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DOI:
10.1016/j.tifs.2022.06.018

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Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Onyeaka, DH, Nwaizu, C & Ekaette, I 2022, 'Mathematical modeling for thermally treated vacuum-packaged foods: A review on sous vide processing', *Trends in Food Science & Technology*, vol. 126, pp. 73-85. https://doi.org/10.1016/j.tifs.2022.06.018

Link to publication on Research at Birmingham portal

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Download date: 20. Apr. 2024

Trends in Food Science & Technology 126 (2022) 73–85

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Mathematical modeling for thermally treated vacuum-packaged foods: A review on sous vide processing

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ARTICLE INFO

Keywords:
Sous vide
Modeling
Nutritional quality
Sensory quality
Microbiological quality

ABSTRACT

Background: Consumer dietary awareness drives a need for minimally processed foods with quality sensory and nutritional attributes and extended shelf life. Sous vide cooking techniques are a viable technology for meeting these consumer demands. Sous vide is the process of cooking vacuum-sealed foods in plastic pouches at low temperatures, generally 55–60 °C, for an extended period under strictly controlled conditions. Despite the high-quality, nutritional, and sensory benefits of sous vide cooking, the use of temperatures significantly lower than typical cooking raises microbiological/safety issues for customers.

Scope and approach: This review aims to highlight the numerous mathematical approaches used in modeling the quality and microbial safety of sous vide processed foods, as well as the effects of sous vide processing on texture, physiochemical, and nutritional quality. Sous vide processing has been mathematically modeled in a variety of ways, ranging from totally kinetic or empirical to completely physics-based approaches.

Key findings and conclusions: The emerging picture from this review suggests that mathematical modeling of SV processing has been approached in several ways, from completely kinetic or empirical to completely physics-based approaches to improve sous vide processing technologies in the future. A more general modeling approach, real-time quality evaluation during sous vide processing, and hurdle technology in sous vide are all future areas to investigate in the application of mathematical modeling to improve sous vide processing. There is potential for future applications of mathematical modeling in SV processing to optimize the overall process conditions and the cooking methods for different types of foods and sizes.

1. Introduction

Pasteurization of vacuum-packaged foods is common with ready-to-eat (RTE) meals. Some of the RTE foods are cooked prior to vacuum-packaging, while some are vacuum-packed prior to cooking. Whichever way, the 'vacuum-packed cooked foods' require further preservation steps, to prevent the growth of microorganisms like *Listeria monocytogenes*, and *Staphylococcus aureus*, among others (Onyeaka et al., 2022). This implies that 'vacuum-packed cooked foods' are doubly pasteurized because the cooking process is also a pasteurization step. Cooking imparts flavor, texture, aroma, color, and kills microorganisms and enzymes in foods, thereby improving their sensorial and safety qualities. Vacuum-packed cooked foods include meats, vegetables, and fruits, which are processed by various techniques; thermal (sous vide, boiling), and non-thermal (irradiation, high pressure processing, modified atmosphere packaging, freezing) (Benedito et al., 2011; Dima et al., 2016; Djekic et al., 2020; Rinaldi et al., 2021; Sakowska et al., 2017; Slongo et al., 2009). The advantage of sous vide processing over other thermal processing methods is that sous-vide processing combines the thermal treatment (cooking), and the vacuum-packaging to modify the food properties and extend shelf life. Its uniqueness is the vacuum-sealing which removes oxidation reactions and minimizes cooking loss (Djekic et al., 2020).

To fully describe the problems in vacuum-packed foods, mathematical modeling has been employed to optimize the problems and provide solutions to heat and mass transfer, physicochemical quality changes, and shelf-life prediction (Serra-Castello et al., 2022; Yin et al., 2022; Dima et al., 2016; Maldonado et al., 2015; Benedito et al., 2011; Weiqing et al., 2011; Slongo et al., 2009; Cárdenas et al., 2008). In these reports, an important parameter is a temperature-time combination required to

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https://doi.org/10.1016/j.tifs.2022.06.018
Received 8 February 2022; Received in revised form 22 June 2022; Accepted 30 June 2022

achieve the desired quality or food safety change. Sous vide (SV) refers to cooking vacuum-sealed foods in plastic pouches at low temperatures, typically at 55–60 °C, for an extended period under precisely monitored conditions (Baldwin, 2012; Bryony & Yang, 2012; Burke, 2021). Sous vide foods can be held at the heating temperature until served (cook-hold sous vide) or rapidly chilled, after which the food will be refrigerated or frozen until re-heating for service (cook-chill sous vide, Baldwin, 2012). Sous vide is considered a transformation of conventional cooking towards an improved quality on the color, flavor, and nutritional value of the cooked food. Mathematical modeling of sous vide processing has been based on using simple fourier conduction heat transfer equations or convection heating described by the Navier Stokes equation. However, sous vide processing covers much more complex physics in addition to conduction and convection heat transfer processes. The objective of this paper is to critically discuss the effect of temperature-time combinations during sous vide processing on the quality parameters of foods and to review the advantages and progress of employing mathematical models to solve problems in sous vide processing and food quality.

2. Relevance of sous vide technology in food processing

The increase in consumer awareness about health and wellness, and the demand for fresh-like ready-to-eat foods with extended shelf life, is the driving force for minimally processed foods that retains their natural nutritional and sensorial qualities (Olatunde & Benjakul, 2021; Zavadlav et al., 2020). To fully respond to these consumer demands, the food industry is gradually adopting the use of sous vide processing. Generally, when foods are exposed to traditional high-temperature cooking, some nutrients in the food are damaged or lost. For example, the breakdown of fats, degradation of vitamins, and the extensive hydrolysis of carbohydrates, phenolic compounds, and antioxidants. In addition, the cellular structure of foods destroyed during high-temperature cooking can lead to the loss of nutrients stored within these structures. But with the sous vide slow-cooking, protein structure can transform into more elastic and tender forms, and vegetables will retain most of their rich flavor (Zavadlav et al., 2020).

Sous vide also has the advantage of easy operation, and because of this, SV has gained widespread adoption in restaurants (Głuchowski et al., 2020; Stankov et al., 2020). Sous vide can also be utilized for cooking different food types ranging from vegetables (Rizzo et al., 2018; Zavadlav et al., 2020), to seafood (Humaid et al., 2020) to meat (Ruiz-Carrascal et al., 2019), with meat having more popularity. For these food types, SV has been acclaimed for improving the texture as well as flavor of the cooked food. This characteristic of sous vide cooked foods relies upon the use of very specific combinations of long cooking time at low temperatures (LTLT). However, the low temperature and long cooking time employed during sous vide might be disadvantageous because the food might not reach the desired temperature to achieve microbiological safety or the inactivation of vegetative cells.

