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Da-Wen Sun, Series Editor

HANDBOOK OF FOOD PROCESSING

Food Preservation

EDITED BY
Theodoros Varzakas • Constantina Tzia

HANDBOOK OF FOOD PROCESSING

Food Preservation

Contemporary Food Engineering

Series Editor

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Dedicated to my wife, Elia, and my daughter, Fotini,
for their endless support and love.

To my mother for her love and understanding and to the memory of my father.

Theodoros Varzakas

Dedicated to the memory of my parents.

Constantina Tzia

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Series Preface

CONTEMPORARY FOOD ENGINEERING

Food engineering is a multidisciplinary field of applied physical sciences combined with the knowledge of product properties. Food engineers provide the technological knowledge transfer essential for the cost-effective production and commercialization of food products and services. In particular, food engineers develop and design processes and equipment to convert raw agricultural materials and ingredients into safe, convenient, and nutritious consumer food products. However, food engineering topics are continuously undergoing changes to meet diverse consumer demands, and the subject is being rapidly developed to reflect market needs.

In the development of food engineering, one of the many challenges is to employ modern tools and knowledge, such as computational materials science and nanotechnology, to develop new products and processes. Simultaneously, improving food quality, safety, and security continues to be a critical issue in food engineering studies. New packaging materials and techniques are being developed to provide more protection to foods, and novel preservation technologies are emerging to enhance food security and defense. Additionally, process control and automation regularly appear among the top priorities identified in food engineering. Advanced monitoring and control systems are developed to facilitate automation and flexible food manufacturing. Furthermore, energy saving and minimization of environmental problems continue to be important food engineering issues, and significant progress is being made in waste management, efficient utilization of energy, and reduction of effluents and emissions in food production.

The Contemporary Food Engineering Series, consisting of edited books, attempts to address some of the recent developments in food engineering. The series covers advances in classical unit operations in engineering applied to food manufacturing as well as such topics as progress in the transport and storage of liquid and solid foods; heating, chilling, and freezing of foods; mass transfer of foods; chemical and biochemical aspects of food engineering and the use of kinetic analysis; dehydration, thermal processing, nonthermal processing, extrusion, liquid food concentration, membrane processes, and applications of membranes in food processing; shelf life and electronic indicators in inventory management; sustainable technologies in food processing; and packaging, cleaning, and sanitation. These books are aimed at professional food scientists, academics researching food engineering problems, and graduate-level students.

The editors of these books are leading engineers and scientists from different parts of the world. All the editors were asked to present their books to address the market's needs and pinpoint cutting-edge technologies in food engineering.

All contributions are written by internationally renowned experts who have both academic and professional credentials. All authors have attempted to provide critical, comprehensive, and readily accessible information on the art and science of a relevant topic in each chapter, with reference lists for further information. Therefore, each book can serve as an essential reference source to students and researchers in universities and research institutions.

Da-Wen Sun
Series Editor

Series Editor

Born in Southern China, Professor Da-Wen Sun is a global authority in food engineering research and education; he is a member of the Royal Irish Academy (RIA), which is the highest academic honor in Ireland; he is also a member of Academia Europaea (The Academy of Europe) and a fellow of the International Academy of Food Science and Technology. He has significantly contributed to the field of food engineering as a researcher, as an academic authority and as an educator.

His main research activities include cooling, drying, and refrigeration processes and systems; quality and safety of food products; bioprocess simulation and optimization; and computer vision/image processing and hyperspectral imaging technologies. Especially, his many scholarly works have become standard reference materials for researchers in the areas of computer vision, computational fluid dynamics modeling, vacuum cooling, and so on. Results of his work have been published in over 800 papers, including more than 400 peer-reviewed journal papers (Web of Science h-index = 64). He has also edited 14 authoritative books. According to Thomson Reuters's Essential Science Indicators SM, based on data derived over a period of ten years from Web of Science, there are about 4,500 scientists who are among the top one percent of the most cited scientists in the category of Agriculture Sciences, and in the past many years, Professor Sun has consistently been ranked among the very top 50 scientists in the world (he was at the 25th position in March 2015, and in 2nd position if ranking was based on "Highly Cited Papers").

He received a first class BSc Honors and MSc in mechanical engineering and a PhD in chemical engineering in China before working in various universities in Europe. He became the first Chinese national to be permanently employed in an Irish university when he was appointed college lecturer at the National University of Ireland, Dublin (University College Dublin [UCD]), in 1995, and was then continuously promoted in the shortest possible time to senior lecturer, associate professor, and full professor. Dr. Sun is now a professor of Food and Biosystems Engineering and the director of the Food Refrigeration and Computerised Food Technology Research Group at the UCD.

As a leading educator in food engineering, Professor Sun has significantly contributed to the field of food engineering. He has trained many PhD students, who have made their own contributions to the industry and academia. He has also delivered lectures on advances in food engineering on a regular basis in academic institutions internationally and delivered keynote speeches at international conferences. As a recognized authority in food engineering, he has been conferred adjunct/visiting/consulting professorships from 10 top universities in China, including Zhejiang University, Shanghai Jiaotong University, Harbin Institute of Technology, China Agricultural University, South China University of Technology, and Jiangnan University. In recognition of his significant contribution to food engineering worldwide and for his outstanding leadership in the field, the International Commission of Agricultural and Biosystems Engineering (CIGR) awarded him the "CIGR Merit Award" in 2000, and again in 2006, the Institution of Mechanical Engineers based in the United Kingdom named him "Food Engineer of the Year 2004." In 2008, he was awarded the "CIGR Recognition Award" in honor of his distinguished achievements as the top 1% of agricultural engineering scientists in the world. In 2007, he was presented with the only "AFST(I) Fellow Award" in that year by the Association of Food Scientists and Technologists (India), and in 2010, he was presented with the "CIGR Fellow Award"; the title of fellow is the highest honor in CIGR and is conferred to individuals who have made sustained, outstanding contributions worldwide.

In March 2013, he was presented with the "You Bring Charm to the World" Award by Hong Kong–based Phoenix Satellite Television with other award recipients including the 2012 Nobel Laureate in Literature and the Chinese Astronaut Team for Shenzhou IX Spaceship. In July 2013, he received the "Frozen Food Foundation Freezing Research Award" from the International Association for Food Protection (IAFP) for his significant contributions to enhancing the field of food freezing technologies. This is the first time that this prestigious award was presented to a scientist outside the United States. In June 2015, he was presented with the "IAEF Lifetime Achievement Award". This International Association of Engineering and Food (IAEF) award highlights the lifetime contribution of a prominent engineer in the field of food.

He is a fellow of the Institution of Agricultural Engineers and a fellow of Engineers Ireland (the Institution of Engineers of Ireland). He also serves as the editor in chief of *Food and Bioprocess Technology—An International Journal* (2012 Impact Factor = 4.115), former editor of *Journal of Food Engineering* (Elsevier), and editorial board member for a number of international journals, including the *Journal of Food Process Engineering, Journal of Food Measurement and Characterization,* and *Polish Journal of Food and Nutritional Sciences.* He is also a chartered engineer.

On May 28, 2010, he was awarded membership to the RIA, which is the highest honor that can be attained by scholars and scientists working in Ireland; at the 51st CIGR General Assembly held during the CIGR World Congress in Québec City, Canada, on June 13–17, 2010, he was elected. Incoming President of CIGR, became CIGR President in 2013–2014, and is now CIGR Past President.

On September 20, 2011, he was elected to Academia Europaea (The Academy of Europe), which is functioning as the European Academy of Humanities, Letters and Sciences and is one of the most prestigious academies in the world; election to the Academia Europaea represents the highest academic distinction.

Preface

This book presents the necessary information to design food processing operations and methods. It deals with food preservation and describes the equipment needed to carry them out in detail. For every step in the sequence of converting the raw material to the final product, the book covers the most common food preservation processes required.

Chapter 1 describes blanching. Blanching is an important unit operation before processing fruits and vegetables for freezing, pureeing, or dehydration. A case study on the effect of blanching conditions on sulforaphane content in purple and roman cauliflower (*Brassica oleracea l. Var. Botrytis*) is presented.

Chapter 2 deals with thermal processing of foods referring to the application of heat in order to preserve product quality and extend its shelf life. Principles of thermal processing are well described along with thermal process calculations.

Canning of fishery products is described in detail in Chapter 3.

Chapter 4 refers to extrusion cooking with applications in the production of ready-to-eat cereals, pasta, snacks, pet food, fish foods, and confectionery products.

Drying or dehydration of foods is an extremely important food processing operation used to preserve foods for extended periods of time and is described in Chapter 5.

The most popular method for the preservation of fresh foods, especially meat, fish, dairy products, fruit, vegetables, and ready-made meals is chilling and is explored in Chapter 6.

Freezing is continued in Chapter 7, where freezing equipment used, novel methods proposed for freezing, new approaches for the control and optimization of the current cold chain in frozen food distribution, as well as the latest trends, are presented.

Some more recent thermal technologies, for example, microwave energy heating technology, are explored in Chapter 8 in an attempt to find alternatives to conventional heating methods. A case study on microwave preservation of fruit-based products, application to kiwifruit puree, is shown.

Advances in food additives and contaminants are described in Chapter 9. The use of food additives as agents for the improvement of food quality and preservation is well documented.

Ohmic heating, which is comparable to microwave heating, along with its principles and applications are described in Chapter 10.

Chapters 11 and 12 deal with high pressure (HP) processing and especially HP pasteurization which is one of the most interesting nonthermal processes of foods. They cover process design issues, evaluation, technology, and applications.

Pulsed electric field (PEF) processing is one of the promising novel technologies used to process liquid or low-viscosity foods and is described in Chapter 13.

Chapter 14 deals with the basics of magnetic fields technology for food processing and preservation along with some equipment and devices. The use of magnetic fields for microbial inactivation is briefly discussed, and several cases are presented.

Other nonthermal technologies such as ultrasound in food disinfection are described in Chapter 15. The important issues addressed include mechanism of ultrasound disinfection, parameters affecting the effectiveness of ultrasound in disinfection, effects of ultrasound on food quality, and effects of combining ultrasound with other techniques.

The use of edible films and coatings in fresh fruits and vegetables preservation is described in Chapter 16.

Chapters 17 and 18 deal with food packaging—aseptic packaging and modified-atmosphere packaging in fruits and vegetables.

Finally, Chapter 19 describes biosensor technology in food, and Chapter 20 deals with ozone applications presenting a general overview of the use of ozone in the food industry, along with a discussion on the chemical properties of this chemical.

Editors

Theodoros Varzakas earned a bachelor's (honors) degree in microbiology and biochemistry (1992), a PhD in food biotechnology, and an MBA in food from Reading University, United Kingdom (1998). Dr. Varzakas was a postdoctoral research staff member at the same university. He has worked for large pharmaceutical and multinational food companies in Greece for five years and has also for at least 14 years experience in the public sector. Since 2005, he has served as assistant and associate professor in the Department of Food Technology, Technological Educational Institute of Peloponnese (ex Kalamata), Greece, specializing in the issues of food technology, food processing, food quality, and safety. Dr. Varzakas has been a reviewer in many international journals such as *International Journal of Food Science & Technology*, *Journal of Food Engineering*, *Waste Management*, *Critical Reviews in Food Science and Nutrition*, *Italian Journal of Food Science*, *Journal of Food Processing and Preservation*, *Journal of Culinary Science and Technology*, *Journal of Agricultural and Food Chemistry, Journal of Food Quality*, *Food Chemistry*, and *Journal of Food Science*. He has written more than 90 research papers and reviews and has presented more than 90 papers and posters in national and international conferences. He has written two books in Greek; one on genetically modified food and the other on quality control in food. He edited a book on sweeteners that was published by CRC Press in 2012 and another book on biosensors published by CRC Press in 2013. Dr. Varzakas has participated in many European and national research programs as coordinator or scientific member. He is a fellow of the Institute of Food Science & Technology (2007).

Constantina Tzia earned a diploma in chemical engineering (1977) and a PhD in food engineering (1987) from the National Technical University of Athens, Greece. Her current research interests include quality and safety (HACCP) of foods, sensory evaluation, fats and oils, dairy and bakery technology, and utilization of food by-products. Professor Tzia's work has been widely published and presented, appearing in prestigious publications such as the *Journal of Food Science*, *LWT–Food Science and Technology*, *Innovative Food Science and Emerging Technologies*, *Food and Bioprocess Technology*, and *Journal of the American Oil Chemists' Society.*

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1 Blanching

Theodoros Varzakas, Andrea Mahn, Carmen Pérez, Mariela Miranda, and Herna Barrientos

CONTENTS

1.1 INTRODUCTION

Blanching is an important unit operation before processing fruits and vegetables for freezing, pureeing, or dehydration.

Blanching also lowers the mass of vegetables; so process profitability can be affected by over-treatment. Commercial blanchers used in the vegetable canning industry are relatively intensive with energy and water consumption. Energy utilization is affected by the equipment used and also by the configuration of the following freezing step.

Furthermore, conventional blanching produces wastewater that can reduce the nutritional value of vegetables by leaching of soluble compounds and subsequently increasing the pollutant discharge (Poulsen, 1986; Williams et al., 1986).

1.2 BLANCHING AND CARROTS

Carrots are well known for their sweetening, antianemic, healing, diuretic, and sedative properties. The enzymes commonly found to have deteriorative effects in carrots are peroxidases (PODs) and catalase. In order to minimize deteriorative reactions, fruits and vegetables are heat

treated or blanched to inactivate the enzymes. Blanching of fruits and vegetables is done either in hot water, steam, or selected chemical solutions (Luna-Guzmán and Barret, 2000; Severini et al., 2004a,b).

Blanching in a hot calcium chloride solution is used to increase the firmness of fruits and vegetables because of the activation of pectin methylesterase (PME) (Quintero-Ramos et al., 2002).

The inactivation of POD is usually used to indicate blanching sufficiency as POD is ubiquitous.

Moreover, optimization of the blanching process with respect to nutrient retention (β-carotene, vitamin C loss) and product yield should be considered along with enzyme inactivation (Shivhare et al., 2009). They determined the optimum blanching conditions for carrots in terms of nutrient (vitamin C and β-carotene) retention and studied the kinetics of the inactivation of POD in carrot juice. Various enzyme inactivation models were tested on the basis of statistical and physical parameters to ascertain a suitable model capable of explaining POD inactivation kinetics.

