380.

110. Sethi, S. and Gupta, S. 2016, Antimicrobial spices: Use in antimicrobial packaging. In J. Barros-Velazquez (Ed.), Antimicrobial Food Packaging (pp. 433-444). Elsevier & Academic Press.

111. Ramesh, T., Nayak, B., Amirbahman, A., Tripp, C. P. and Mukhopadhyay, S. 2016, Innovative Food Science & Emerging Technologies, Volume 38, Part A, pp. 105-115.

112. Perez Espitia, P. J. and Batista, R. A. 2016, Vitae, 23, S56-S59.

113. Kerry, J. P., O'Grady, M. N. and Hogan, S. A. 2006, Meat Science, 74(1), 113-130.

114. Brockgreitens, J. and Abbas, A. 2016, Comprehensive Reviews in Food Science and Food Safety, 15, 3-15.