3. Types of sous vide processing

Cook-hold and cook-chill SV are the two main types of SV processing (Baldwin, 2012). Cook-hold SV is the most basic and safest way of SV cooking (Fig. 1). It is the common SV processing technique in the food service sector where raw (or partially cooked) foods are vacuum-sealed, pasteurized, and then stored at a minimum of 54.4 °C/130 °F, until served (Baldwin, 2012). Holding the food at this hot temperature prevents the proliferation of food pathogens. *Salmonella* species and pathogenic strains of *E. coli* are reportedly the principal pathogens of interest for cook-hold SV (Baldwin, 2012; Stringer & Metris, 2018). While cook-hold SV prevents the proliferation of food pathogens, meat and vegetables will continue to soften and may get mushy if held for an extended period. Cook-chill SV is more popular in the meat industry, it involves raw (or partially cooked) foods being vacuum sealed, pasteurized, rapidly chilled, and then refrigerated or frozen until re-heating for serving. Pathogenic *Bacillus cereus, Clostridium perfringens*,

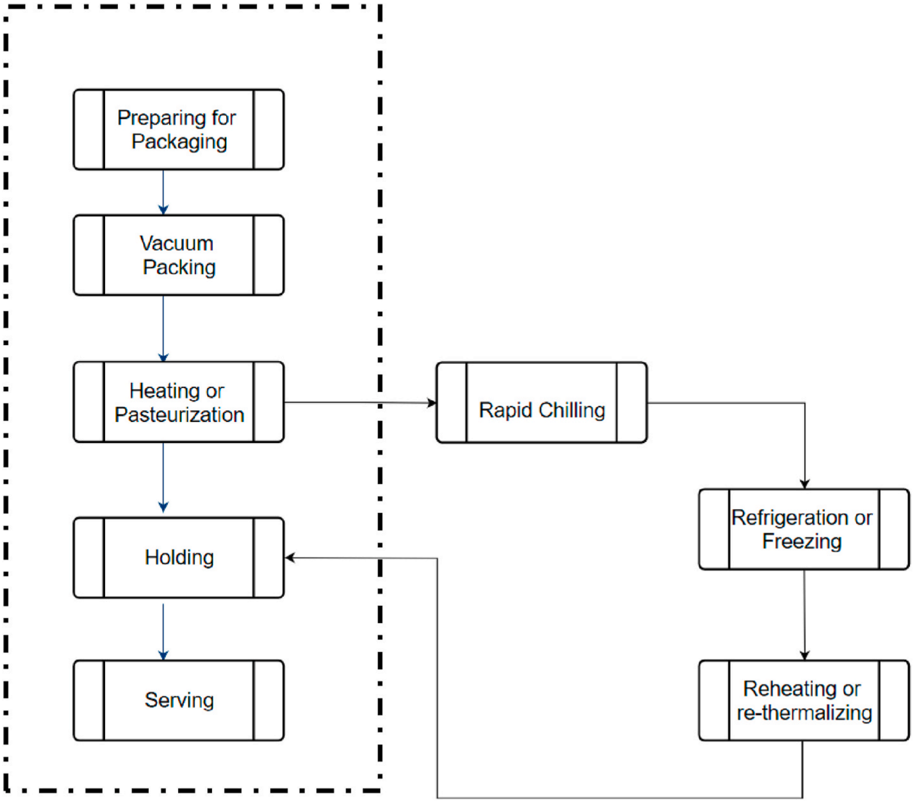

Fig. 1. Schematic Representation of Cook-hold (dot lines) and cook-chill sous vide.

Clostridium botulinum are spore-forming bacteria of interest for cook-chill SV (Baldwin, 2012; Carlin, 2014, 2018; Stringer & Metris, 2018).

4. Factors influencing sous vide processing

Using vacuum packaging/sealing eliminates evaporative losses of moisture and flavor volatiles during the SV heat treatment and allows efficient convective heat transfer from the hot water or steam to the food. Also, via vacuum packaging, the air removal from the food reduces aerobic bacterial growth. The vacuum-packed food is placed inside the SV equipment, either a water-bath immersion system or a convective steam system. The convective steam system is common in industrial-scale applications to accommodate a larger quantity of food. However, steam SV equipment may not achieve cooking uniformity (Sheard & Rodger, 1995). The non-uniformity results from the relatively poor distribution of steam at temperatures below 212 °F (100 °C) and the oven's dependence on condensing steam as the heat transfer medium. Another important factor in SV is the time required for the center of the food to reach the required temperature. The time to reach the center temperature depends on the food's thermal conductivity, thermal diffusivity, size/shape of the food, and the surface heat transfer coefficient of the equipment. In addition, the equipment should reach the processing temperature to achieve a particular level of microbial inactivation. In industrial-scale applications, the SV time and temperature of heating must exceed the minimum pasteurization conditions, especially for meats, to bring about the required changes in organoleptic quality. Exceeding the minimum pasteurization conditions is required because the minimum pasteurization conditions usually do not inactivate spore-forming pathogenic bacteria to a safe level. In such cases, it is necessary to either freeze SV cooked foods or chill them rapidly (to less than 3 °C within 90 min) to prevent spore germination and toxin production.

5. Temperature-time combination for sous vide foods

Meats, seafoods, vegetables, and foods in general in the native state are diverse in chemical composition, physical structure, sensorial attributes, and microbial population. Therefore, the heat treatment of different food types requires varying temperature-time levels, producing diverse quality changes in the microbial and physicochemical characteristics of SV cooked foods (Tables 1–4). For example, in Table 1, the effect of SV at temperatures between 50 and 100 °C and 0.75–36 h on reducing microbial population varied considerably for different meat.

5.1. Microbial profiling of sous vide foods

The bacteria commonly associated with SV cooked foods are those that form spores and multiply in the absence of oxygen. For example, *Clostridium perfringens* and other bacteria that can tolerate low-oxygen conditions (facultative anaerobes) include *Salmonella* spp, pathogenic strains of *Escherichia coli*, *Staphylococcus aureus*, *Yersinia enterocolitica*, *Listeria monocytogenes*, and in seafoods, *Vibrio* spp. (Baldwin, 2010). Also, non-bacterial infection or intoxication risks from Norwalk virus, Rotavirus, and Hepatitis viruses, as well as parasites including *Trichinella, Taenia, Toxoplasma, Cryptosporidium,* and *Giardia*, may relate to sous vide food intake (O'Shea et al., 2019; Lorenzo et al., 2018. The safety issues of SV products, particularly those involving spore-pathogen bacteria, must be examined product-by-productively. Many pathogenic bacteria growing on food products have a maximum growth temperature between 42 and 49 °C, while some have been reported to develop slowly at temperatures between 50 and 55 °C. As a result, the temperatures utilized for SV may be within the development temperature ranges of foodborne pathogens (Hudson, 2011). Slowly heating food products to the cooking temperature may cause the bacteria to respond with a heat shock response, making them more heat-tolerant to the cooking temperature (Zavadlav et al., 2020). As a result, an effective operating procedure calls for pre-heating the water bath to the right cook temperature. This is especially relevant when the cooking temperature is close to the upper growth temperature of a specific microbe because it may result in a slower inactivation rate. At temperatures below 55 °C, spore-forming bacteria may survive and germinate, resulting in an increase in bacterial cell quantity during cooking and, as a result, a rise in the incidence of foodborne illness (Zavadlav et al., 2020). To further improve the microbial inactivation in SV cooked foods, SV is usually combined with other bio preservatives or non-thermal preservation technologies such as high pressure and pulsed electric field (Humaid et al., 2019; Jeong et al., 2020; Rizzo et al., 2018). The use of rosemary essential oil as a natural antibacterial and antifungal to process fresh-cut potatoes was introduced in a recent line of SV

Table 1
Optimized sous vide temperature-time combinations for microbial safety of different meat products.

Reference	Temperature (°C)	Time (h)					Comments
		0.75	1.5	2.4–10	6–24	36	
Abel et al. (2020)	50–55	–	Roe deer	Wild boar	-	-	A 6-log reduction time for *L. monocytogenes*
Jeong et al. (2018)[1]	61–64	Pork ham[1]	-	-	-	-	Not detected: Total viable count (Log 10 CFU/g) Coliform count (Log 10 CFU/g)
Biyikli et al. (2020)[2] Akoğ;lu et al. (2018)[3] Roldán et al. (2013)[4]	65–70	Turkey cutlets[2,3]	Pork ham[1]	–	Lamb loins[4]	-	Not detected: [2,3] *Salmonella* spp., *L. monocytogenes*, *Cl. Perfringens*. Detected: [2] Total Enterobacteriaceae (log CFU/g): <1 *E. Coli* (log CFU/g): <1 TMAB (log CFU/g): 65 °C: 3.81, 70 °C: 2.96 Mesophilic counts:[4] 6 h: 0.9, 12 h: 2.7, 24 h: 1.4 Detected: <1 Psychrotrophic counts, Lactic acid bacteria, *Enterobacteriaceae,* Coliforms
Rinaldi et al. (2014)	75–100	-	-	-	-	Beef muscle (ST)	Number (*n*) of decimal reductions of *C. perfringens*: 75 °C/36 h: 0.8 100 °C/2 h: 43.5

TMAB, total mesophilic aerobic bacteria, TBARS (thiobarbituric acid reactive substance) expressed as mg malonaldehyde (MDA)/kg sample, CFU - Colony-forming unit. ST-semitendinosus. – (dash) means not available.