Steam blanching resulted in nonuniformity of enzyme inactivation, and the inactivation times of catalase and POD during steam blanching were consistently higher than that of hot water, acetic acid, or calcium chloride solution blanching.

The best blanching treatment for carrots based on these process parameters was 95°C for 5 min in water. At this time–temperature combination, both POD and catalase were inactivated and 8.192 mg/100 g vitamin C, 55% yield of carrot juice, and 3.18 mg/100 g β-carotene content were observed.

Blanching treatment of carrots prior to juice extraction has been found to be an important step in the production of carrot juice, which improves color and cloud stability (Martin et al., 2003; Zhou et al., 2009).

The effect of three processing steps (blanching, enzyme liquefaction, and pasteurization) on polyphenol and the antioxidant activity of carrot juices was investigated by Ma et al. (2013).

Water blanching was carried out at 86°C for 10 min.

Polyphenols and antioxidant activity of carrot juices varied with different processes. Five polyphenolic acids were identified in fresh carrot juice, and the predominant compound was chlorogenic acid. Compared with fresh carrot juice, blanching and enzyme liquefaction could result in the increase of total polyphenol content (TPC) and antioxidant activity in scavenging DPPH free radicals (DPPH) and Fe^{2+}-chelating capacity (FC), whereas pasteurization could result in the decrease of TPC and antioxidant activity in DPPH and FC. Meanwhile blanching, enzyme liquefaction, and pasteurization showed little influence on the antioxidant activity in lipid peroxidation protection. The antioxidant activities in DPPH and FC increased with increasing concentration while no correlation between lipid peroxidation protection and polyphenols concentration was evident. Polyphenols still retained high antioxidant activity after the processes, which have potential health benefits for consumers.

Blanching and enzyme liquefaction helped the dissolution of polyphenols into the juice.

Freezing of vegetables is generally accompanied by other processing operations such as blanching, which is applied to inactivate enzymes implicated in color change, flavor deterioration, and tissue softening during frozen storage. This thermal treatment (i.e. blanching), when conducted at temperatures higher than 80°C, catalyzes the degradation of pectins due to β-elimination reaction (Sila et al., 2008) and their solubilization from the cell wall and the middle lamella between adjacent cell walls.

Blanching, freezing, and frozen storage, depending on the process conditions, can cause dramatic effects on the textural properties of frozen products (Prestamo et al., 1998; Roy et al., 2001).

Numerous investigations have been carried out on the texture of carrots effected by different blanching treatments (Lee et al., 1979; Bourne, 1987; Verlinden and De Baerdemaeker, 1997; Vu et al., 2004) and different rates of freezing (Rahaman et al., 1971; Fuchigami et al., 1994). In particular, low-temperature (60°C–75°C) blanching has been acknowledged to increase the cell wall strength in carrots (Fuchigami et al., 1995; Sanjuan et al., 2005) due to PME activation. In fact, this enzyme is able to demethylate cell wall pectins, producing cross-linking of pectin molecules in the

presence of calcium ions, and this results in the strengthening of the cell walls (Quintero-Ramos et al., 2002; van Buggenhout et al., 2006; Rastogi et al., 2008).

Typically, blanching is carried out by treating the vegetable with steam or hot water for 1–10 min at 75°C–95°C; the time/temperature combination selected is dependent on the type of vegetable. In the case of carrots, low-temperature/long-time and high-temperature/short-time blanching methods have been applied (Sanjuan et al., 2005; Shivhare et al., 2009).

The effect of previous ultrasound and conventional blanching treatments on drying and quality parameters (2-furoylmethyl amino acids—as indicators of lysine and arginine participation in the Maillard reaction—carbohydrates, total polyphenols, protein profile, rehydration ratio, microstructure changes) of convective dehydrated carrots has been assessed by Gamboa-Santos et al. (2013). The most striking feature was the influence of blanching on the subsequent 2-furoylmethyl-amino acid formation during drying, probably due to changes in the protein structure. The highest values of 2-furoylmethyl amino acids were found in carrots conventionally blanched with water at 95°C for 5 min. However, samples previously treated by ultrasound presented intermediate values of 2-furoylmethyl amino acids and carbohydrates as compared to the conventionally blanched samples. Dried carrots previously subjected to ultrasound blanching preserved their total polyphenol content and showed rehydration properties, which were even better than those of the freeze-dried control sample. The results obtained here underline the usefulness of 2-furoylmethyl amino acids as indicators of the damage suffered by carrots during their blanching and subsequent drying.

1.3 BLANCHING AND ACIDIFIED VEGETABLES

In the case of acidified vegetables, it is important to understand the effect of different pretreatments, such as blanching and equilibration of the product in a solution containing acid and salt, on the dielectric properties of food materials. Within these treatments, factors, such as acid and salt concentrations as well as the equilibration time, may affect dielectric properties, and in turn influence microwave heating.

Sarang et al. (2007) reduced electrical conductivity variation, thereby improving heating uniformity of chicken chow mein through selective blanching treatments of food components in a highly conductive, salt-containing sauce prior to ohmic heating. This finding is highly relevant to dielectric heating since electrical conductivity is a major component of the dielectric loss factor.

Koskiniemi et al. (2013) examined the effects of acid and salt concentration on the dielectric properties of acidified vegetables. Broccoli florets and sweet potato cubes (1.2 cm) were blanched to facilitate acid and salt equilibration by heating for 15 s in boiling deionized water. Red bell pepper cubes were not blanched. The vegetable samples were then acidified in solutions of 1%–2% sodium chloride with 0.5%–2% citric acid. Dielectric properties were measured at 915 MHz from 25°C to 100°C after 0, 4, and 24 h soaking periods in the solutions using an open-ended coaxial probe connected to a network analyzer. Equilibration occurred within 4 h of salting and acidification. Acid and salt concentration had no significant effect on the dielectric constant (ε'). However, ε' was significantly different among vegetables ($p < 0.05$). Dielectric loss factor (ε'') was not affected by the acid, but significantly increased with salt concentration. These results provide the necessary dielectric property information to apply microwave heating technology in the processing of acidified vegetables.

1.4 BLANCHING AND SUGARS

The nutritive, physicochemical, and technological characteristics of several intermediate food products (IFPs) from Spanish Confitera fresh date coproducts were investigated by Martin-Sanchez et al. (2014). Three IFPs were obtained, two from unblanched dates in different ripening stages (Khalal and Rutab) and a third one from blanched Khalal fruits. The IFPs were rich in dietary fiber (13%–16%, dry matter), phenolics (0.56–4.26 g GAE/100 g, dry matter), and sugars (55%–82%, dry matter), with glucose and fructose as the predominant sugars.

Malic acid was the major organic acid, and potassium was the main mineral. Blanching Khalal dates helped prevent browning in the IFP, but the thermal treatment modified the sugars profile. The results indicated that both maturity stages yield IFPs with potential in the food industry; and according to their sugar and phenolic content, they could be suitable for the elaboration of new ingredients with different industrial applications. In addition, it would be recommendable to blanch unripe fruits.

Both IFPs from unblanched fruits presented similar total dietary fiber (TDF) values ($p > 0.05$), although some decrease during maturation has been reported related to the enzymatic activity responsible for the softening of dates by Ashraf and Hamidi-Esfahani (2011). Khalal-blanched dates presented the highest TDF, insoluble dietary fiber (IDF), and soluble dietary fiber (SDF) ($p < 0.05$) effect due to the loss of other components into the boiling water, which has affected the proportion of the components.

Blanching did not affect ($p > 0.05$) the total sugar content; however, it caused a decrease of glucose and fructose but an accumulation of sucrose. The same effect was observed by Perkins-Veazie et al. (1994) and Barrett et al. (2000), who found higher sucrose content in blanched sweet corn and more reducing sugars in unblanched samples.

Scalded dates duplicated their TPC ($p < 0.05$), possibly due to the polyphenoloxidase inactivation during blanching, protecting the phenolics against oxidation, particularly during homogenization.

Wen et al. (2010) explained this increase after blanching in vegetables by a different hypothesis: as a possible breakdown of tannins due to the high temperatures favoring their extractability; as a disruption of the cell membranes, which could provoke that phenolics, usually bonded to dietary fiber, proteins, or sugars in complex structures in the plants, become more available; and, also as the possible formation of phenolic compounds during the thermal process due to a higher availability of precursors.

The potential thermo-protective effect of sugars on the microstructure and the mechanical properties of the carrot tissue during blanching were investigated in a recent study (Neri et al., 2011). The protective effect of trehalose and maltose on the microstructural properties of the carrot tissue was highlighted by cryo-scanning electron microscopy (SEM) analysis.

However, when slices of the vegetable underwent heat treatments at 90°C for 3 and 10 min, no meaningful effects were noticed at the textural level.

Raw carrots and carrots blanched in water and in 4% trehalose and maltose solutions at 75°C for 3 (A) and 10 min (C) and at 90°C for 3 (B) and 10 min (D) were frozen and stored at −18°C for 8 months. The effects of heating conditions and exogenous added sugars on the mechanical properties and microstructure of the vegetable after blanching and during frozen storage were studied by Neri et al. (2014).

By the SEM analysis, no significant differences were observed among samples A and B water-blanched and raw carrots, while a thermo-protective effect due to the addition of sugars was evidenced in sample D, which had undergone the most severe thermal treatment. Freezing and frozen storage determined several fractures on both raw and blanched carrots due to ice crystals formation and recrystallization.

The cryoprotective effect of the sugars on the vegetable microstructure was observed only in the "over-blanched" sample D.

The mechanical properties of carrots were affected by blanching, which caused a decrease in hardness, but after freezing and 1 month of frozen storage, all samples showed a further dramatic reduction of hardness.

Only samples characterized by a pectinesterase residual activity showed softening after 1 month of frozen storage likely due to a competitive effect of the thermo-protective ability of trehalose on this enzyme. The exogenous trehalose was able to limit the loss of hardness of carrots that had undergone B, C, and D blanching pretreatments.

1.5 WATER BLANCHING

Water blanching is employed to extend the shelf life of certain vegetable-based foods such as ready meals and frozen vegetables, since blanching inactivates enzymes responsible for food deterioration, and it also reduces microbial count (Bahceci et al., 2005; Olivera et al., 2008; Volden et al., 2009). However, thermal processing such as blanching can induce losses of important compounds due to thermal degradation and leaching into cooking water (Rungapamestry et al., 2007; Olivera et al., 2008; Volden et al., 2008, 2009).

Alvarez-Jubete et al. (2014) investigated the effect of combined pressure/temperature treatments (200, 400, and 600 MPa, at 20°C and 40°C) on key physical and chemical characteristics of white cabbage (*Brassica oleracea* L. var. *capitata alba*). Thermal treatment (blanching) was also investigated and compared with high-pressure processing (HPP). HPP at 400 MPa and 20°C–40°C caused significantly larger color changes compared to any other pressure or thermal treatment.

All pressure treatments induced a softening effect, whereas blanching did not significantly alter the texture. Both blanching and pressure treatments resulted in a reduction in the levels of ascorbic acid, an effect that was less pronounced for blanching and HPP at 600 MPa and 20°C–40°C. HPP at 600 MPa resulted in significantly higher total phenol content, total antioxidant capacity, and total isothiocyanate content compared to blanching. To conclude, the color and texture of white cabbage were better preserved by blanching. However, HPP at 600 MPa resulted in significantly higher levels of phytochemical compounds. The results of this study suggest that HPP may represent an attractive technology to process vegetable-based food products that better maintains important aspects related to the content of health-promoting compounds. This may be of particular relevance to the food industry sector involved in the development of convenient, novel food products with excellent functional properties.

Conventional blanching and pre-drying are two separate processes and have the drawbacks of having low energy efficiency and long processing time (Tajner-Czopek et al., 2008). In a typical water blanching operation, first the water needs to be procured and heated and second, after a certain amount of blanching operations, this water needs to be replaced since it becomes saturated with sugars leaching from the potato strips. This results in not only excessive energy consumption due to the reheating of the water to the blanching temperatures but also the consumption of high amounts of water.

Among all the pretreatment methods for drying fruits and vegetables, hot-water blanching is one of the most frequently used methods as it can accelerate the drying rate and prevent quality deterioration by expelling intercellular air from the tissues, softening the texture, denaturing the enzymes, and destroying microorganisms (Jayaraman and Gupta, 2007; Neves et al., 2012; Xiao et al., 2012). However, grape drying with hot-water pretreatment has not been reported in the literature due to the special structure of grapes.

1.6 VACUUM PULSE OSMOTIC DEHYDRATION AND BLANCHING

Pulsed vacuum osmotic dehydration (PVOD) is an efficient process for obtaining semi-dehydrated food.

Osmotic dehydration (OD) is an alternative pretreatment for processes such as drying and freezing (Correa et al., 2011; Reno et al., 2011). It consists of immersing the food in a hypertonic solution with the consequent water loss (WL) from the food to the osmotic solution and the solid gain (SG) of osmotic solution by the food. The use of vacuum pulse at the beginning of the process, called PVOD, causes the expansion and subsequent compression of occluded gas in the product pores due to the action of hydrodynamic mechanisms (HDM), enhanced by pressure changes, and promotes the exchange of the pore gas/liquid for the external liquid with higher mass transfers than standard OD (Fito, 1994; Moraga et al., 2009; Correa et al., 2010; Fante et al., 2011; Moreno et al., 2011; Viana et al., 2014).

The effects of temperature (30°C–50°C), solute concentration (NaCl, 0–15 kg per 100 kg solution, sucrose, 15–35 kg per 100 kg solution), and vacuum pulse application (50–150 mbar and 5–15 min) on WL, SG, water activity (aw), and total color difference (ΔE) of previously blanched pumpkin slices were assessed through the Plackett–Burman experimental design by Correa et al. (2014). Temperature was not statistically significant in the process. Later, with the aid of a central composite design (CCD), it was found that the concentration of sucrose and NaCl was influent on the WL, SG, aw, and ΔE, and the pressure and time of application of vacuum were influent on the WL and SG. The optimal conditions of the process were stabilized with the desirable function, and the simulated data were similar to the experimental ones.