Table 2
Effects of sous vide temperature-time combinations on the physicochemical quality of meat foods.

Parameters		Effect of Processing Factors		References
		Increasing Temperature	Increasing Time	
Nutritional	Cooking loss	Increases	Increases	Biyikli et al. (2020), Jeong et al. (2018), Roldán et al. (2013), Sánchez del Pulgar et al. (2012)
	Cooking yield	Decreases	-	Biyikli et al. (2020)
	TBARS	Varies with product	Increases	Biyikli et al. (2020), Sánchez del Pulgar et al. (2012)
	Salt	Decreases	-	Biyikli et al. (2020)
Textural	Shear force	Increases	Increases	Karpińska-Tymoszczyk et al. (2020), Jeong et al. (2018), Roldán et al. (2013).
	Hardness	Varies with product	Increases	Biyikli et al. (2020), Jeong et al. (2018), Sánchez del Pulgar et al. (2012)
	Adhesiveness	Increases	-	Biyikli et al. (2020), Sánchez del Pulgar et al. (2012)
	Springiness	Decreases	Varies with product	Biyikli et al. (2020), Jeong et al. (2018)
	Cohesiveness	Varies with product	Increases	Jeong et al. (2018), Sánchez del Pulgar et al. (2012)
	Gumminess	Increases	-	Biyikli et al. (2020)
	Chewiness	Varies with product	Increases	Biyikli et al. (2020), Jeong et al. (2018), Sánchez del Pulgar et al. (2012)

TBARS (thiobarbituric acid reactive substance) expressed as mg malonaldehyde (MDA)/kg sample, – (dash) means not available. Varies with product means either increases or decreases depending on the meat type.

Table 3
Combinations and comparisons of sous vide with other processing methods and food additives.

Food Material	Processing Condition		Texture Parameters									Reference
	Sous vide (SV)	Other Methods	CL	SF	HDN	ADH	SPR	COH	GUM	CHW	RES	
Chicken breasts	60 °C/2h	Oven cooked 180 °C to internal temperature of 71 °C	–	I	I	I	–	–	I	I	–	Lee et al. (2021)
Pumpkin cubes	90 °C/18 min	Steaming (ST) 100 °C/9 min	–	–	NSD	–	NSD	NSD	–	I	I	Rinaldi et al. (2021)
		Vacuum cooking (VC) 130 °C/0.8 bar/ 29 min	–	–	D	–	NSD	D	–	D	D	
Pork Ham	62 °C/45 min	Cooking (C): in boiling water for 45 min	I	I	I	D	I	NSD	I	I	D	Djekic et al. (2020)
		Grilling (G): to internal temperature of 72 °C	NSD	NSD	I	D	I	NSD	I	I	I	
Beef ST	60 °C/24 h	Pulsed Electric Field (PEF) (2.0 kV/cm), 200 μs, <3 °C.	I	D[d]	–	–	–	–	–	–	–	Jeong et al., (2020)
		[c]Roasting (R): 230 °C/5 min.	nr	D[d]								
Pork steaks	Marinating with food additive at 4 °C/3 days SV: 60 °C/6 h	Additives Ratio of additive: meat (1:9) Kefir (K),	–	–	D	–	–	–	–	NSD	–	Latoch (2020)
		Yoghurt (Y)	–	–	NSD	–	–	–	–	NSD	–	
		Buttermilk (B)			D					NSD		
Carrot	90 °C/3 min +85 °C/ 11 min	Cooking (C): 90 °C/3 min +85 °C/11 min	–	–	I	–	–	–	–	–	–	Guillén et al. (2017)
[a, b]Beef ST	60 °C/270 min. Ice-water cooling at 2 °C/ 1h.	Cooking (C): at 75 °C, cooling at RT/1h.	NSD	I	I	–	NSD	D	I	I	–	Botinestean et al. (2016)
		Freezing & cooking (FC): frozen at −20 °C/48 h, cooking at 75 °C, cooled RT/1h	NSD	I	NSD	–	I	D	I	I	–	
		Freezing & Sous vide (FSV): frozen at −20 °C/48 h, SV at 60 °C,/270 min, ice-water cooling at 2 °C/1h.	NSD	NSD	NSD	–	NSD	D	NSD	NSD	–	

Beef muscles [*M. semitendinosus* (*ST*)]. [a]Warner-Bratzler shear force. [b]Cooking was carried out in a water bath at 75 °C, to core temperature of 70 °C. Room temperature (RT). [c]Core temperature of 70 °C. Cooking loss (CL), Shear force (SF), Hardness (HDN), Adhesiveness (ADH), Springiness (SPR), Cohesiveness (COH), Gumminess (GUM), Chewiness (CHW), Resilience (RES). nr – not reported. NSD -not significantly different to SV sample, I - increased in comparison to SV sample, D - Decreased in comparison to SV sample, – (dash) means not available, [d] compared to PEF only.

research (Rizzo et al., 2018).

According to FDA, 2011, a 6D process time or 6-log$_{10}$ drop in *L. monocytogenes* is recommended for increased shelf-life. The shelf-life can then only be limited by spore-forming pathogens' germination, growth, and toxin formation. If the food is pasteurized for *Salmonella* species instead of *L. monocytogenes*, the proliferation of L. monocytogenes will subsequently limit the shelf-life between 0.4 °C/31.3 °F and 5 °C/41 °F (FDA US, 2022). While keeping the food sealed in its plastic pouches after cooking prevents recontamination because spores of *C. perfringens, C. botulinum,* and *B. cereus* can survive pasteurization's mild heat treatment. To prevent spores of non-proteolytic *C. botulinum* from outgrowing and producing deadly neurotoxin, food must be frozen or stored at temperatures below 2.5 °C/36.5 °F for up to 90 days, below 3.3 °C/38 °F for less than 31 days, below 5 °C/41 °F for less than 10 days, or below 7 °C/44.5 °F for less than 5 days following rapid chilling (Baldwin, 2012). Sous vide could be optimized to increase microbial food quality by reducing the risk of food re-infection during storage (Díaz et al., 2008).

5.2. Physicochemical characteristics of sous vide foods

5.2.1. Nutritional quality and sensorial changes

Physicochemical properties of SV cooked foods, such as tenderness, color, and water retention (Ismail et al., 2022; Martínez-Hernández et al., 2013) are important parameters in determining the efficacy of SV processing. The effect of SV on tenderness is discussed in texture qualities. Employing SV for boiling carrots better preserves carotenoids (orange color) compared to samples boiled in water (Patras et al., 2010). This agrees with the heat sensitivity of many biochemical compounds. During thermal treatments, foods leach moisture. It was observed that

Table 4
Quality indices of sous vide cooked vegetable and seafood products.

Food Type	Treatment	Findings	Reference
Lobster (*Homarus americanus*)	High-Pressure Processing (HPP): 150 MPa or 350 MPa for 10 min at 4 °C Sous-vide: 65 °C for 10 min	• During storage, raw lobster pressurized at 350 MPa or sous vide cooked had significantly fewer microbial counts. • HPP pretreatment had no effect on the shelf life of sous vide cooked items.	Humaid *et al.* (2019)
Pumpkin (*Cucurbita moschata* cv. Leite)	Sous vide—90 °C, 30 min	• Reduced total flavonoids by 30.27%	Silva et al. (2019)
Tomato powder	Sous vide cooking: 60 °C, 4 h	• Losses for L-ascorbic acid (20.35%), total phenolic content (15.98%), and lycopene (10.93%) were found after sous-vide treatment of tomato powder. • Sous vide-treated tomato powder had stronger antioxidant activity than untreated samples.	Yang et al. (2020)
Bonito	Sous vide: 70 °C for 10 min	• The raw materials mesophilic (3.46-log CFU/g) and psychrophilic (2.72-log CFU/g) bacterial counts were decreased to undetectable levels (<1.00-log CFU/g) after 10 min of sous vide cooking at 70 °C. • The quality of sous vide bonitos was deemed highly acceptable until the 15th day of storage at 12 °C. • Cold-stored (4 °C) sous vide bonitos have a 28-day shelf life.	Mol, Ozturan, and Cosansu (2012)
Atlantic mackerel (*Scomber scombrus*)	Sous vide: 60, 75 and 90 °C for 10, 15 and 20 min	• The length of cooled storage had the greatest effect on the formation of primary and secondary lipid oxidation products. • Prolonged refrigerated storage of sous-vide cooked samples harmed their physicochemical properties. • During storage, sous vide cooking reduced the hardness of the fish muscle.	Cropotova et al. (2019)
Pirarucu (*Arapaima gigas*)	Sous vide: 60 °C for 9.48 min	• In comparison to other raw pirarucu cuts, the dorsal cut was the most appropriate for developing the sous vide product. • On day 0, the sous vide product received sensory ratings for acceptance of 7 on the hedonic scale, while on the 49th day, the qualities received an average of 5 on the hedonic scale. • Mesophilic and psychrotrophic anaerobes remained within permitted limits during storage.	Pino-Hernández et al. (2020)

chicken breast fillet cooked with SV at 55 °C/4.33 h had remarkable moisture retention of 74% compared to the moisture content of the raw meat of 76% (Karpińska-Tymoszczyk et al., 2020). However, this SV-derived result was not compared with other cooking methods. A possible reason for the moisture retention is the vacuum packaging. Despite extended heating time during SV, the vacuum packaging creates a mechanical barrier that prevents moisture from escaping. This moisture retention effect caused by slow and uniform heating allows moderate coagulation of muscle proteins in meat (Stankov et al., 2020). The relatively low heating of the muscle fibers (35–40 °C) reduced their gross contraction and generated a delicate texture of the muscles, with fluid (fat, water) in the form of protein sol in the intracellular space (Baldwin, 2012). According to Christensen et al. (2013), bull meat was cooked using LT-LT at 53 °C for 19.5 h and was evaluated by differential scanning calorimetric analysis (25–90 °C at a rate of 1 °C/min). The myosin and collagen peaks dropped, indicating improved juiciness. The temperature and duration for using the sous vide method of meat processing must be chosen to achieve a high degree of collagen protein breakdown and low myofibrillar protein contraction (Roldan et al., 2015).

Although SV retains moisture, the moisture loss causes an increased concentration of other food constituents such as fat and protein. Also changes in the thiobarbituric acid reactive substance (TBARS) level are observed (Karpińska-Tymoszczyk et al., 2020). During storage of SV turkey cutlets treated at 65 °C/0.75 h, the level of oxidative deterioration increased, indicated by TBARS value from 0.61 to 1.15 mg MDA/kg after 28 days which is slightly above the TBARS value of 1.0, at which oxidative rancidity cannot be detected by a sensory panel (Wang et al., 2004). This means that sous vide foods have relatively positive sensory characteristics. Another physical and economic parameter is cooking loss. Cooking loss is associated with drip loss (moisture loss with nutrients) and increases with increasing temperature or time (Biyikli et al., 2020; Jeong et al., 2018; Roldán et al., 2013), but decreased when pork was air-packed (Sánchez del Pulgar et al., 2012). This might be related to the pressure difference between the pork and its environment. Cooking loss was observed in other SV-treated meat (turkey, beef, lamb, fish) Table 2. Drip loss also carries water-soluble compounds, including salts (Biyikli et al., 2020).

The fact that SV food is prepared in low-oxygen conditions at mild precisely controlled temperatures is critical for keeping the nutritional value of the finished product while also considering the sensory perception and satisfaction of consumers (Iborra-Bernad et al., 2013). Furthermore, in contrast to traditional cooking, SV uses plastic pouches to reduce mineral loss and increase their bioavailability (Ronadelli et al., 2017). These findings were verified by Da Silva et al. (2017), who investigated the bioavailability of calcium, copper, iron, potassium, and magnesium in bovine liver. Furthermore, SV food processing outperforms steaming and boiling in terms of preserving vitamins, particularly those that are sensitive to high temperatures and oxygen, such as thiamine (vitamin B1), riboflavin (vitamin B2), and ascorbic acid (vitamin C) (Kilibarda et al., 2018). In addition, the content of anthocyanins and polyphenols in SV vegetables is comparable to that of fresh plants (Iborra-Bernad et al., 2015; Renna et al., 2014), and several studies have confirmed that SV red onion, shallot, broccoli, tomato, green beans, artichokes, carrots, parsley root, and cauliflower retain their antioxidative capacity (Jaiswal et al., 2012; Redfern et al., 2021).

5.2.2. Textural quality changes

The texture profile analyses show that all meat responds differently toward tenderness after SV treatment, possibly owing to the type of muscle protein or the temperature-time conditions (Tables 2 and 3). In turkey meats, hardness, adhesiveness, gumminess, and chewiness increase with an increase in temperature from 65 to 75 °C at 0.75 h (Biyikli et al., 2020). The same trend is observed for pork meats as shear force, hardness, springiness, cohesiveness, and chewiness increase with an increase in temperature from 61 to 71 °C at 0.75 h (Jeong et al., 2018). However, springiness decreases in turkey meat with an increase in temperature from 65 to 75 °C at 0.75 h (Biyikli et al., 2020). Springiness defines the rate at which a deformed food product can regain its former shape (Biyikli et al., 2020), therefore based on the effect of higher temperature, pork has better springiness than turkey. There is no change in springiness and cohesiveness in beef as the temperature increases from 75 °C/36 h to 100 °C/2 h (Rinaldi et al., 2014). Sous vide treatment time offsets the effect of sous vide treatment temperature as observed with the lamb loin's shear force decreasing from 70 °C at 12 h to 70 °C at 24 h. Adhesiveness, which defines the strength of the internal structure of the food, was reported to increase in SV pork treated in the presence of air/absence of vacuum at 80 °C and 12 h (Sánchez del Pulgar et al., 2012). This is supported by Jeong et al. (2018) that textural changes are a result of vacuum packaging. Fish (Largemouth bass) showed reduced hardness, springiness, chewiness, and resilience after sous vide treatment of 85 °C/0.33 h (Wan et al., 2019). The effect of changes in temperature and time combinations was not mentioned. Texture parameters of meat are described by Biyikli et al. (2020). Comparison of SV and other processing technologies such as boiling, grilling, vacuum cooking, steaming, oven cooking, roasting, freezing, and pulsed electric field (Table 3) revealed that sous vide produces the most tender meats. This is shown with the shear force and hardness values of pork, ham, beef, and chicken (Table 3). During SV heating of meat, there occurs myofibrillar protein denaturation, fiber shrinkage, solubilization of connective tissue, and gelation of collagen, myosin, or sarcoplasmic proteins (Tornberg, 2005; Zielbauer et al., 2016). These structural changes cause meat tenderization, as observed in beef (Botinestean et al., 2016), lamb (Roldán et al., 2013), pork (Jeong et al., 2018), and fish (Wan et al., 2019).