Sliced pumpkin samples underwent blanching by immersion in boiling water for 3 min. The blanching was stopped by immersing the samples for 2 min in mineral water. The slices had their surface carefully dried with a paper towel to remove the bath water. The blanching conditions were based on Tunde-Akintunde and Ogunlakin (2011) and Falade and Shogaolu (2010). Blanching is indicated for peroxidase inactivation (Pinheiro et al., 2007), color, and texture improvement (Silva et al., 2011) and higher water loss and solid gain (Kowalska et al., 2008).

1.7 MICROWAVE BLANCHING

Mild blanching for a short period retains the freshness and results in texture softening and the liberation of flavor compounds.

Moreover, blanched fish meat can be used for the preparation of value-added products, as it retains the taste and textural profiles closer to that of fresh fish meat.

Microwave heating is being investigated to improve, replace, or complement conventional processing technology for pasteurizing or sterilizing food products as well as to meet the demands of on-the-go consumers who want quick food preparation and superior taste and texture (Ahmed and Ramaswamy, 2007). Domestic microwave ovens are conveniently used to heat foods as they do it faster than conventional methods. The sensory properties of muscle foods, such as texture and color, primarily depend on the time–temperature history of the product.

On the other hand, mild heating or blanching for a short period using a microwave oven improves the texture of fresh fish as it softens the connective tissue proteins, while maintaining the functionalities of myofibrillar proteins.

The effect of microwave blanching on quality characteristics of vacuum and conventional polyethylene-packed sutchi catfish fillets was evaluated under chilled conditions by Binsi et al. (2014). Emphasis has been given to retain the sensory characteristics such as color and textural properties, which is a major problem in sutchi catfish fillets during extended chill storage. In general, microwave blanching imposed minimum changes on fatty acid and mineral composition of fish meat. A marginal increase in fat content was recorded after microwave heating of fish fillets. The microwave-blanched fillets showed minimum cooking loss of 3.2 mL per 100 g meat. A slower increase in spoilage parameters was obtained with microwave-blanched samples compared with unblanched samples, demonstrating the higher storage stability of the sample under chilled conditions. Microwave heating of fish fillets coupled with quick chilling and packing under vacuum improved the color and texture stability of sutchi catfish fillets to a considerable extent. Microwave blanching increased the hardness and chewiness values and decreased the stiffness values of fish fillets. The biochemical and sensory evaluation of microwave-blanched and vacuum-packed sutchi catfish fillets showed an extended storage life of 21 days, compared with 12 days for unblanched vacuum-packed samples.

Since microwave blanching is considered as a dry technique, the volume of wastewater generated could be diminished and therefore losses of water-soluble nutrients could be minimized (Quenzer and Burns, 1981; Günes and Bayindirli, 1993). Several studies on microwave blanching of vegetables and fruits have been reported. Brewer et al. (1994) considered the effect of different blanching methods on the ascorbic acid content and the peroxidase activity in 225 g batches of green beans,

and they concluded that a 3 min microwave treatment at 700 W resulted in a product similar to that obtained by steam blanching. Muftugil (1986) observed that the time to complete the peroxidase inactivation in green beans was less with microwave blanching than with water and steam treatment, whereas a higher greenness remained with the two latter methods. Brewer and Begum (2003) studied the effects of power and irradiation time on ascorbic acid, color, and peroxidase activity in microwave blanching of green beans, among other vegetables.

Microwave blanching of green beans (*Phaseolus vulgaris* L.) was explored as an alternative to conventional hot-water blanching by Ruiz-Ojeda and Peñas (2013). Batches of raw pods were treated similarly to an industrial process employing a hot-water treatment but using a microwave oven for blanching. The effects of microwave processing time and nominal output power on physical properties (shrinkage, weight loss, texture, and color), enzyme activities (guaiacol peroxidase, L-ascorbate peroxidase, and catalase), and the ascorbic acid content of pods were measured and modeled by first-order kinetics. Inactivation of POD was the best indicator to assess the efficiency of microwave blanching of green beans. No significant differences in product quality were found between hot-water blanched and microwaved pods at optimal processing conditions. Furthermore, since shorter processing times and higher ascorbic acid retention were found, microwave processing of green beans can be a good alternative to conventional blanching methods.

Microwave blanching of green bean pods has been proved as a reliable alternative method to the conventional heating process used in the vegetable canning industry. The overall quality of the product processed by microwave heating under optimal conditions was comparable to that of the current industry process.

The microwave treatment of pods, in addition to an effective enzyme inactivation in less processing time, led to a better retention of ascorbic acid.

1.8 INFRARED BLANCHING

In industrial production, the potato strips are generally blanched with water (60°C–85°C) for more than 10 min mainly to inactivate enzymes and to obtain a uniform color (Nonaka et al., 1977; Tajner-Czopek et al., 2008), and then predried with warm air to improve texture (Andersson et al., 1994). The blanched potato strips are par-fried in hot oil (170°C–190°C), cooled at room temperature, frozen, packaged, and distributed.

Infrared (IR) heating, which delivers energy by electromagnetic waves, has been shown to be an effective heating technology with advantages of versatility and simplicity in terms of the equipment required (Sandu, 1986; Chou and Chou, 2003). IR heating was used to dry various agricultural and food materials such as onion slices, carrots, apple slices, and almonds (Hebbar et al., 2004; Sharma et al., 2005; Zhu and Pan, 2009; Yang et al., 2010). In a previous research reported by Bingol et al. (2012), they have observed that by using IR heat, complete inactivation of polyphenol oxidase (PPO) enzyme could be achieved in 3 min with 4.7% moisture loss for 9.43 mm regular cut french fries. Furthermore, for fresh-finish-fried french fries, at the end of 7 min frying, compared to unblanched samples, IR-blanched samples had 37.5%, 32%, and 30% less total oil at frying temperatures of 146°C, 160°C, and 174°C, respectively.

Given the successful application of IR blanching for fresh-finish-fried french fries (Bingol et al., 2012) and due to the widespread use of water blanching in industry for par-finish-fried french fries, Bingol et al. (2014) compared IR blanching (IRB) with water blanching (WB) for par-finish-fried french fries in terms of (1) oil uptake, (2) color formation, and (3) the cost of blanching.

Bingol et al. (2014) compared IRB with WB as a pretreatment method for producing lower calorie french fries. It was observed that complete inactivation of polyphenol oxidase enzyme for 9.43 mm potato strips could be achieved in 200 s and 16 min by using IRB and WB, respectively. Following the blanching, the samples were deep-fat par-fried at 174°C for 1 min and were then deep-fat finish-fried at 146°C, 160°C, and 174°C for 2, 3, 4, and 5 min. At all frying times and temperatures, IR-blanched samples had less oil content than water-blanched ones. The energy analysis

of both blanching operations showed that energy expenditure-wise operation cost for pretreating french fries with IRB would be head-to-head with WB. The final moisture contents of IR and water-blanched samples were between 40% and 50% after 5 min of finish-frying. The chromatic color components of IR and water-blanched samples were significantly ($p < 0.05$) affected by finish-frying time and temperature, and a^* and b^* values for IR-blanched samples developed faster than water-blanched samples during deep-fat finish frying.

To prevent the swelling of the strip surfaces which were exposed to IR heat, they applied a three-stage blanching process. In the first stage only IR heat was applied for 120 s, and then in the second stage, IR heat was coupled with an air flow of 2.49 ± 0.24 m/s for 45 s, and finally in the last stage, the air velocity was increased to 5.14 ± 0.27 m/s. The total blanching time was 200 s.

Generally, exposure of PPO to temperatures of 70°C–90°C destroys their catalytic activity (Queiroz et al., 2008), and low-temperature blanching (55°C–70°C) reduces the porosity of potato strips, which thereby will reduce oil absorption (Aguilar et al., 1997).

Therefore, for WB, the potato strips were immersed in a 2 L beaker, containing 1 L of water at 70°C, which was held in a water bath for 16 min. Following water blanching, the strips were dried in a convective dryer for 15 min at 60°C.

The surface and center temperatures of potato strips during IRB and WB were measured using type T thermocouples (response time <0.15 s) and were recorded every 1 s with a data logger thermometer.

1.9 BLANCHING AND LEAFY VEGETABLES

Rai et al. (2014) studied the effect of different food processing techniques like blanching, microwave processing, boiling, frying, and different drying methods on the depletion of minerals especially magnesium in green leafy vegetables (leaves of *Trigonella foenum*, common name methi, and *Spinacia oleracea*, common name spinach) using laser-induced breakdown spectroscopy (LIBS). These processing techniques are frequently used at home as well as in food processing industries. The LIBS spectra of the fresh leaves of methi and spinach and their pellets (made by drying, grinding, and pressing the leaf) were recorded in a spectral range from 200 to 500 nm. After applying the aforementioned processing techniques, different pellets of these leaves were made in the same way. The LIBS spectra of these processed leaf samples were also recorded using the same experimental parameters as used for the fresh samples. Their results showed that among the aforementioned processing techniques, frying most significantly reduces the content of magnesium, whereas the least loss of Mg is observed in the case of boiling. They have verified this result by recording the LIBS spectra of the intact fresh leaves and of those processed with different techniques. The same results were also obtained from the LIBS spectra of the intact leaves and their pellets. The LIBS spectra of methi and spinach leaves were also recorded after drying them using two different techniques—drying in vacuum and in a hot air oven. The results show that vacuum drying is more suitable in terms of minimizing the loss of Mg content in leaves.

The loss of magnesium is attributed to the leaching of Mg in water and degradation of the pigment during processing. In blanching, magnesium is leached in two stages, that is, a substantial amount of it is lost in hot water and a small fraction in cold water.

Blanching treatment involved blanching of 100 g of the sample in 1 L of hot water (~85°C) in a stainless steel vessel for 3 min. Following hot water blanching, the samples were plunged into icy water (1 L, temperature of 3°C–4°C) and analyzed both immediately and after forming the pellets.

1.10 BLANCHING AND HIGH-PRESSURE PROCESSING

HPP is known as an alternative nonthermal food preservation method that can be applied to a wide variety of products. HPP is based on the application of pressures between 200 and 900 MPa to food that inactivates foodborne microorganisms and certain enzymes implied in food spoilage (Bayindirli et al., 2006).

HPP is particularly useful for acid foods such as fruit pieces, purees, and juices (Jordan et al., 2001; Bull et al., 2004; Bayindirli et al., 2006; Garcia-Parra et al., 2014).

The application of HPP to some fruit purees at industrial level is limited due to the resistance of browning-related enzymes, such as the PPO, to the treatment. This enzyme reduces the shelf life of the product due to the formation of brown compounds, which could modify the original color of the puree during storage (Gonzalez-Cebrino et al., 2012).

Other practice frequently applied during the manufacture process of purees is the application of thermal blanching. It consists in a short heating of the puree at the beginning of the processing line to maintain the original color of the puree by the inactivation of enzymes such as the PPO and also to reduce initial microbial levels. However, in some cases, this heating could also increase the oxidation of nutritive compounds and reduce the original quality of the processed fruit products. The application of pretreatments would be a necessary step before HPP as suggested by Contador et al. (2012) in pumpkin puree, Landl et al. (2010) in apple puree, and Gonzalez-Cebrino et al. (2012) in plum puree.

A nectarine puree was manufactured with different pretreatments (thermal blanching or ascorbic acid—AA—addition), and then, the puree was processed by high-pressure treatment to evaluate the effect of the initial manufacture conditions in the stability of the processed purees as described by Garcia-Parra et al. (2014). A thermal treatment was also carried out to compare the effect with the HPP. All applied processes were effective to ensure the microbiological safety of the purees. However, the pretreatment (thermal blanching or AA addition) applied during manufacturing affected the final quality of the processed purees. Initially, the AA addition had a protective effect on color degradation during the manufacture of the purees; however, when these purees were treated by HPP, they showed less color stability during storage, lower bioactive compounds content, and antioxidant activity. In contrast, purees with an initial thermal blanching maintained better quality after HPP and during storage.

Puree with thermal blanching was manufactured at 80°C during the last 40 s of the blending process to simulate industrial preheating.

1.11 STEAM BLANCHING

Freeze drying can be combined with heat treatments to promote good quality of the final product and a simultaneous improvement on color and nutritional value.

When tomatoes are submitted to treatments of drying, depending on the parameters and methods used, the concentration or degradation of nutrients can occur. The changes in the composition and color were verified when different drying processes were used. Freeze drying, oven drying, the combination of both, and also the effect of the pretreatment (blanching) using steam were studied by Jorge et al. (2014).

Tomato quarters were placed on a sieve and exposed to boiling water steam for 5 min.

The fresh tomato composition was compared with the composition of dehydrated tomato powder. After dehydration, the moisture content reduced 78% from the total initial moisture. In addition, a nutrient concentration was observed with an increase of about 57% of citric acid content and 3% in the pH. The ash content also increased from 0.53% to 8% (15 times) and 60%, the carbohydrates from 3.94% to 60% (15 times) and the proteins were increased from 1% to 11% (10 times). The blanching resulted in different types of changes, such as greater stability for the proteins, carbohydrates, fat, lycopene, and β-carotene.

There was a significant fat content difference in all treatments when exposed to steam blanching. A slight increase in the fat content was noted in the powder obtained by all drying treatments when the blanching treatment was used. The enzymatic action of lipase was inactivated with the steam application, reducing the degradation reactions of this nutrient in the product (Anese and Sovrano, 2006).

The increase in lycopene and β-carotene content after the blanching was evidenced because heating promotes the change from *cis* to *trans* conformation form, intensifying the detection of

these components. Furthermore, it is seen that the heating time can cause the degradation of these pigments. However, the degradation was lower in the drying treatments with previous blanching when compared with those that did not undergo steam blanching (Jorge et al., 2014).

Steam and water blanching seem to be suitable initial operations when processing parsley into paste-like products. The parsley products obtained were characterized by bright green colors and enhanced antioxidant capacity; however, the total phenolic contents were lowered due to leaching (Kaiser et al., 2012). Furthermore, steam and water blanching at various temperature–time regimes of parsley and marjoram had different effects on polyphenol stabilities. Both increases and decreases of individual phenolic compounds were observed (Kaiser et al., 2013a). In a previous study, coriander leaves and fruits were blanched and subsequently processed into a powder. Blanching resulted in reduced microbial loads and retention of bright green color (Schweiggert et al., 2005).