Vegetables like carrots and pumpkins were also SV tenderized at 90 °C of 3–18 min, respectively (Guillén et al., 2017; Rinaldi et al., 2021). Texture parameters such as gumminess and chewiness of SV food (pork ham, beef, chicken, and pumpkin) are lower than the gumminess and chewiness values of the same products cooked in boiling water or by grilling (Table 3). This may be related to the processing temperature. Biyikli et al. (2020) states that gumminess is linearly correlated with cooking temperatures. Sous vide pork ham has a lower springiness than boiled or grilled pork ham. The textural behavior of pumpkin is not consistent between SV (90 °C/18 min) and other processing of steaming (100 °C/9 min) and vacuum cooking (130 °C/0.8 bar/29 min) Rinaldi et al. (2021). Regarding broccoli texture, SV samples (90 °C/15 min) had less stem softening than boiled samples (100 °C/3.5 min). The measurements of shear force dropped by 49%. It was hypothesized that using a lower temperature and vacuum packaging reduced cell wall disruption and improved stem firmness (Martínez-Hernández et al., 2013). All texture parameters are based on force or energy with respect to time or distance. Various foods have different texture responses or behaviors because of the internal arrangement of the fibers, food components, or polymers. Predicting tenderness and/or texture of the food during SV has been the subject of several research studies (Dilger et al., 2021; Ramos et al., 2017).

6. Mathematical modeling of sous vide processing

Most changes in the quality of food that occur during SV processing are very complex, and conducting experimental studies might be difficult and, most time, not feasible. Hence, it is easier to analyze them using mathematical models that can predict the effects of processing parameters on microbial and quality changes during SV processing and/or storage. Mathematical modeling of SV processing has been approached in several ways, from completely kinetic or empirical to completely physics-based approaches (Hosseini et al., 2021; Nartea et al., 2021; Pino−Hernández et al., 2021; Ureta et al., 2019; Llave et al., 2018; Stringer & Metris, 2018; Ramos et al., 2017; Lenz et al., 2015; Baldwin, 2012).

6.1. Modelling quality attribute changes during sous-vide processing

Most degradation of nutrients and/or quality attributes such as color, texture, development of off-odors or off-taste and loss of freshness or nutrient during SV have been found to fit perfectly to the mathematical equation shown in Eq. (1) (Jaiswal et al., 2012; Llave et al., 2018; Ramos et al., 2017)

$$-\frac{dA_i}{dt} = k_i[A_i]^{n_i} \tag{1}$$

Where the subscript i indicates the specific quality attribute (e.g., color, texture, protein etc.), $[A]$ represents the concentration (or value) of the quality attributes. The symbol k_i is the corresponding proportionality constant, also known as reaction rate constant $[min^{-1}]$, t is the reaction time $[min]$, and n_i is the order of the reaction that depends on the quality attribute decay kinetics, determined based on goodness of fit of observations to a preselected reaction order model.

Equation (1) can be solved differentially for a constant temperature to give a mathematical expression where the quality attribute decreases linearly over time with the magnitude of the slope equals k_i for zero-order reactions or an exponential decrease for first-order reactions or hyperbolic relationship between concentration of the reactant and time for the second-order reaction. These are shown in Eqs. (2)–(4) for zero-order, first-order, second-order reactions, respectively (Ling et al., 2015).

$$A_i(t) = A_{0,i} - k_i t \tag{2}$$

$$A_i(t) = A_{0,i} e^{-k_i t} \tag{3}$$

$$\frac{1}{A_i} = \frac{1}{A_{0,i}} + 2k_i t \tag{4}$$

where $A_{0,i}$ is the concentration or the amount of the quality attribute i at the start of the process (when $t = 0$). The reaction rate constant k_i is not constant, it is dependent on the processing conditions, for example, temperature (cooking temperature, rapid chilling temperature, cold-storage, or frozen temperature) during sous-vide processing. Xie (2000) used a first-order kinetic model to fit experimental data of textural changes for dry pea during sous vide (SVCC) and traditional cook-chill (CC), respectively. In the study, the texture was measured based on punctured and compression forces, respectively and Arrhenius equation shown in eq. (5) was used to relate temperature (T) with the reaction rate constant (k).

$$k_i(T) = k_o e^{-\left(\frac{E_{a,i}}{RT}\right)} \tag{5}$$

where k_i is reaction rate constant (min^{-1}) dependent on absolute temperature T, E_a is the activation energy $(Jmol^{-1})$ (that is, the minimum energy requirements for a reaction to start) and R is the ideal gas constant (8.314 $Jmol^{-1}K^{-1}$). They substituted eq. (5) into the first-order eq. (2) to obtain eq. (6) which relate the quality attribute (texture) to the heating time (t) and temperature (T) using estimated model parameters $(E_{a,}$ and $k_o)$ obtained from the experimental data.

$$A_i(t) = A_{0,i} - k_o e^{-\left(\frac{E_{a,i}}{RT}\right)} \, . \, t \tag{6}$$

From their study, for the compression force, fitting parameter $E_{a,}$ were estimated as 146.7 and 125.8 kJ/mol for CC and SVCC cooked peas, and for the peak puncture force, they were 112.4 and 168.3 kJ/mol, respectively. It is interesting to note that from this study, the estimated value of $E_{a,}$ for the compression force was smaller for CC compared to SVCC, while for the peak puncture force the opposite phenomenon can be observed. The author accounted that this may be related to the different mechanisms in the two peak force measurements. Also, the value of $E_{a,}$ estimated in this study were higher compared to a similar study conducted by Xie et al. (1998) where first-order reaction kinetic was used to model texture changes of pea in a long time cooking similar to sous vide. The kinetic parameter $E_{a,}$ were estimated as 92.0 kJ/mol and 84.3 kJ/mol for hardness (puncture force) and compression force, respectively. Although both studies modeled the texture change of cooked pea using the first-order kinetics, the difference observed in their estimated $E_{a,}$ values may be because of the slight differences in their cooking methods.

Ramos et al. (2017) studied changes in textural quality of tambaqui sous vide during refrigerated storage under three different temperatures (1, 4, and 10 °C) using degradation kinetics and concluded that the zero-order kinetic model gave the best fitting to the experimental data. Similarly, Ovissipour et al. (2013) used a first-order kinetic model to predict the compression force of the whole mussel during thermal heating.

Further studies have used rate reaction kinetics to model degradation in quality apart from texture during sous vide. Table 5 summarises some of the kinetic models applied in predicting other quality attributes, such as color, total phenolic, etc., during sous vide and other heating processes. Llave et al. (2018) developed a first-order kinetic model to analyze the effect of protein denaturation during sous vide cooking on quality attributes, such as color, appearance, shrinkage, drip loss, and texture of tuna. Moreover, Ureta et al. (2019) used a first-order kinetic model to predict color changes in meat during sous vide cooking. Most rate reaction kinetic models are usually developed using data collected under iso-thermal conditions for a single attribute of the food quality. Although, processes during SV such as heating, holding, and cooling are non-isothermal processes, changes in various quality attributes (appearance, texture, and flavour) might occur simultaneously. Also, complex reactions such as Maillard browning or thermal degradation of vitamin C might be difficult to account for using simple rate reaction kinetics (Ling et al., 2015). Other mathematical approaches, such as the empirical model, have been used to model quality changes during sous vide processing. Apart from the limitations stated above, rate reaction kinetic models are built upon the power-law function and tend to predict changes with respect to time (Jaiswal et al., 2012; Nartea et al., 2021; Ramos et al., 2017; Ureta et al., 2019), while empirical models imply that changes are not dependent on time alone, but rather on other variables. Empirical modeling is useful where an underlying mechanism is not readily available. The developed model could be able to predict experimental results or commonly observed phenomena accurately. Iborra-Bernad et al. (2013) studied changes in color and texture of green bean pods as a function of temperature and time for vacuum applied cooking, cook-vide and sous-vide cooking. They developed an empirical regression model to describe the color changes ($-a^*$, greenness) and texture (puncture test and Kramer cell test) based on variable time (in the range of 13.8–56.21 min) and temperature (in the range of 77.9–92.1 °C). They concluded using their developed model the

Table 5

Some published kinetic model parameters during sous-vide and water-bath heating of different food products.

Product	Heating method	Quality attribute	Kinetic model	Kinetic parameter		References
				E_a ($kJmol^{-1}$)	k_0 (min^{-1})	
Chicken Breast	Water bath	Texture				
		Hardness	First-Order	39.30	1.96×10^{-1}	Rabeler & Feyissa (2019)
		Gumminess	Zero-Order	35.90	6.4×10^{-2}	
		Chewiness	First-Order	44.60	7.73×10^{-1}	
Beef muscle	Sous vide	Color				
		L	First-Order	40.76	8.05×10^{5}	Ureta et al. (2019)
		a	First-Order	64.09	1.56×10^{9}	
		b	First-Order	38.87	2.14×10^{5}	
Tuna	Sous Vide	Protein				
		Myosin	First-Order	362	2.83×10^{59}	Llave et al. (2018)
		Actin	First-Order	354	1.16×10^{54}	
Pork Sirloin	Water bath	Protein				
		Collagen	First-Order	326	4.63×10^{48}	Kajitani et al. (2011)
		Actin	First-Order	250	1.47×10^{37}	
Green Pea	Sous-Vide	Texture				
		Hardness	First-Order	92.00	0.38×10^{1}	Xie et al. (1998)
		Compression	First-Order	84.30	0.31×10^{1}	
Tomato paste	Water bath	Color				
		L	First-Order	48.00	7.7×10^{-3}	Barreiro et al. (1997)
		a	First-Order	41.00	9.4×10^{-3}	
		b	First-Order	86.00	1.3×10^{-3}	

optimum value of cooking temperature was determined as 92 $^{\circ}C$ for both treatments and the best cooking time was 28 and 14 min for 1 and 7 days of storage for the sous-vide treatment, respectively. Similarly, Nartea et al. (2021) developed an empirical model to study the effect of sous vide processing on basic cellular elements in softening and extractability of sterols and tocopherols in cauliflower. One main disadvantage of the empirical model is that it would be erroneous to extrapolate outside the experimentally tested regions. However, unlike empirical modeling, which involves estimating response over a range of variables that are of interest, physics-based modeling is based on determining the underlying physical mechanism(s) of the process under study. Heat transfer operations (heating, cooling, freezing etc.) are the most important unit operations in SV processing and largely determine the quality, stability, and safety of SV cooked foods (De Baerdemaeker & Nicolaï, 1995; Popov et al., 2019). Recently, Pino−Hernández et al. (2021) developed computational model to evaluate the influence of grilling pre-treatment on the physical characteristics of pirarucu fillets and to optimize the sous vide process parameters. The model was developed based on transient heat transfer equation shown in eq. (6)

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q=\rho c\left(\frac{\partial T}{\partial t}\right) \tag{7}$$

Where T is the temperature ($^{\circ}C$), k is the thermal conductivity ($Wm^{-1\circ}C^{-1}$); ρ is the density (kgm^{-3}); c is specific heat capacity ($Jkg^{-1\circ}C^{-1}$); Q is the internal heat generation (Wm^{-3}) and x, y, and z are the space coordinates. Their simulation was conducted on a geometrical model (15 × 8 × 2.5 cm, length x width x thickness) representing the fillet for all the temperatures defined for different grilling pre-treatments. Several similar physics-models based on the heat transfer conduction have been applied to study heat transfer in foods during sous vide and consequently predict the effect of the heating and/or cooling processes during sous vide on quality attributes (Baldwin, 2012; Hong et al., 2014). Hong et al. (2014) developed a 3D conduction model to estimate temperature distribution and heat transfer rate in carrots packed inside sealed pouches with different geometries. They used the developed model to investigate the effect of heating temperature on the hardness and color of carrot sticks. Heat transfers in vacuum-packed and nonvacuum-packed plastic pouches of crab meat were modeled using the finite element method, and the predicted numerical model was compared with the experimental data (temperature-time records, proximate composition, and thermophysical properties). Results showed that the heat transfer coefficient for vacuum pouches was higher (40 $Wm^{-2}K^{-1}$) than the nonvacuum pouches (25–27 $Wm^{-2}K^{-1}$) (Dima et al., 2016). This means that a vacuum provides a better heat transfer rate during cooking, and therefore is less energy-consuming. Purnell et al. (2005) used a vacuum to improve the steam entry rate and condensation on beef primals and retail cuts. High heat transfer rate also influences microbial reduction rate, such as with 5D process times for *S. aureus* which at 82 °C was less for vacuum-packed crab meat (15.5 min) compared to nonvacuum-packed crab meat (20 min) (Dima et al., 2016). This theory of vacuum enhancing microbial reduction was also observed in ground beef (not cooked), where the growth of *Klebsiella* sp., *Pseudomonas* sp., and *E. coli*, during storage at 0–10 °C was slowed in vacuum-packed films compared to aerobic conditions using only polythene (Cárdenas et al., 2008). In all, the purpose of the vacuum is to increase SV process efficiency and, ultimately, the shelf-life of cooked and uncooked foods. The combination of temperature and vacuum is beneficial to overall product and safety quality. The combination of proper temperature and time duration in SV cooking could provide good water-holding capacity, color parameters, and tender cooked meat.

From the heat equation (eq. (6)), it can be observed that changes in temperature because of conduction inside the food would be affected by both product parameters, such as thermal conductivity and specific heat capacity, as well as process parameters (such as surface heat transfer coefficients and the equipment temperatures etc.). Moreover, in most cases, these parameters are not constant because of the complex heterogenous nature of foods. Furthermore, assuming constant parameters may affect the accuracy of using a physics-based model in predicting quality attributes in sous vide processing.

6.2. Modelling microbiological safety and stability of sous-vide processed foods

Sous vide processed foods are based on a mild heat treatment at low temperature - a long time combined with effective refrigerated storage to ensure product safety and stability. Generally, severally countries have developed a recommendation for SV processed foods. For example, CFIA in Canada recommends that all sous vide foods with a shelf-life of less than 10 days should be pasteurized at 70 °C for 2 min or equivalent, aimed at achieving a 6-log reduction of the most heat-resistant vegetative pathogen, *Listeria monocytogenes*. Furthermore, for a shelf life of greater than 10 days, heat treatment of 90 °C for 10 min or equivalent should be subjected to a 6-log reduction of spores C. botulinum. However, recent years have seen an increase in the number of SV-cooked foods being cooked at low temperatures (e.g., 40 °C–70 °C). Such temperatures have traditionally been in the "temperature danger zone" for foods; thus, their effect on bacterial behavior has not been studied greatly. This creates difficulties when assessing product safety. It is therefore vitally important to understand the effect of the heating process on any pathogens in these products. Mathematical modeling could be used to determine the degree of inactivation and/or pasteurization resulting from a sous vide process. One of the simplest forms of microbial thermal inactivation model is based on the first-order reaction kinetics, which can be constructed by measuring pathogen cell numbers against time as a function of temperature (eq. (7)) (Halder et al., 2007)

$$\frac{dN}{dt}=kN^{n} \tag{8}$$

where k (s^{-1}) is the rate constant, and n is the order of kinetic model. This general model describes the reduction in the microbial population (N) as a function of time (t). And the rate constant can then be related to temperature using the Arrhenius equation stated in eq. (5).