Fresh coriander leaves were steam and water blanched at 100°C and at 90°C and 100°C, respectively, for 1–10 min, and subsequently comminuted to form a paste as reported by Kaiser et al. (2013b). Pasty products obtained from coriander fruits were processed after water blanching, applying the same time–temperature regimes. Among the 11 phenolics characterized in leaves by high-performance liquid chromatography coupled with mass spectrometric detection, several caffeic acid derivatives, 5-feruloylquinic, and 5-*p*-coumaroylquinic acids were tentatively identified for the first time. In fruits, 10 phenolics were detected, whereas rutin, a dicaffeic acid derivative and 2 feruloylquinic and caffeoylquinic acid isomers were newly detected. Upon steam blanching for 1 min, phenolic contents and antioxidant capacities remained virtually unchanged. In contrast, water blanching and extended steam blanching even yielded increased levels compared to the unheated control, whereas short-time water blanching resulted in higher values than prolonged heat treatment. Thus, short-time water blanching is recommended as the initial unit in the processing of coriander leaves and fruits into novel pasty products.

1.12 BLANCHING AND FOLATE REDUCTION

Blanching is commonly used to reduce enzyme activity, which can cause undesirable changes in color, flavor, odor, or nutritive value during frozen storage of vegetables (Selman, 1994). It has also been shown to reduce the folate content in vegetables (McKillop et al., 2002; Stea et al., 2006). Blanching is still used in the Egyptian food industry prior to canning of dried legumes as reported by Hefni and Witthöft (2014). They reported that blanching according to common practice reduced the folate content in faba beans and chickpeas by only 10% and 20%, respectively, probably by leaching into the blanching water as reported by others (Hoppner and Lampi, 1993; Dang et al., 2000).

Industrial food processing and household cooking are reported to affect folate content. This study by Hefni and Witthöft (2014) examined the effects of industrial and household processing methods on folate content in traditional Egyptian foods from faba beans (*Vicia faba*) and chickpeas (*Cicer arietinum*). Overnight soaking increased folate content by ~40%–60%. Industrial canning including soaking, blanching, and retorting did not affect folate content ($p = 0.11$) in faba beans but resulted in losses of ~24% ($p = 0.0005$) in chickpeas.

Germination increased folate content 0.4–2.4-fold. Household preparation increased the folate content in germinated faba bean soup (nabet soup) onefold and in bean stew (foul) by 20% ($p < 0.0001$). After deep-frying of falafel balls made from soaked faba bean paste, losses of 10% ($p = 0.2932$) compared with the raw faba beans were observed. The folate content (fresh weight) in the traditional Egyptian foods, foul and falafel, and in the beans in nabet soup was 30 ± 2, 45 ± 2, and 56 ± 6 μg/100 g, respectively. The traditional Egyptian foods foul, falafel, and nabet soup are good folate sources and techniques like germination and soaking, which increase the folate content, can therefore be recommended.

There are some studies on folate losses in vegetables during cooking, blanching, or freezing. McKillop in 2002 determined that spinach blanching for 3.5 min involves a folate loss of 51% (McKillop et al., 2002). Holasova et al. (2008) obtained similar results with a percentage of retention of around 40% after 12 min boiling. DeSouza and Eitenmiller (1986), studied the impact of different treatments such as blanching and freezing on folate loss in spinach, showed 17% retention after blanching at 100°C for 4 min.

Folates are described to be sensitive to different physical parameters such as heat, light, pH, and leaching. Most studies on folates degradation during processing or cooking treatments were carried out on model solutions, or vegetables only with thermal treatments.

Delchier et al. (2013) identified the steps involved in folates loss in industrial processing chains and the mechanisms underlying these losses. For this, the folates contents were monitored along an industrial canning chain of green beans and along an industrial freezing chain of spinach.

Folates contents decreased significantly by 25% during the washing step for spinach in the freezing process, and by 30% in the green beans canning process after sterilization, with 20% of the initial amount being transferred into the covering liquid. The main mechanism involved in folate loss during both canning green beans and freezing spinach was leaching.

Limiting the contact between vegetables and water or using steaming seems to be an adequate measure to limit folates losses during processing.

1.13 BLANCHING AND FROZEN VEGETABLES

Commercially frozen vegetables undergo blanching prior to freezing, a process utilizing hot water or steam to inactivate enzymes that otherwise cause degradative changes, limiting shelf life severely (Andress and Harrison, 2006). Destruction of the thermally stable enzyme peroxidase is most frequently the endpoint used in determining the choice of temperature and time for the blanching process (USDA 2013). However, the use of peroxidase as an indicator enzyme is controversial, due to the fact that it often has no role in causing or enhancing degradation during storage of frozen product (Barrett and Theerakulkait, 1995). With an increase in blanching time and temperature, not only does the cost increase, but there is also a greater loss of nutrient content (Lim et al., 1989).

Yet typical blanching protocols for processing broccoli prior to freezing often exceed the limit of myrosinase stability (Lund, 1977). It was previously determined that commercially frozen broccoli lacks the ability to form sulforaphane pre- and post-cooking (Dosz and Jeffery, 2013a).

Frozen broccoli can provide a cheaper product, with a longer shelf life and less preparation time than fresh broccoli. Dosz and Jeffery (2013b) previously showed that several commercially available frozen broccoli products do not retain the ability to generate the cancer-preventative agent sulforaphane. They hypothesized that this was because the necessary hydrolyzing enzyme myrosinase was destroyed during blanching, as part of the processing that frozen broccoli undergoes. This study was carried out to determine a way to overcome loss of hydrolyzing activity. Industrial blanching usually aims to inactivate peroxidase, although lipoxygenase plays a greater role in product degradation during frozen storage of broccoli.

Blanching at a temperature of 86°C or higher inactivated peroxidase, lipoxygenase, and myrosinase. Blanching at 76°C inactivated 92% of lipoxygenase activity, whereas there was only an 18% loss in myrosinase-dependent sulforaphane formation. They considered that thawing frozen broccoli might disrupt membrane integrity, allowing myrosinase and glucoraphanin to come into contact. Thawing frozen broccoli for 9 h did not support sulforaphane formation unless an exogenous source of myrosinase was added. Thermal stability studies showed that broccoli root, as a source of myrosinase, was not more heat stable than broccoli floret. Daikon radish root supported some sulforaphane formation even when heated at 125°C for 10 min, a time and temperature comparable to or greater than microwave cooking. Daikon radish (0.25%) added to frozen broccoli that was then allowed to thaw supported sulforaphane formation without any visual alteration to that of untreated broccoli.

1.14 HIGH-HUMIDITY HOT AIR IMPINGEMENT BLANCHING

High-humidity hot air impingement blanching (HHAIB) is a new and effective thermal treatment technology which combines the advantages of steam blanching and impingement technologies, resulting in minimum solids loss, a uniform, rapid and energy-efficient blanching process.

In HHAIB jets of high-humidity hot air impinge on the product surface at high velocity to achieve a high rate of heat transfer. It has been observed that the heat transfer coefficient of HHAIB at the initial stage is about 1400 W/(m^2 K) at 14.4 m/s, 135°C, and 35% as its velocity, temperature, and relative humidity, respectively, which is about 12 times that of pure hot air impingement at the same temperature and velocity (Du et al., 2006). Furthermore, the materials are heated by steam or high humidity hot air, not dipped in water, which avoids loss of water-soluble nutrients during blanching. Xiao et al. (2012) found that appropriately HHAIB pretreatment can accelerate drying and improve the whiteness index of yam slices probably due to the absence of oxygen. Bai et al. (2013a) reported that HHAIB pretreatment is an effective pretreatment for Fuji apple quarters to inactivate PPO and, meanwhile, to maintain produce quality.

Seedless grapes blanched by HHAIB at different temperatures (90°C, 100°C, 110°C, and 120°C) and several durations (30, 60, 90, and 120 s) were air-dried at temperatures ranging from 55°C to 70°C. The PPO activity, drying kinetics, and the product color parameters were investigated to evaluate the effect of HHAIB on drying kinetics and color of seedless grapes. The results clearly show that HHAIB not only extensively decreases the drying time but also effectively inhibits enzymatic browning and results in desirable green–yellow or green raisins (Bai et al., 2013b). In view of the PPO residual activity, drying kinetics and color attributes, HHAIB at 110°C for 90 s followed by air drying at 60°C are proposed as the most favorable conditions for drying grapes. These findings indicate a new pretreatment method to try to enhance both the drying kinetics and quality of seedless grapes.

Drying grapes is more difficult than some other biological materials, since a thin layer of wax covers on its surface peel. Currently, chemical pretreatment methods are used frequently to dissolve the wax layer and accelerate dry rate. However, the chemical additive residue in the raisins may cause food safety problems and how to deal with larger quantities of corrosive chemicals is a serious problem. HHAIB is a new and effective thermal treatment technology with advantages such as minimum solids loss, uniform, rapid and energy-efficient blanching process. The current work indicates that HHAIB may be a useful nonchemical pretreatment technology for seedless grape drying, which can not only accelerate drying kinetics but also improve color parameters of seedless grape.

1.15 BLANCHING AND ANTIOXIDANT CAPACITY OF FOODS

Processing often results in either a depletion of or increase of the antioxidant properties of foods. Processing can induce the formation of compounds with novel antioxidant properties, which can maintain or even enhance the overall antioxidant potential of foods (Ioannou et al., 2012). However, during processing, loss of antioxidants or formation of compounds with prooxidant action may lower the antioxidant capacity.

In previous studies, leek extracts lost 20% of their total phenolic content when subjected to a thermal treatment (100°C, 60 min; this mimicked typical soup preparation).

The degree to which antioxidants change during processing depends on the sensitivity of the compound to modification or degradation and the length of exposure to a processing technique. But losses or gains of antioxidants can also vary with cooking or processing method (Ewald et al., 1999; Ioku et al., 2001; Lee et al., 2008).

Evaluating the effect of domestic cooking on the health benefits of vegetables has great practical importance. However, only a limited number of reports provide information on the effect of these treatments on the antioxidant capacity, polyphenol and *S*-alk(en)yl-L-cysteine sulfoxide

(ACSO, e.g., isoalliin and methiin) content of the white shaft and green leaves of leek (*Allium ampeloprasum* var. *porrum*).

Bernaert et al. (2013) studied the antioxidant capacity of leek and reported that it was highly influenced by cooking (blanching, boiling, and steaming). Boiling had a negative effect on total phenolic content in the white shaft and green leaves. An obvious increase could be observed in the antioxidant capacity of the steamed green leaves, while steaming did not influence the polyphenolic content. Remarkably, blanching resulted in a slight increase in the ACSO content. Subjecting leek samples to a longer thermal treatment appeared to have a negative influence on the ACSO content in leek. Steaming was also responsible for a decrease in ACSOs. Methiin was less susceptible to heat treatment than isoalliin.

Blanching and boiling did not influence the antioxidant capacity of the white shaft of leek, as measured using the oxygen radical absorbance capacity (ORAC assay). Blanching of the green leaves resulted in a 19% higher antioxidant capacity compared with the raw samples.

In general, steaming appeared to be responsible for better retention of the bioactive compounds present in leek compared with boiling.

Incorporation of ground peanut skins (PS) into peanut butter at 1.25%, 2.5%, 3.75%, and 5.0% (w/w) resulted in a marked concentration-dependent increase in both the TPC and antioxidant activity as reported by Ma et al. (2014).

PS, as the other edible part of peanuts, have attracted attention because they are a rich, inexpensive source of potentially health-promoting phenolics and dietary fiber (DF).

Using dry-blanched PS to illustrate, the TPC increased by 86%, 357%, 533%, and 714%, respectively, compared to the peanut butter control devoid of PS; the total proanthocyanidins content (TPACs) rose by 633%, 1933%, 3500%, and 5033%, respectively.

PACs are complex flavonoid polymers; their phenolic nature makes them excellent candidates as food antioxidants.

Normal phase high-performance liquid chromatography (NP-HPLC) detection confirmed that the increase in the phenolics content was attributed to the endogenous proanthocyanidins of the PS, which were characterized as dimers to nonamers by NP-HPLC electrospray ionization mass spectrometry (NP-HPLC/ESI-MS).

Ferric reducing antioxidant power assay (FRAP) values increased correspondingly by 62%, 387%, 747%, and 829%, while hydrophilic-oxygen radical absorbance capacity-fluorescein (H-$ORAC_{FL}$) values grew by 53%, 247%, 382%, and 415%, respectively.

Dry blanching of raw peanuts, to remove the seed coat (i.e., testa) from the kernel, is achieved by transporting peanuts on a belt through a low-temperature heating zone (at a maximum of 96°C) for ~45 min.

The dietary fiber content of dry-blanched PS was ~55%, with 89%–93% being insoluble fiber. Data revealed that PS addition enhances the antioxidant capacity of the peanut butter, permits a "good source of fiber" claim, and offers diversification in the market's product line.

1.16 LOW-TEMPERATURE BLANCHING

Low-temperature blanching (LTB), in the temperature range of 55°C–75°C, had been shown to improve the firmness of cooked vegetables and fruits, reducing physical breakdown and sloughing during further processing and providing an excellent and safe way of texture preserving (Verlinden et al., 2000; Dominguez et al., 2001; Ni et al., 2005; Perez-Aleman et al., 2005). Pectin methylesterase (PME), naturally present in many fruits and vegetables including sweet potato, had the potential to play a major role in cell wall strengthening at LTB (Ni et al., 2005; Abu-Ghannam and Crowley, 2006).

Free starch rate has been one of the most important criteria to evaluate the quality of sweet potato flour. LTB of sweet potatoes before steam cooking has shown significant increase in tissue firmness and cell wall strengthening by He et al. (2013). This research indicated that pectin methylesterase (PME) activity decreased by 87.8% after 30 min of blanching in water at 60°C, while

polygalacturonase (PG) and β-amylase activity decreased 69.4% and 7.44%, respectively, under the same condition. Both PME and β-amylase played important roles in tissue firmness. Further studies of tissue firmness and methyl esterification showed that the combination of LTB and Ca^{2+} could increase the activity of PME and significantly enhance the pectin gel hardness to strengthen the cell walls and decrease free starch rate from 12.83% to 7.28%.

1.17 BLANCHING AND SORPTION ISOTHERMS

Several studies concern the influence of blanching on the progress of drying and the quality attributes (Severini et al., 2005; Prajapati et al., 2011).

Jin et al. (2014) used the Flory Huggins free volume (FHFV) theory to interpret the sorption isotherms of broccoli from its composition and using physical properties of the components.

This theory considers the mixing properties of water, biopolymers, and solutes and has the potential to describe the sorption isotherms for varying product moisture content, composition, and temperature. The required physical properties of the pure components in food became available in recent years and allow now the prediction of the sorption isotherms with this theory. Sorption isotherm experiments have been performed for broccoli florets and stalks, at two temperatures. Experimental data shows that the FHFV theory represents the sorption isotherm of fresh and blanched broccoli samples accurately. The results also show that blanching affects the sorption isotherm due to the change of composition via leaching solutes and the change of interaction parameter due to protein denaturation.

Blanching changes the cellular structure (Gómez et al., 2004; Galindo et al., 2005), and consequently changes the organization of the cell structure.

1.18 BLANCHING AND REHYDRATION

In order to tackle the problem of rehydration of freeze-dried vegetables van der Sman et al. (2013a) distinguished three length scales: (1) the microscale of molecules, (2) the mesoscale of pores, and (3) the macroscale of the product.

At the microscale water interacts with the molecules, which constitute the food. This interaction determines the driving force and kinetics for the moisture transport. Recently, they have developed predictive theories for them (van der Sman and Meinders, 2011, 2013; Jin et al., 2011; van der Sman, 2012, 2013; van der Sman et al., 2013b).

At the mesoscale they describe the simultaneous transport of water and solutes via the food matrix and the pore space. While moisture transport in the solid food matrix is governed by diffusion and swelling, the moisture transport in the pore space is governed by capillary transport. Experimental data are obtained via an experimental multiscale approach, combining NMR, Magnetic resonance (MRI), and XRT, targeting the molecular scale, the pore scale, and the macroscopic product scale (Vergeldt et al., 2012; Voda et al., 2013).

They presented a pore-scale model describing the multiphysics occurring during the rehydration of freeze-dried vegetables. This pore-scale model is part of a multiscale simulation model, which should explain the effect of microstructure and pretreatments on the rehydration rate. Simulation results are compared to experimental data, obtained by MRI and XRT. Time scale estimates based on the pore-scale model formulation agree with the experimental observations. Furthermore, the pore-scale simulation model provides a plausible explanation for the strongly increased rehydration rate, induced by the blanching pretreatment.

The increased insight in the physical processes governing the rehydration of porous or freeze-dried food gives more rationale for optimizing all processing steps. Industry is seeking for means to give dried fruits and vegetables more conveniently, but also higher quality concerning health and texture. This study shows that blanching pretreatment prior to freeze-drying strongly enhances the rehydration, while the loss of nutrients is hardly affected.

1.19 CASE STUDY: EFFECT OF BLANCHING CONDITIONS ON SULFORAPHANE CONTENT IN PURPLE AND ROMAN CAULIFLOWER (*BRASSICA OLERACEA L. VAR. BOTRYTIS*)

ABSTRACT

Brassicaceae offer many health-promoting properties due a high content of glucosinolates (glucoraphanin), whose hydrolysis through myrosinase yields sulforaphane, the most powerful anti-cancer compound derived from foodstuffs. Depending on the chemical conditions, a competition reaction occurs catalyzed the epithiospecifier protein, yielding sulforaphane-nitrile, a non-bioactive and potentially toxic compound. Epithiospecifier protein is more thermo-labile than myrosinase, then its inactivation through an adequate blanching step should be possible, thus favoring sulforaphane synthesis. The effect of blanching conditions on sulforaphane content in roman and purple cauliflower was investigated. A factorial 2^2 design in two blocks was used; whose factors were temperature (50°C and 70°C) and immersion time (5 and 15 min). Both factors affected significantly sulforaphane content. The maximum sulforaphane content was achieved after blanching at 70°C. Our results demonstrate that it is possible to favor, and even optimize, sulforaphane synthesis by blanching using an adequate combination of temperature and immersion time.

Keywords: cauliflower, sulforaphane, blanching

INTRODUCTION

The *Brassicaceae* plants, such as broccoli, white cauliflower, roman cauliflower, Brussels sprouts, and radish, offer many health-promoting properties owing to their high content of ascorbic acid, vitamin K, dietary fiber, and carotenoids. Besides, they exhibit a high content of glucosinolates (GSL), a group of secondary metabolites that share a common basic structure comprising a β-D thioglucose group, a sulphonated oxime moiety and a variable side chain derived from amino acids (Kushad et al., 1999; Fahey et al., 2001; Jia et al., 2009). In recent years GSL have become popular due to the chemoprotective properties that offer some of their hydrolysis products: isothiocyanates. Epidemiological studies have shown that consumption of a *Brassicaceae* rich diet significantly reduces the risk of developing some types of cancer, such as lung, colorectal, prostate, and breast cancer. This anticancer effect has been related to the GSL glucoraphanin, whose hydrolysis results in sulforaphane [4-(methylsulfinyl) butyl isothiocyanate] (Giovannucci et al., 2003; Ambrosone et al., 2004; Manchali et al., 2012). Sulforaphane has been recognized as the most powerful anticancer compound derived from foodstuff (Matusheski et al., 2004). Sulforaphane exerts its anticancer effect by inducing phase II enzymes (quinone reductase and glutathione S-transferase), as shown by *in vitro* and *in vivo* studies (Zhang et al., 1992; Maheo et al., 1997; Chung et al., 2000; Matusheski and Jeffery, 2001). Additionally, sulforaphane has been associated with the prevention of cardio vascular diseases (Wu et al., 2004) and inflammatory illnesses such as arteriosclerosis (Kim et al., 2012).

In intact vegetal tissues, sulforaphane is absent, since its synthesis proceeds through the hydrolysis of glucoraphanin by the action of the enzyme myrosinase (thioglucoside glucohydrolase, EC 3.2.1.147), and this enzyme is differently compartmentalized in specific myrosin cells. When the vegetal tissue is broken by mastication, harvesting, or processing, myrosinase enters in contact with glucoraphanin and then the hydrolysis proceeds (Latté et al., 2011). However, depending on the chemical conditions, a competition reaction occurs through the action of the epithiospecifier protein (ESP), which results in sulforaphane nitrile, a non-bioactive and potentially toxic compound (Mithen et al., 2000, 2003). At neutral pH the spontaneous conversion to sulforaphane proceeds, while as at acidic pH or in the presence of Fe^{2+}, the production of sulforaphane nitrile by the action of ESP is favored (Williams et al., 2008; Mahn and Reyes, 2012). Figure 1.1 shows a scheme of

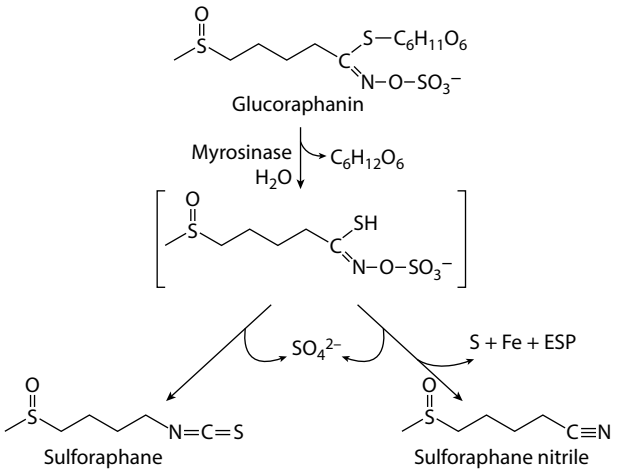

FIGURE 1.1 Mechanism of glucoraphanin hydrolysis. (Adapted from Matusheski, N.V. et al., *J. Agric. Food Chem*., 54, 2069, 2006. With permission.)

glucoraphanin hydrolysis. ESP is more thermolabile than myrosinase, and accordingly it should be possible to inactivate it through an adequate blanching step. The effect of blanching and cooking conditions of *Brassicaceae* vegetables on GSL content has been studied by several authors (Matusheski et al., 2006; Cieślik et al., 2007; Jones et al., 2010; Pellegrini et al., 2010; Sarvan et al., 2012). However, no study about the effect of blanching conditions on sulforaphane synthesis or content in cauliflower has been reported so far.

This work presents a study of the effect of different blanching conditions on the sulforaphane content in roman and purple cauliflower (*Brassica oleracea L.* var. *Botrytis*).

EXPERIMENTAL

Chemicals

Sulforaphane standard, Acetonitrile (HPLC grade), anhydrous sodium sulfate were purchased form Sigma-Aldrich (Schnelldorf, Germany) and methylene chloride was purchased from J.T. Baker (USA). HPLC grade water was produced in the laboratory using an ultrapure water system (Barnstead, Thermo Scientific, Waltham, Massachusetts).

Vegetable Material

Purple and roman cauliflower were purchased at the local market (Santiago, Chile). All vegetables had 3 days from harvesting. Leaves and stems were discarded and the inflorescences were cut in 5–7 cm pieces (vertical).

Experimental Design

A factorial 2^2 design in two blocks was used to study the effect of blanching conditions on sulforaphane synthesis. The experimental factors were temperature (50°C and 70°C) and immersion time (5 and 15 min) (see Table 1.1). A total of 300 g of vegetable were used in each run. Blanching was performed by immersion in distilled water using a thermostatic bath (RE300, Stuart). After blanching, samples were immediately put in an ice bath, and then they were stored at −20°C until analyses.

TABLE 1.1
Blanching Conditions

Treatments	Temperature (°C)	Time (min)
1	50	5
2	50	15
3	70	5
4	70	15

Sulforaphane Content

Sulforaphane content was assessed by reverse phase HPLC, using the method proposed by Liang et al. (2006) with some minor modifications. Fresh and blanched vegetable samples were pulverized with liquid nitrogen in a mortar, until obtaining a homogeneous meal. A total of 5 g of the meal were left to autolyze at room temperature for 30 min. After that, the meal was extracted two times with 50 mL methylene chloride. Extracts were combined and salted with 2.5 g sodium sulfate anhydrous. The methylene chloride fractions were dried at 30°C under vacuum on a rotary evaporator (RE300, Stuart). The residue was dissolved in acetonitrile and was then filtered through a 0.22 μm membrane filter prior to injection into HPLC. The equipment was a HPLC-DAD (Agilent mod. 1110), and a reversed-phase C_{18} column (15.5 × 4.6 mm, i.d., 5 μm) was used. The solvent system consisted of 20% acetonitrile in water; this solution was then changed linearly over 10 min to 60% acetonitrile, and maintained at 100% acetonitrile for 2 min to purge the column. The column oven temperature was set at 30°C. The flow rate was 1 mL/min, and 10 mL portions were injected into the column. Sulforaphane was detected by absorbance at 254 nm. Quantification was carried out by comparison with a sulforaphane standard curve.

Statistical Analysis

Statistical analysis was performed by ANOVA, Fisher's protected LSD and Dunett's test for comparison with the control samples. A 95% confidence interval was considered ($p \leq 0.05$). The analyses were made using JMP 9.0.1 software (SAS Institute Inc.)

RESULTS AND DISCUSSION

Figure 1.2 shows the sulforaphane content in purple (Figure 1.2a) and in roman cauliflower (Figure 1.2b) after blanching under the different conditions given in Table 1.1. In all runs, blanching increased significantly the sulforaphane content in purple cauliflower with respect to fresh vegetable, agreeing with the results informed by Matusheski et al. (2004) for broccoli (*Brassica oleracea* var. *Italica*) subjected to blanching at 60°C during 5 min. This demonstrates that it is possible to favor sulforaphane synthesis by blanching using an adequate combination of temperature and immersion time. The highest sulforaphane content was obtained at 70°C and 5 min of immersion (run 3) in purple cauliflower, resulting in 17 mmol/g dw, representing an increase of 170% with respect to the fresh vegetable.

In roman cauliflower, only run 4 (70°C and 15 min immersion) resulted in significantly higher sulforaphane content, achieving a concentration equal to 31 mmol/g dw. This represents an increase of 500% with respect to the untreated vegetable. The increase of sulforaphane synthesis under some blanching conditions can be attributed to the inactivation of ESP at temperatures lower than 70°C. In this temperature range (50°C–70°C), myrosinase remained active (Matusheski et al., 2004), and therefore sulforaphane synthesis was favored in detriment to nitrile formation. This observation agrees with the results reported by Jones et al. (2010), who found that sulforaphane content in

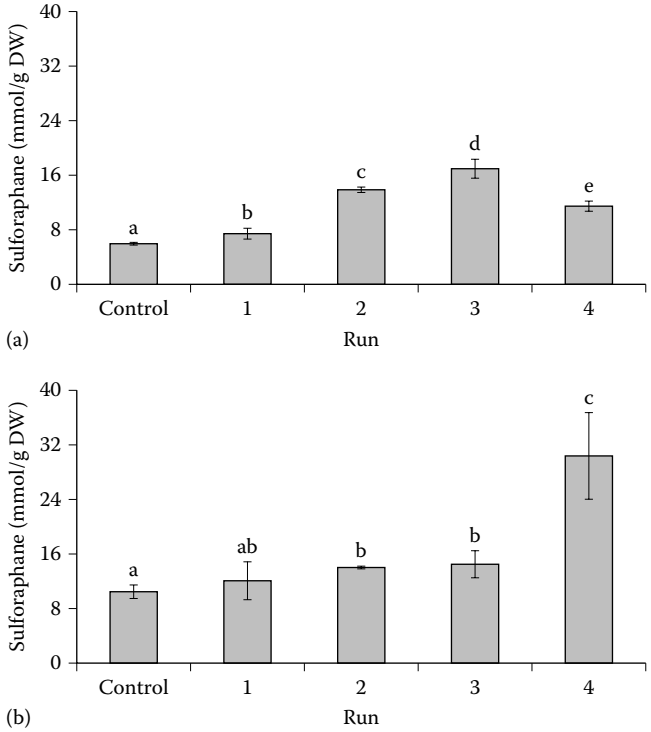

FIGURE 1.2 Sulforaphane content following the different treatments for (a) purple cauliflower and (b) roman cauliflower. Different letters indicate statistically significant differences between treatments.

broccoli diminished after blanching at temperatures higher than 70°C during 2–5 min. The authors attributed this behavior to myrosinase inactivation and also to partial leaching of glucoraphanin in the blanching water.