Rinaldi et al. (2014), in their study with beef semitendinosus muscles cooked in sous vide using two different time/temperature treatments, a typical low temperature–long time (LT-LT) condition realized by cooking 36 h at 75 °C (SV75) and an innovative high temperature–short time (HT-ST) one for 2 h at 100 °C (SV100). They compared the two treatments based on determined sterilizing value (F_0 , min), weight loss, texture, color, vitamins of B group as well as volatile compounds profile were evaluated. The sterilizing values (F_0 , min) shown in eq. (8) were obtained from the integration of the experimental heat penetration curve. Assuming the effect of heat treatment is cumulative, using an integrated F value allows the severity of dynamic thermal processes

$$F_0=\int_0^t 10^{\left[\frac{T-T_{ref}}{z}\right]}dt \tag{9}$$

Where T_{ref} is the reference temperature and is commonly used as 121.1 $^{\circ}C$. And F_0 (min) is the cumulative thermal effect on microbial reduction. The z value ($^{\circ}C$) is the heat resistance, which is known for the bacteria of interest (e.g., for *Clostridium botulinum*, $z=10$ $^{\circ}C$) and is usually determined based on D-value as shown in eq. (9). The z -value (°C) is the increase in processing temperature that would cause reduce 90% reduction or one-log reduction in D value. For the first-order reaction, the z-value can be calculated as a function of the temperature below (Halder et al., 2007; Ling et al., 2015; Ramaswamy et al., 1989)

$$z=\frac{T_2-T_1}{logD_1-logD_2} \tag{10}$$

where D_1 and D_2 are the decimal reduction times at temperatures T_1 and T_2, respectively.

Also, z – value can relate to the activation energy (E_a) as stated in eq. (10)

$$z = \frac{2.303RT_{ref}^2}{E_a} \tag{11}$$

The D-value is the time required for a 90% or 1 log reduction in viable micros at a given temperature. The logarithm of D is an approximately linear function of heating temperature. And this is related to the kinetic rate constant (eq. (11)).

$$D(T) = \frac{2.303}{k(T)} \tag{12}$$

Using the z-value and the time-temperature history from the samples during heating, the cumulated sterilizing effect (or value) can be determined. Baldwin (2012) simplified the heat conduction equation into a one-dimensional (1D) heat equation from a three-dimensional (3D) coordinate based on the explanation that the interest was in temperature at the slowest heating point of the food (typically the geometric center of the food). He coupled the developed 1D equation used in predicting temperature at the slowest heating point of the meat with the classical model for the log reduction in pathogens shown in Eq. (8) Based on the developed coupled models, Baldwin (2012) predicted worst-case scenario SV's cooking time based on the temperature, thickness, and food type that would result into highest reduction in the microbial population. Baldwin's predictions may over-exaggerate the predicted values because of the simplified assumptions taken during the model development. Increased accuracy could be attained from two or three-dimensional models at the expense of computation. Huang (2007) developed a 2D physics-based model to simulate the temperature distributions during the sous vide process of frankfurter meat immersed in water for the inactivation of *Listeria monocytogenes*. In his conclusion, he stated that simulated temperature histories predicted both at the center and on the surface of the frankfurter meat packages were in close agreement with the experimentally observed data. Hong et al. (2014) developed a 3D conduction model to estimate temperature distribution and heat transfer rate in carrots packed inside sealed pouches with different geometries. They used the developed model to investigate the effect of heating temperature on the hardness and color of carrot sticks and to determine the F-value and C values based on a reference temperature of 71.1 °C and a z-value of 10 °C, previously reported in experimental thermal resistance data for pathogenic microorganisms including *Listeria monocytogenes, Salmonella* spp., and *Escherichia coli O157:H7*. However, Hong et al. (2014) did not use real geometry, they simulated the carrot's geometry as a rectangular parallelepiped. There is a need to develop models that would employ real geometries of foods during sous vide processing. Also, according to Sun et al. (2019) further, work should be conducted to optimize both the overall sous vide process parameters and the cooking techniques to ensure maximum consumer acceptability. These developed 3D models can be solved numerically through finite-element or finite difference method. Also, computation fluid dynamics (CFD) software packages have been used in solving the developed model using appropriate boundaries and initial conditions. De Baerdemaeker and Nicolaï (1995) used the temperature boundary condition between the package and the surroundings to solve the equation. Also, convection and radiation boundary conditions may be imposed. Boundary conditions can be explicitly applied in which heat gain by food through conduction during the sous vide processing equals to the convective (sensible) heat exchange with the environment. In real sense, during sous vide, the temperature difference between adjacent vacuum sealed package is usually rather small during the process. Therefore, radiation exchange between different vacuum sealed packages would be negligible and can be ignored.

The use of D and z values for predicting thermal processes is based on the assumption of linearity. However, nonlinear kinetic models have been introduced to account for more accurate representations of microbial death during the thermal processing of food (Heldman and Newsome 2003). A study completed by Halder et al. (2007) compared the effect of uncertainties in the parameters of linear and non-linear kinetic models describing microbiological death kinetics and heat transfer on process lethality computed by using Monte Carlo simulation. Their work demonstrated that variability should be included in lethality computations, and such inclusion is very important in improving the kinetic model.

During the cooling of SV processed foods, if the pouches are properly sealed, the most serious threat to safety would be from the multiplication of spore-forming pathogens. Such as *C. botulinum*, *B. cereus* and *C. perfringens,* which typically survive heat treatments used in the manufacture of SV cooked foods. However, to cause illness, these organisms require suitable conditions for growth, for example, based on the study reported by Li and McClane, (2006) *C. perfringens* will grow quickly at temperatures as high as 54 °C. Mathematical model has been used to assess the potential for growth of microorganisms during cooling of sous-vide processed food in storage. Duan et al. (2016) produced a new model for the outgrowth and inactivation of *C. perfringens* in meat products during low-temperature long-time heat treatment. They enumerated cells during a period of slowly increasing temperature followed by inactivation at 53 °C and found that the rate of temperature increase had a significant effect on the subsequent rate of inactivation at 53 °C.

7. Potential applications of mathematical modeling in sous vide processing

Although there have been continuous applications of mathematical modeling to SV processing, much research work still needs to be carried out. The following sections identify several possible areas where further study could be performed with mathematical modelling applications in sous vide processing.

7.1. More general modeling approach for sous vide processing

During SV, heat is transferred to the surface of the food by convection from the water or steam and then by conduction through the interior matrix of solid foods or convection for liquid food products. Over time, sous vide processing has solely been modeled using simple fourier conduction heat transfer equations or convection heating described by the Navier Stokes equation. However, SV processing covers much more complex physics in addition to conduction and convection heat transfer processes. For example, there is significant moisture loss during SV, which could result in changes to the food volume and transport of moisture away from the surface of the food into the sealed vacuum pouches. Furthermore, diffusive mass transfers also occur within the food matrix during sous vide. Therefore, to improve modeling accuracy and effectiveness, mathematical model(s) must be developed to accommodate all the diverse phenomena occurring during SV or changes within the food matrix, such as deformation or swelling. For example, Datta, Ukidwe, and Way (2020) developed the deformable porous media framework, which can effectively be applied to model SV process even though, solution(s) to such mathematical models can be very complex. However, numerical techniques can be used. Recent developments in computational fluid dynamics (CFD) also could assist in getting a better understanding of how to optimize SV processing parameters to alleviate challenges of non-uniform spatial temperature distribution within SV cooked foods. There is a large amount of work that can be done towards alleviating this problem. It is essential to obtain sufficient data on the actual temperatures inside food of different shapes, surface characteristics and package dimensions. Also, the so-called "package ballooning" (inflating of the sealed vacuum package) problem that occurs during SV as a result of insufficient vacuuming caused by in-pack pressure can be eliminated through profound mathematical optimization study. Effect of the package ballooning phenomena during SV on heat transfer and food product characteristics could be studied using a more general mathematical modeling approach.