Matusheski et al. (2004) found that at temperatures higher than 70°C sulforaphane synthesis was disfavored in broccoli, probably due to thermal inactivation of myrosinase. Then, it can be speculated that at 70°C the maximum sulforaphane synthesis would occur. Besides, since the competition reaction that yields sulforaphane nitrile is disfavored, the ESP was probably inactivated at a temperature lower than 70°C.

Figure 1.3 shows the Pareto charts for purple (a) and roman (b) cauliflower. Here, the standardized effects of the experimental factors on sulforaphane content are presented. The experimental factors had significant effects (p-value <0.05) on sulforaphane content in both cauliflower varieties. In purple cauliflower, temperature had a significant positive effect, indicating that an increase in temperature form 50°C to 70°C produced a significant increase in sulforaphane content. Besides, the binary interaction between temperature and immersion time had a significant negative effect, suggesting the existence of an optimum combination of temperature and time that maximizes sulforaphane synthesis. Immersion time had no significant effect on the response. In roman cauliflower both factors, as well as their interaction, had significant positive effects on sulforaphane content, leading to conclude that if there is an optimum, it should be outside the experimental region examined in this work. Our results agree with results obtained in broccoli by Matusheski et al. (2004), van Eylen et al. (2008) and Jones et al. (2010), and can be attributed to thermal inactivation of myrosinase.

Sulforaphane content behavior differed between both cauliflower varieties considered in this study, most likely due to different kinetic and physicochemical properties of myrosinase in both vegetables (Yen and Wei, 1993), or to different glucoraphanin contents in the fresh vegetables.

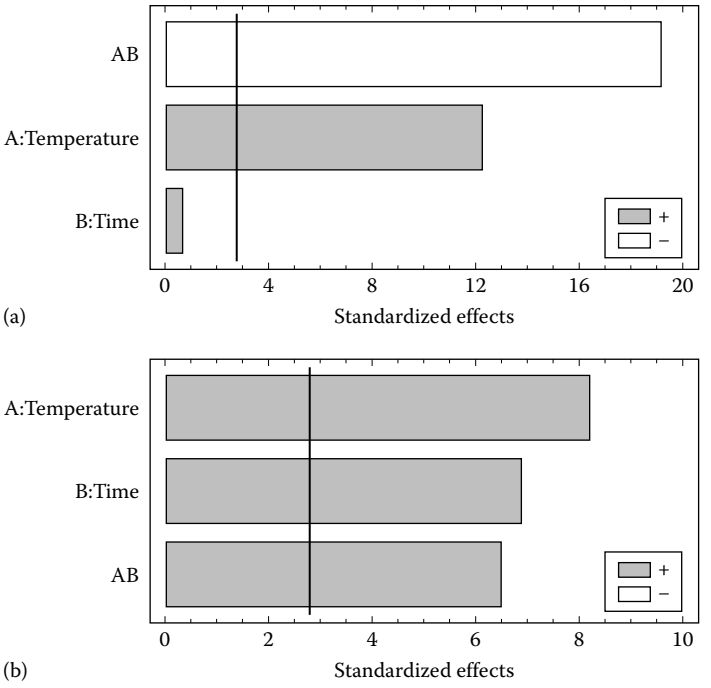

FIGURE 1.3 Pareto chart for the effects of the blanching conditions on sulforaphane content in (a) purple cauliflower and (b) roman cauliflower.

This is supported by the results of Kushad et al. (1999) and Branca et al. (2002), who found that the glucoraphanin content differed considerably between different varieties of cauliflower, ranging from 0.2 to 0.9 μmol/g dw.

The maximum sulforaphane content achieved in both cauliflower varieties in this study were considerably lower than the values reported by Jones et al. (2010) for broccoli subjected to steam blanching during 2 min (145 mmol/g dw). Additionally, Matusheski et al. (2004) reported a maximum sulforaphane content in blanched broccoli (immersion in water at 60°C during 5 min) equal to 10,000 mmol/g dw. The lower sulforaphane contents obtained in cauliflower are attributed to the lower content of glucoraphanin in *Brassica oleracea L.* var. *Botrytis* (up to 900 mmol/g dw), while in broccoli (*Brassica oleracea* var. *Italica*) glucoraphanin content is up to 21,700 mmol/g dw (Kushad et al., 1999). Despite this, cauliflower is still a source of sulforaphane, as evidenced by our results. Besides, purple cauliflower also has a high content of anthocyanins, which show high antioxidant activity, and then this vegetable has great potential as functional food.

CONCLUSION

This work is the first attempt of studying the effect of blanching conditions on sulforaphane content in cauliflower. Blanching temperature and immersion time had statistically significant effect (p <0.05) on sulforaphane synthesis in purple and in roman cauliflower. The maximum sulforaphane content was achieved after blanching at 70°C in both varieties, agreeing with the hypothesis of different inactivation temperatures of ESP and myrosinase. Roman cauliflower showed the highest sulforaphane content after blanching (31 mmol/g dw). Besides, even though purple cauliflower showed a lower sulforaphane content, both cauliflower varieties present high potential as functional food intended to prevent some types of cancer and other diseases. Finally, this study demonstrates that it is possible to favor sulforaphane synthesis by blanching using an adequate combination of temperature and immersion time.

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2 Thermal Processing

Nikolaos G. Stoforos

CONTENTS

2.1 INTRODUCTION

While the application of heat in the food industry can serve a variety of purposes, thermal processing of foods refers to the application of heat in order to preserve product quality and extend its shelf life. Thermal processing represents a major food preservation technique. It consists of heating a product at a rather high temperature for a relatively short time in an accurately designed and well-executed process. The product either before (traditional canning) or after (aseptic processing) the thermal treatment is enclosed into hermetically sealed containers. Unlike a number of food preservation methods, such as drying, freezing, or cold storage, which rely on altering product or environmental conditions in order to diminish product degradation reactions, thermal processing acts by destroying the undesirable agents, including pathogenic or spoilage microorganisms, enzymes, and toxins that could limit product shelf life. High-pressure processing, food irradiation, and a number of novel food preservation methods aiming also at destroying unwanted and quality- and shelf-life-reducing parameters are, in fact, following the thermal process design principles introduced almost a century ago (Bigelow et al., 1920).

Thermal processing is the first man-devised preservation procedure not having a homologous prototype in nature, in contrast to some other preservation methods (such as drying, freezing, and cooling), which were developed and improved based on nature's paradigm and systematic observations. Frenchman Nicolas François Appert (1749–1841), a Parisian confectioner and distiller, is considered as the inventor of the process, for which he won the 12,000-franc prize offered by the

French government under Napoleon, to anyone who could present a method for food preservation, in order to supply safe and nutritious food to the French troops (Valigra, 2011a). However, it seems that there was some form of "canned" food for at least 30 years before the publication of Appert's work (Atherton, 1984). The efforts of Appert in developing his technique are extremely well documented in his original work on "the art of maintaining of animal and vegetable substances for several years" (Appert, 1810).

In his book, Appert (1810) presented details on the preparation of the product, the method of filling and sealing the containers (glass bottles and jars with cork stoppers), and the time in boiling water required for the process. Finally, he suggested how to use the processed foods before consumption. Particular emphasis was placed on the quality of processed foods. For example, while describing the production and heat treatment of meat cooked with vegetables (pot-au-feu), he concludes that "after a year or 18 months, the meat and the soup were as good as having been prepared on the same day."

The basic steps followed today during thermal processing practically do not differ from those proposed by Appert (1810), a time at which the reason why thermal processing ensures the stability of the food was not known. The scientific basis of the process was found much later, in 1860, by Luis Pasteur, who explained that during heat treatment the microorganisms responsible for food spoilage were "killed," and by Prescott and Underwood (1897 and 1898), who showed that microorganisms surviving thermal processing were responsible for the spoilage of canned foods. Details of the historical developments of thermal processes are given, inter alia, by Lopez (1987), Holdsworth and Simpson (2008), and Tucker and Featherstone (2011), while a series of some early important works on thermal processing and the microbiology of thermally processed foods were presented by Goldblith et al. (1961).

The intensity of a thermal process depends on its objectives. A thermal process might be applied to a food product for blanching, pasteurization, or commercial sterilization. While sterilization refers to any process, chemical or physical, resulting in complete destruction of all living organisms, in view of the logarithmic nature of thermal destruction of microorganisms, the term "commercial sterilization" is used. The following definitions are adopted here through a compilation of descriptions given in different sources (Lopez, 1987; Potter and Hotchkiss, 1995; Tucker and Featherstone, 2011):

Blanching: A mild heat treatment by direct contact with hot water or live steam applied to fruits and vegetables primarily to inactivate indigenous food enzymes. Depending on its intensity, blanching destroys some microorganisms reducing the initial microbial load of the product. Additionally, blanching softens the tissues, eliminates air from the tissues, washes away raw flavors, expels respiratory gases, and sets the natural color of certain products.

Pasteurization: A relatively mild heat treatment of food, usually lower than 100°C, aimed at destroying the vegetative cells of all pathogenic as well as most nonpathogenic microorganisms. Pasteurization is usually combined with another means of preservation, such as acidity, low water activity, and low-temperature storage.

Commercial sterilization: Application of heat (or other appropriate treatment) to render food free from any viable form of pathogenic and toxin-forming microorganisms, as well as of non-health significant microorganisms, which, if present, could grow in the food under normal conditions of storage and distribution of the product.

We must notice that the same definitions have been adopted for any other appropriate treatment applied to a food product with the same objective. Thus, we talk about "cold" pasteurization when high hydrostatic pressure processing is used to achieve the goals of pasteurization described earlier.

There is no clear borderline between pasteurization and commercial sterilization, especially when the terms are used with acidic or acidified foods. According to Stumbo (1973), "Whether the term sterilization or pasteurization is used to label a heat treatment designed to reduce the microbial

population of a food, the basic purpose of the heat treatment is the same—that is, to free the food of microorganisms that may endanger the health of food consumers or cause economically important spoilage of the food in storage and distribution." Moreover, the principles governing the design and evaluation of either one of the earlier described processes (blanching, pasteurization, and commercial sterilization) remain the same. In fact, *cooking* (boiling and frying), a way used to control food texture and palatability, is a process that can also be described with similar mathematics.

Apart from the positive results, as far as the destruction of undesirable agents is concerned, degradation of quality characteristics of the product inevitably occurs during a thermal process. Thus, precise design, implementation, and monitoring of the effects of thermal processes are required. Characteristically, Appert (1810) stated that for some products, even heating for 1 min longer (than planned and needed) would be harmful to the product. In the remaining part of the chapter, the basic principles that govern the design and control of thermal processes will be presented. The production of safe-to-eat products with the highest possible quality is the basis of the presentation that follows.

2.2 PRINCIPLES OF THERMAL PROCESSING

Knowledge of the kinetics of thermal destruction of the heat-labile substance under consideration is the first requirement in analyzing a thermal process. Unless otherwise stated, in the remaining of the chapter, bacterial spores or microbial destruction, in general, will be used as an example when referring to any undesirable agent that can be targeted in a thermal process. Thus, for example, the substitution of spore concentration by enzyme activity into the same equations that will be presented in the following paragraphs will enable enzyme inactivation calculations governing a blanching process.

2.2.1 Kinetics of Microbial Destruction

We assume that thermal destruction of a heat labile substance (e.g., microbial spores, Esty and Meyer, 1922) follows first-order kinetics, that is, at constant temperature:

$$-\frac{dN}{dt} = k_T N \tag{2.1}$$

where

N represents the microbial load, that is, the number of spores/mL (or microorganisms per container, or any other appropriate unit)

t is the processing time in min

k_T is the thermal destruction rate constant in min^{-1} (or s^{-1})

Subscript T in k_T indicates the dependence of the rate constant on temperature.

For N_o being the initial (at $t = 0$) microbial load, the solution of Equation 2.1 is given by

$$\ln(N) = \ln(N_o) - k_T t \tag{2.2}$$

and switching from natural logarithms (ln) to common logarithms (base 10 logarithms, log) we obtain

$$\log(N) = \log(N_o) - \frac{k_T}{\ln(10)} t \tag{2.3}$$

Equation 2.3 indicates the logarithmic nature of microbial thermal destruction. N approaches zero at infinite time. A negative log(N), that is, an N value less than 1, must be statistically interpreted. Thus, for example, $N = 10^{-4}$ spores/can indicates the surviving of 1 spore in 10^4 cans. Interpreting this reversely, we can say that 9,999 cans (out of 10,000) are spore-free. Thus, in a given experimental

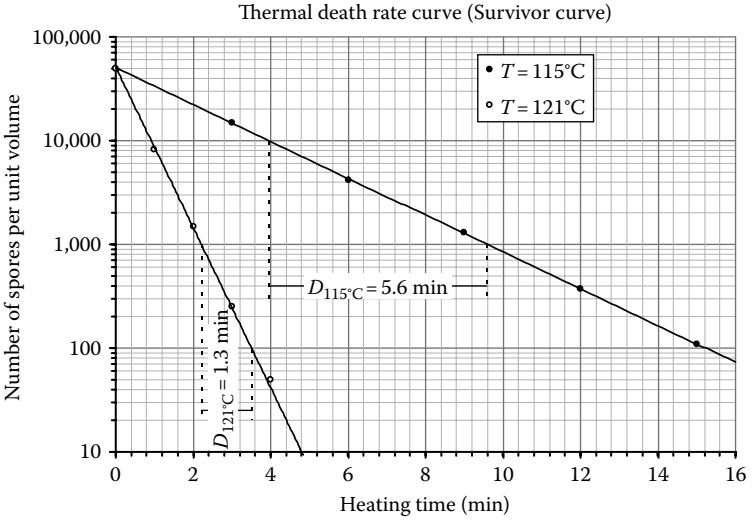


FIGURE 2.1 Log-linear thermal destruction kinetics of heat resistant bacterial spores. Graphical determination of decimal reduction times (D_T) at two temperatures.

observation of, for example, six cans, we will most probably find and report "complete" spore destruction.

As suggested by Equation 2.3, a plot of log(N) versus time is linear with the slope being equal to $-k_T/\ln(10)$. In the classical thermobacteriological literature (Ball and Olson, 1957; NCA, 1968; Stumbo, 1973), experimental N values (in logarithmic scale) were plotted versus heating time (in linear scale) in semi logarithmic paper (as depicted in Figure 2.1); the slope of the "best fit" straight line, the Thermal Death Rate (or Survivor) Curve, was described through the decimal reduction time D_T. The decimal reduction time is defined as the time, at a constant temperature T, required to reduce the microbial population by a factor of 10. In reference to Figure 2.1, D_T can be graphically determined as the time required for the Thermal Death Rate Curve to traverse a logarithmic cycle.

The slope of the straight line (Figure 2.1) is given as

$$slope = \frac{d(\log(N))}{dt} = \frac{\log(N_2) - \log(N_1)}{t_2 - t_1} \tag{2.4}$$

where indices 1 and 2 represent any two points on the straight line. For $N_2 = 0.1 \cdot N$, by definition, $t_2 - t_1 = D_T$. Thus, Equation 2.4 reduces to

$$slope = \frac{\log(0.1N_1) - \log(N_1)}{D_T} \quad \text{or} \quad D_T = -\frac{1}{slope} \tag{2.5}$$

Equation 2.5 can be used to calculate D_T from the slope of the Thermal Death Rate Curve, the slope being estimated from a computerized linear least square regression analysis applied to the experimental log(N) versus t data. Furthermore, recalling the slope of the same line defined by Equation 2.3, an expression between decimal reduction time and thermal destruction rate constant can be obtained

$$D_T = \frac{\ln(10)}{k_T} \tag{2.6}$$

In view of Equation 2.6, Equation 2.3 can be explicitly written in terms of N as

$$N = N_o 10^{-(t/D_T)} \tag{2.7}$$

From Equation 2.7, one can easily evaluate the survivors, N, from a microbial population characterized by a decimal reduction time D_T, for a given processing time t at a given temperature, T, if the initial microbial population, N_o is known. Alternatively, one can calculate the required processing time at a given constant temperature in order to achieve a specific microbial destruction. Rearranging Equation 2.7, the required processing time is given by

$$t_T = D_T(\log(N_o) - \log(N)) \tag{2.8}$$

In Equation 2.8, the symbol t_T was used for the required time in order to emphasize its temperature dependence.

In Figure 2.1, the Thermal Death Rate Curves for bacterial spores at two different temperatures are plotted. As the temperature increases, the time required to reduce the microbial population decreases. For the particular data shown in Figure 2.1, the decimal reduction time at 115°C is equal to 5.6 min, and it reduces to 1.3 min when the temperature rises to 121°C. A secondary model is needed to fully describe the effect of temperature on decimal reduction time or the thermal destruction rate constant. In the classical thermobacteriological analysis, a linear relationship between $\log(D_T)$ and temperature is assumed. In analogy to the decimal reduction time, the D_T values are plotted versus temperature in semilogarithmic paper to form the Phantom Thermal Death Time (TDT) Curve, as depicted in Figure 2.2. The slope of the "best fit" straight line is described through the z value. The z value is defined as the temperature difference required for changing the decimal reduction time by a factor of 10. In reference to Figure 2.2, z can be graphically determined as the temperature required for the Phantom TDT Curve to traverse a logarithmic cycle. As previously shown when analyzing the Thermal Death Rate Curve, similarly, the slope of the Phantom TDT Curve is equal to $-1/z$. Each point on the Phantom TDT Curve represents

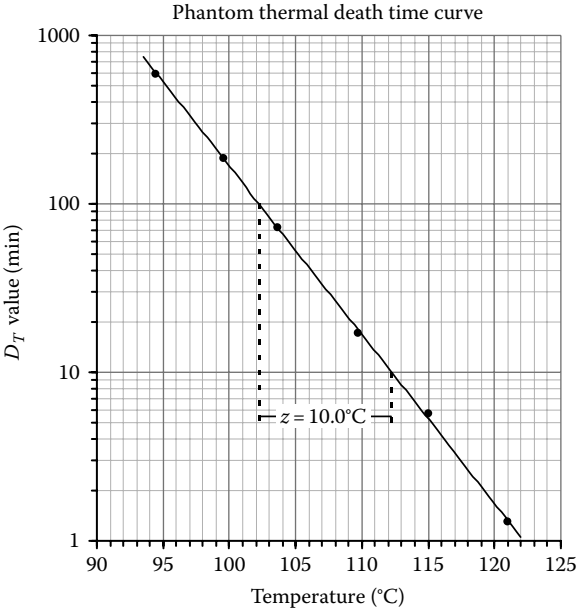


FIGURE 2.2 Effect of temperature on decimal reduction time. Graphical determination of the z value.

time–temperature combinations capable of reducing the microbial population by 90%. On the contrary, a TDT Curve refers to time–temperature combinations needed for "complete" destruction of a given microbial population.

In analogy to Equation 2.7, an expression defining the z value can be written as

$$D_T = D_{T_o} 10^{(-T/z)} \tag{2.9}$$

where D_{To}, a meaningless value, represents the D_T value at zero temperature. For a reference temperature, T_{ref}, within the lethal temperature range of data collection, Equation 2.9 gives

$$D_{T_{ref}} = D_{T_o} 10^{(-T_{ref}/z)} \tag{2.10}$$

and by combining Equations 2.9 and 2.10, we obtain the following expression, the formal mathematical definition of the z value:

$$D_T = D_{T_{ref}} 10^{((T_{ref}-T)/z)} \tag{2.11}$$

In converting z values to different temperature units, we must remember that z represents a temperature difference. Thus, a z value of 10°C is equivalent to 10 K or 18°F.

D_T is used to describe the heat resistance of microorganisms. Indeed, between two different microorganisms, the one characterized by a longer decimal reduction time at a particular temperature is the most heat resistant. However, one must remember the effect of temperature on D_T. If the two microorganisms differ in their sensitivity to temperature changes, that is, if they are characterized by different z values, then, the choice of the most heat-resistant microorganism can be temperature dependent. This is illustrated in Figure 2.3, where below 96°C the microorganism characterized by $D_{100°C} = 8$ min and $z = 5$°C is the most heat resistant, while above 96°C the microorganism characterized by $D_{110°C} = 2$ min and $z = 10$°C becomes the most heat resistant. In a typical thermal process, where product temperature is not constant, the selection of the target microorganism, among

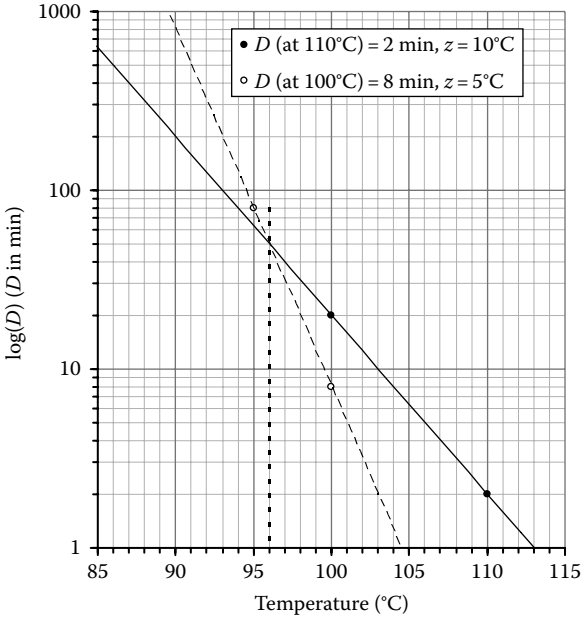


FIGURE 2.3 Selection of the target microorganism based on the Phantom TDT Curves of the microorganisms.

those characterized by different z values, requires complete calculations, the choice being based on the remaining microbial populations at the end of the entire thermal process.

While the secondary model used to describe the effect of temperature on decimal reduction time is given in terms of the z value, the Arrhenius equation is typically used to express the effect of temperature on the reaction rate constant, as given here by (Lund, 1975)

$$k_T = k_{T_{ref}} 10^{-\frac{E_a}{\ln(10)\cdot R_g}\frac{(T_{ref}-T)}{T_{ref}T}} \tag{2.12}$$

Note that T and T_{ref} in Equation 2.12 represent absolute temperatures (i.e., expressed in Kelvin).

The discrepancy between Equations 2.11 and 2.12 is given. Some critical discussion on this matter can be found in the literature (Jonsson et al., 1977; Ramaswamy et al., 1989; David and Merson, 1990; Datta, 1993). Nevertheless, both equations have been used to analyze the thermal destruction of a number of heat-labile substances during heat processes. Equation 2.11 is the choice when dealing with microbial destruction, while Equation 2.12 is preferred when the degradation of chemical substances is considered. Both equations are considered appropriate, as long as they are used within the temperature range where the inactivation data have been collected. However, one should not overestimate their empirical nature (Barsa et al., 2012).

At this point, we must also mention concerns about the appropriateness of first-order kinetics to describe microbial thermal inactivation. Deviations from first-order kinetics do exist. A number of alternative models have been proposed (Valdramidis et al., 2012). However, given the simplicity of the first-order kinetics and its successful application in the thermal processing industry for about a century, the first-order model is considered as an appropriate engineering tool for thermal process design calculations (Pflug, 1987).

2.2.2 *F* Value

If two thermal processes, applied to identical products, are applied for the same processing time, then the one using higher processing temperature is more intense, that is, resulting in higher destruction of a given microbial population. Similarly, if the temperature of two processes is the same, the one lasting longer is more severe. However, if both the processing time and temperature of two thermal processes are different, for example, one is for 30 min at 115°C and the other for 15 min at 120°C, then it is not obvious which one is more destructive.

Among a number of choices, the comparison of different thermal processes in terms of their destructive effect on a heat-labile substance is traditionally made by means of the equivalent processing time, that is, the F value. The F value of a process is formally defined as the equivalent processing time of a hypothetical thermal process at a constant, reference temperature, T_{ref}, that produces the same destructive effect as the actual thermal process. Selection of a different hypothetical thermal process at a different reference temperature results in a different F process value. Thus, when reporting an F value, the reference temperature used must be always explicitly stated. Alternatively, a subscript with the T_{ref} always accompanies the symbol F, that is, $F_{T\text{ref}}$. Furthermore, in view of the discussion when introducing the z value, the F value of a process depends on the z value of the particular microbial population. Thus, the subscript z is also placed on the symbol F when the z value is not explicitly stated; that is, the complete symbol for the F value is $F^z_{T_{ref}}$. If we use the constant product temperature T (when applicable) as the reference temperature, then following the F value definition, the time, t_T, defined by Equation 2.8 for constant temperature processes, coincides with the process F_T value. With the preceding comment, if we write Equation 2.8 for two equivalent thermal processes with constant but different product temperatures, T_1 and T_2, we obtain

$$F^z_{T_1}(=t_{T_1}) = D_{T_1}(\log(N_o) - \log(N)) \tag{2.13}$$

and

$$F_{T_2}^{z}(=t_{T_2}) = D_{T_2}(\log(N_o) - \log(N)) \tag{2.14}$$

On Equations 2.13 and 2.14, the logarithmic microbial reduction, $\log(N_o/N)$, as well as the z value were kept the same since we are referring to equivalent thermal processes (Stoforos and Taoukis, 2006). Expressing D_{T_2} in terms of D_{T_1}, through Equation 2.11, that is,

$$D_{T_2} = D_{T_1} 10^{((T_1 - T_2)/z)} \tag{2.15}$$

and substituting it to Equation 2.14, we end up with

$$F_{T_2}^{z} = 10^{((T_1 - T_2)/z)} F_{T_1}^{z} \tag{2.16}$$

The aforementioned equation suggests how to convert an F value from one reference temperature to another. It also explains mathematically the z dependency of the F value.

The preceding information would be sufficient for thermal process calculations, requiring only minor additions and clarifications, if product temperature remained constant during a thermal process. However, in typical thermal processes, product temperature varies with time, as illustrated in Figure 2.4 for the geometric center of a conduction-heated product processed in metal cans. In reference to Figure 2.4, we must notice that a cooling cycle must always follow the heating cycle of a thermal process in order to cease the detrimental effects of heat on the quality characteristics of the product. In defining the F value for such processes, that is, with product temperature varying with time, we can proceed as follows:

- Total processing time (including heating and cooling time) is divided to n equal-spaced time steps (through $i = 0$ to n nodes); each time step is equal to Δt, while the ith time step, Δt_i, is confined between the $(i - 1)$th and the ith node.
- Within each time step, we approximate product temperature with a constant value, for example, the temperature value at the end of the time step, as illustrated in Figure 2.4. Thus, product temperature at the end of the ith time step is equal to T_i.

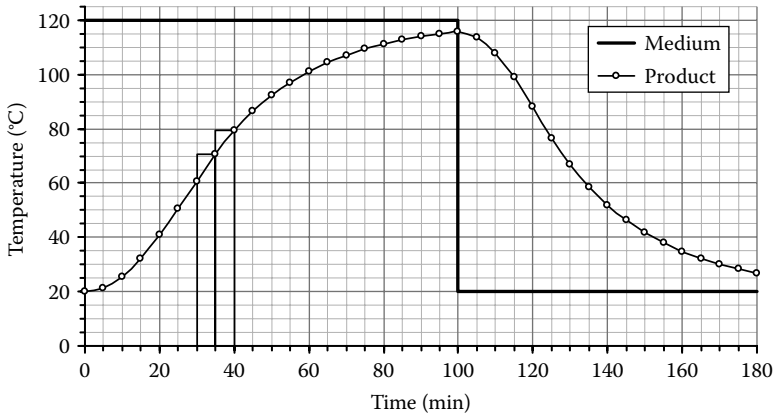


FIGURE 2.4 Typical temperature profile at the geometric center of a conduction-heated canned product during the heating and cooling cycles of a thermal process. The approximation of product temperature, used for the F value derivation, is illustrated at two time steps with the rectangular drawings.

- Next, we calculate the F value for each time step, based on Equation 2.16, due to the constant temperature assumption within the time step, and Equation 2.8:

$$F_{T_{ref}}^{z}\Big|_{i} = 10^{((T_i - T_{ref})/z)}\Delta t_i = D_{T_{ref}}(\log(N_{i-1}) - \log(N_i)) \tag{2.17}$$

where N_i is the microbial population at the end of the ith time interval.