7.2. *Real-time quality assessment during sous vide processing*

Although SV processing has several advantages in terms of physical, chemical, and sensory quality, one of the major problems is the non-uniform cooking effect within large food products such as chicken breast or whole chicken, which can consequently cause patches of pink color appearance distributed within the food products. This hinders widespread industrial adoption of SV. This is needed to monitor real-time temperature distribution within large or whole SV cooked foods. Also, the ability to preserve the quality and nutritional value of SV processed foods during storage depends on effective temperature monitoring. The most common strategy to ensure food quality is to intensify temperature monitoring during the after-sous vide storage. Reductions in the cost of sensors, wireless connectivity, and Internet of Things (IoT) are driving the increase in the monitoring of food processes. Most of the modern SV equipment is equipped with sensors to monitor the temperature at different points within the food as well as the ambient heating chamber. These sensors measure temperature during SV, and data are transmitted to a controller that could regulate the temperature of the SV equipment's chamber (Lopez et al., 2008). There are new advances in the use of these kinds of sensor data to develop digital twins of physical products in various industries, including aerospace, automotive, healthcare, food processing and so on. This digital twin can provide real-time, actionable quality feedback on the physical assets. Recently, the concept of digital twins has also emerged in food processing (Defraeye et al., 2021; Verboten et al., 2019), where temperature sensor data in the vicinity of fruit were used to develop digital replica that evolves and reacts hydrothermally and metabolically in a similar way as the physical fruit. One of the important pieces of the digital twin is the digital master model that connects the physical model to the virtual model, which can be developed with an empirical data-driven or physics-based mathematical model. The application of a digital twin in sous vide processing could substantially bring about a real-time quality assessment of the sous vide process through an in-silico virtual digital twin.

7.3. *Modeling chemical substances from food packaging materials to sous-vide processed foods*

Contamination can easily occur by the migration of chemical constituents from the plastic pouches into food products during the heating and/or cooling storage for SV processed foods. This migration of chemical substances from the packaging materials is an important process that could potentially introduce a risk to human health (Alamri et al., 2021; Sadeghi & Seo, 2021; Taylor & Sapozhnikova, 2022). Several mathematical models such as empirical (Fauconier et al. 2001), stochastic (Helmroth, 2002), and deterministic (physics-based model) (Begley et al., 2005) have been employed to predict the migration of constituents from packages into foods. However, there has not been any application of a mathematical model to study the migration of chemical constituent(s) from vacuumed sealed food-grade packaging materials used in SV into food products. Incorporating such a mathematical model could further help evaluate SV processed foods' food safety evaluation. Also, these models could assist in predicting specific migration limits to describe the concentration change of migrating species with time depending on the processing conditions (time-temperature) both during the sous vide long time cooking or the refrigerated storage. Most of the studies in this area use a physics-based model developed based on the assumption that mass transfer from the packaging material into the food is a diffusional process that can be described by one-dimensional diffusion Fick's law (Helmroth et al., 2002; Poças et al., 2008; Silva et al., 2009),

$$\frac{\partial C_A}{\partial t} = D_A \frac{\partial^2 C_A}{\partial x^2} \tag{13}$$

where C_A represent the concentration of the migrating constituent species A, t is the time, x in the linear dimension of migration and D_A is the diffusivity of migrating constituent species A in the packaging material.

Han et al. (2003) developed a model to evaluate the migration of BHT from LDPE/HDPE packaging material based on Fick's law of diffusion. Their model was solved with the initial condition that the concentration of the migrant in the food is zero and that the migrant is initially homogeneously distributed in the packaging material matrix. Several authors have applied similar initial conditions to achieve a solution for their model (Zhang et al., 2021). However, in modeling SV process, such conditions may be overly simplifying since SV process involves heating for an extended period, the ageing effect of the package in the refrigerated storage could impact the process and migrants might no longer be homogeneously distributed in the material. Also, most studies have assumed a no transfer at the outer surface of the packaging material, which might not be true for SV because the long-time cooking could make the chemical constituent in the package become highly volatile. Therefore, there is a need to develop a model that would incorporate the reality of SV processing during heating and cooling stages into modelling package constituents' migrations.

7.4. *Improve sous vide hurdle technology through mathematical modeling*

The safety issues of SV cooked foods, particularly those involving spore-pathogen bacteria, must be carefully examined product-by-product. Many pathogenic bacteria growing on food products have a maximum growth temperature between 42 and 49 °C, while some have been reported to develop slowly at temperatures between 50 and 55 °C. As a result, the temperatures utilized in SV cooking may be close to or overlap with the development temperature ranges of foodborne pathogens (Hudson, 2011). The foodborne pathogens *E. coli, Enterobacter* spp., *Klebsiella* spp., *Salmonella typhi, Serratia* spp., *Providencia* spp., *Staphylococcus aureus, Pseudomonas aeruginosa*, and other potentially harmful bacteria have been linked to several food products (Azi et al., 2018). Furthermore, some other food products, mostly vegetables and meats, are more prone to spoilage by bacteria such as *Bacillus cereus, Campylobacter jejuni, Clostridium botulinum, E. coli O157: H7, L. monocytogenes, Salmonella* spp., *Shigella, Staphylococcus*, and *Vibrio cholera* (Balali et al., 2020). Most of them are facultative anaerobes, which means their cells can survive and thrive in environments with or without oxygen. Slow heating of food products applied in SV processing may cause bacteria to develop heat shock responses, making them more heat-tolerant to the cooking temperature (Zavadlav et al., 2020). This is especially relevant when the cooking temperature is close to the upper growth temperature of a specific microbe because it may result in a slower inactivation rate. At temperatures below 55 °C, spore-forming bacteria may survive and germinate, resulting in an increase in bacterial cell quantity during cooking and, as a result, a rise in the incidence of foodborne illness (Zavadlav et al., 2020). Hence, the safety of SV cooked a temperature below 55 °C cannot be guaranteed. It is important to protect the safety of SV immediately after cooking to prevent microbial growth. Food safety management systems (FSMS) such as HACCP and/or GMP have been used to ensure the microbiological safety of SV processed meat and pasta products (Smith et al., 1990). Also, hurdle technology creates a barrier for microbial growth using a combination of different "hurdles" such as temperature, pH, water activity, aerobic or anaerobic conditions, some preservatives (e.g., nitrites, lactic acid, or carbon dioxide) and other "hurdles" like the use bio-preservatives in addition to non-thermal barriers have been applied to develop stable and safe SV cooked food products (Abdullahi & Dandago, 2021; Gupta et al., 2012; Tsironi et al., 2020). Apart from food safety, hurdle technology can be applied to the quality aspect of foods. However, there is little to no scientific data exploring developing hurdle technology in optimizing the quality attributes of SV cooked foods. Mathematical modeling can successfully improve hurdle technology by analyzing the effect of different combinations of hurdles on microbial inactivation or describe the combination effect of some of the hurdle parameters such as temperature, pH, water activity, aerobic or anaerobic conditions, and some preservatives (e.g., nitrites, lactic acid, or carbon dioxide) on the SV cooked foods quality attributes.

8. Conclusion

Sous vide cooking has several benefits in terms of product quality, including the preservation of essential elements in foods and good sensory features such as well-preserved colors, rich flavors, and powerful tastes. Sous vide meets the needs of consumers looking for high-quality, nutritionally valuable food with sensory attributes like those of raw food to a large extent. While sous vide food items are generally regarded as safe, outbreaks of foodborne disease are not unexpected because it employs far lower temperatures than standard cooking and avoidance of preservatives. As a result, the microbiological safety of the products is a serious problem in SV processing. Recent studies have applied mathematical modeling to optimize SV processing parameters to maximise quality characteristics and minimise the risk from food pathogens. There is potential for future applications of mathematical modeling in SV processing to optimize the overall process conditions and the cooking methods for different types of foods and sizes.

Data availability

No data was used for the research described in the article.

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