- Doing this for each time step, we progressively obtain

$$\begin{aligned}
F_{T_{ref}}^{z}\Big|_{1} &= 10^{((T_1 - T_{ref})/z)}\Delta t_1 = D_{T_{ref}}(\log(N_o) - \log(N_1)) \\
F_{T_{ref}}^{z}\Big|_{2} &= 10^{((T_2 - T_{ref})/z)}\Delta t_2 = D_{T_{ref}}(\log(N_1) - \log(N_2)) \\
&\vdots \\
F_{T_{ref}}^{z}\Big|_{i-1} &= 10^{((T_{i-1} - T_{ref})/z)}\Delta t_{i-1} = D_{T_{ref}}(\log(N_{i-2}) - \log(N_{i-1})) \\
&\vdots \\
F_{T_{ref}}^{z}\Big|_{n-1} &= 10^{((T_{n-1} - T_{ref})/z)}\Delta t_{n-1} = D_{T_{ref}}(\log(N_{n-2}) - \log(N_{n-1})) \\
F_{T_{ref}}^{z}\Big|_{n} &= 10^{((T_{n-1} - T_{ref})/z)}\Delta t_n = D_{T_{ref}}(\log(N_{n-1}) - \log(N_n))
\end{aligned} \tag{2.18}$$

- Adding the equations, for equal-spaced time intervals, we end up with

$$\sum_{i=1}^{n} F_{T_{ref}}^{z}\Big|_{i} = \sum_{i=1}^{n} 10^{((T_i - T_{ref})/z)}\Delta t = D_{Tref}(\log(N_o) - \log(N_n)) \tag{2.19}$$

- The first summation is equal to the F value of the entire process. Taking the limit as i goes to infinity, the second summation in Equation 2.19 becomes a definite integral:

$$\lim_{n\to\infty} \sum_{i=1}^{n} 10^{((T_i - T_{ref})/z)}\Delta t = \int_{t=0}^{t=t_p} 10^{((T(t) - T_{ref})/z)} dt \tag{2.20}$$

for t_p being the total processing time. Using N instead of N_n, as we have done so far in the text for the microbial population at the end of the process, Equation 2.19 reduces to its final form:

$$F_{T_{ref}}^{z} = \int_{t=0}^{t=t_p} 10^{((T(t) - T_{ref})/z)} dt = D_{T_{ref}}(\log(N_o) - \log(N)) \tag{2.21}$$

An alternative derivation of Equation 2.21 has also been presented in the literature (Stoforos and Taoukis, 2006). Analogous expressions can be obtained in the k_T and E_A approach, that is, when Equations 2.2 and 2.12 are used (Stoforos and Taoukis, 2006). One can also

derive comparable expressions when other than first-order kinetics are used, for example, when an *n*th order model is used to describe microbial destruction. However, description of microbial inactivation in terms of log reduction in such cases is not meaningful.

2.3 THERMAL PROCESS CALCULATIONS

Equation 2.21 represents the fundamental equation used for thermal process design and evaluation. It enables calculation of the F value of a process, either through microbiological destruction data (right-hand side of Equation 2.21) or through time–temperature data (left-hand side of Equation 2.21). Comparison of the destructive effects of two thermal processes can be easily done through calculation of their corresponding F values. Nevertheless, the F value of a process (noted as $F_{process}$) cannot tell if the goal of the thermal process has been achieved, that is, for example, if the thermal process has achieved commercial sterilization, unless we compare the F value of the process with a target, a required F value.

2.3.1 Required *F* Value

A required F value (noted as $F_{required}$) is defined as the time (at a constant reference temperature) required for destroying a given percentage of microorganisms whose thermal resistance is characterized by a particular z value. It sets the target of a thermal process. If

$$F_{T_{ref}}^{z}\Big|_{process} \geq F_{T_{ref}}^{z}\Big|_{required} \tag{2.22}$$

then the thermal process has accomplished its objectives. In view of the negative effects of heat on product quality, the equality in Equation 2.22 is sought.

The right-hand side of Equation 2.21 is commonly used to estimate the required F value. For example, for a given target microorganism (and thus, for known z and D values, let us assume $z = 10°C$ and $D_{121.11°C} = 1$ min) based on an estimated maximum initial load of microorganisms (e.g., $N_o = 1.4 \times 10^6$ spores/container) and aiming, after the thermal treatment, for no more than one spore surviving per 50,000 containers (i.e., $N = 2 \times 10^{-5}$ spores/container), the required F value can be calculated as

$$F_{121.11°C}^{10°C}\Big|_{required} = 1 \times (\log(1.4 \times 10^6) - \log(2 \times 10^{-5})) \Rightarrow F_{121.11°C}^{10°C}\Big|_{required} \approx 11 \text{ min}$$

For low-acid products in which there is the potential for *Clostridium botulinum* growth, a minimum $F_{121.11°C}^{10°C}$ required value is taken equal to 3 min, which corresponds to a 12 logarithmic cycle reduction of the microbial load of *C. botulinum* (Pflug and Odlaugh, 1978; Tucker and Featherstone, 2011). Note that the symbol F_o is used for an F value at $T_{ref} = 121.11°C$ (actually, 250°F—a typical processing temperature for commercial sterilization of low-acid foods) and for a z value of 10°C (18°F) (the z value characterizing the thermal inactivation of *C. botulinum* spores). Note that according to the FDA (2014), *low-acid foods mean any foods, other than alcoholic beverages, with a finished equilibrium pH greater than 4.6 and a water activity greater than 0.85. Tomatoes and tomato products having a finished equilibrium pH less than 4.7 are not classed as low-acid foods.* Usually, target F_o values of 6 min or longer are applied to low-acid foods in order to control heat-resistant spoilage microorganisms. However, the rate of quality degradation during thermal processing and storage are key factors in shaping the objectives of the process and selecting the required F value. Some indicative $F_{required}$ values for low-acid foods are given by Holdsworth and Simpson (2008).

Product pH, water activity, the addition of nitrites, or any other hurdle, in addition to heat, used to preserve the product affects the target F value. Thus, for example, according to the International

Olive Council (IOC, 2004), fermented table olives packed in brine require a pasteurization process with an $F_{62.4°C}^{5.25°C}$ value of 15 min, while for commercial sterilization of unfermented olives darkened by oxidation, a required $F_{121.11°C}^{10°C}$ value of 15 min is recommended. Note the different reference temperatures and the different z values used to describe the requirements of the two processes. The difference in z values is due to the different target microorganisms: propionic acid bacteria characterized by a z value of 5.25°C and *C. botulinum* spores with a z value of 10°C. Different reference temperatures are used to provide a "meaningful" F value. Equation 2.16 can be used to convert one reference temperature to another. So, an $F_{62.4°C}^{5.25°C}$ of 15 min corresponds to an $F_{121.11°C}^{5.25°C}$ value of 6.56×10^{-12} min, a number difficult to comprehend. Usually, reference temperatures close to processing temperatures (which in turn are compatible with the severity of the thermal process needed) are used.

For acidic or acidified foods, target $F_{93.33°C}^{8.89°C}$ values suggested by Tucker and Featherstone (2011) are as follows: for products with pH < 3.9, 0.1 min; for 3.9 ≤ pH < 4.1, 1.0 min; for 4.1 ≤ pH < 4.2, 2.5 min; for 4.2 ≤ pH < 4.3, 5.0 min; for 4.3 ≤ pH < 4.4, 10.0 min; and for 4.4 ≤ pH < 4.5, 20.0 min. Note that the thermal processing literature uses temperature in degrees Fahrenheit. When feasible, we convert them to degrees Celsius. This sometimes gives rise to odd decimal numbers (we use two decimal digits). Thus, the reference temperature of 93.33°C and the z value of 8.89°C are temperature conversions from 200°F and 16°F, respectively.

A guide to required F for acidic products is also given by NCA (1968) and Holdsworth and Simpson (2008). In general, a 6-log reduction of the target microbial population is recommended for acidic foods, where processes are based on spoilage, non-health significant microorganisms (Tucker and Featherstone, 2011). In relation to the right-hand side of Equation 2.21, the F value required for a 6-log reduction is equal to

$$F_{T_{ref}}^{z} = 6 \times D_{T_{ref}} \tag{2.23}$$

A collection of relative $D_{T_{ref}}$ and z values for designing pasteurization processes for shelf-stable, high-acid fruit products has been presented by Silva and Gibbs (2004).

In the absence of appropriate data, the determination of the $F_{required}$ value is done through the TDT Curve. The methodology is described in detail in the literature (NCA, 1968). Briefly, it includes the following steps:

- *Preparation of spores of the target microorganism*: As the left-hand side of Equation 2.21 suggests, the F values of different microorganisms characterized by the same z value and experiencing the same time–temperature history are the same. Thus, a surrogate microorganism can be used in place of the target microorganism as long as it is characterized by the same z value; spores of PA 3679, a putrefactive anaerobe, are often used instead of *C. botulinum* spores.
- *Inoculation of the product under study with the spores*: Typically, an initial load of 10^5–10^6 spores per TDT can (a specially designed 208 × 006 metal can for such experiments) is used.
- *Selection of experimental conditions*: Typically, six temperatures and six processing times are selected based on the information of the thermal sensitivity of the target microorganism. If all times and/or all temperatures would result in the total destruction, or no destruction of the tested microorganism, no conclusions can be drawn. Processing times and temperatures should be chosen so that, in each temperature in some samples, microorganisms should be totally destroyed, and in some other samples they should survive after processing.
- *Heating six samples (e.g., TDT cans) for each time and treatment temperature*: Periodically remove samples and check for survivors.
- *Incubate the samples and check for survivors*: For example, for gas-producing microorganisms check for deformation of the lid of the TDT can.

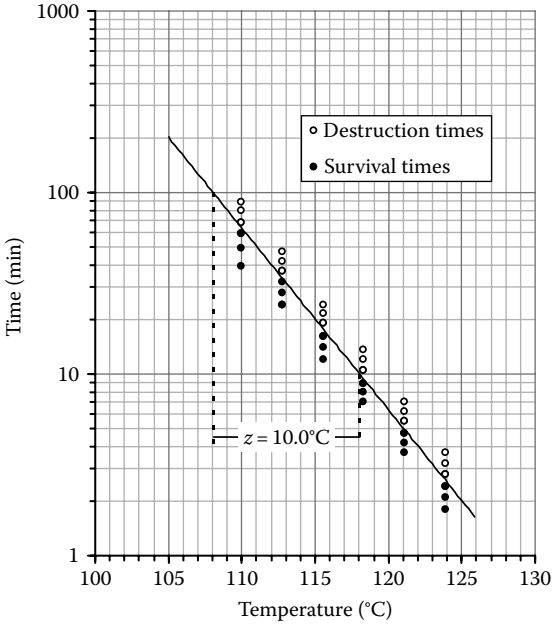


FIGURE 2.5 Thermal death time curve for target $F_{required}$ values determination.

- *Record the results*: Heating times at which no growth of microorganisms is observed in any of the six samples used are recorded as "*destruction times*"; otherwise, heating times which enabled the survival and growth of microorganisms are recorded as "*survival times*."
- *Plot the results*: On a semilogarithmic paper, plot destruction and survival times (on the logarithmic scale) against processing temperature (on the linear scale) as depicted in Figure 2.5. The straight "best fit" line that is above all survival times and at the same time below as many destruction times as possible defines the TDT Curve.

For a given microorganism, the TDT Curve is parallel to the Phantom TDT Curve, its slope being equal to $-1/z$. Each point on the TDT Curve defines required time–temperature combinations, that is, the required F value at a chosen temperature. In doing such experiments, a number of issues must be resolved, the main one probably being the assurance of constant sample temperature during processing. Again, the reader is referred to the NCA (1968) publication for further details.

2.3.2 *F* Value of a Process

The calculation of the F value of a process is based on Equation 2.21. The right-hand side of Equation 2.21 enables the calculation of $F_{process}$ by measuring the initial and final, at the end of the process, population of the target microorganism (*in situ* method) and knowing the kinetics of its thermal inactivation (D and z values). Any other substance or agent can be alternatively used in place of the target microorganism, as long as the corresponding z values are identical (time–temperature integration—*TTI* method). The left-hand side of Equation 2.21 enables the calculation of the $F_{process}$ value by measuring the product temperature evolution throughout the process (*physical–mathematical* procedures). The latter is the method of choice if such temperature data can become available. Relative discussion can be found in Stoforos and Taoukis (2006).

The calculation of the $F_{process}$ value through the evaluation of the integral of Equation 2.21 is rather straightforward. If experimental product temperature data during the thermal process are available, a numerical integration can be performed. Its accuracy can be controlled by the time step and the

method of integration used. If an analytical equation for product temperature predictions is used, the complexity of the equation will direct toward an analytical or a numerical evaluation of the integral. The first published procedure for thermal process calculations used experimental product temperature data and graphical integration for the evaluation of the integral (Bigelow et al., 1920). Since no assumptions about product temperature were made, the method was termed general method.

The ability of calculating the process F value serves a dual purpose. First, it enables the evaluation of the thermal process in terms of its objectives by comparing $F_{process}$ *with* $F_{required}$ (Equation 2.22). In thermal process calculation literature, this is sometimes called *first-type problem*. Second, it enables the design of a thermal process. That is, it allows for the calculation of the heating time required in order for a target $F_{required}$ value to be achieved. This is the *second-type problem*. The mathematical definition of the *second-type problem* is given as follows:

Splitting the integral of Equation 2.21 in two parts, one corresponding to the heating and the other to the cooling cycle of a thermal process, we obtain

$$F_{T_{ref}}^{z} = \int_{t=0}^{t=t_g} 10^{((T(t)-T_{ref})/z)}\,dt + \int_{t=t_g}^{t=t_{end}} 10^{((T(t)-T_{ref})/z)}\,dt \tag{2.24}$$

where

t_g is the time at the end of the heating cycle

t_{end} is the time at the end of the entire process

What we are looking for in designing a thermal process is to determine the heating time, t_g, so that the F value given by Equation 2.24 will be equal to the target $F_{required}$ value. Note that if we totally rely on experimental product temperature data for a single heating time, we will have no means of knowing the product temperature evolution if heating time is to be changed. In fact, this lack of predictive ability associated with the general method is the main drawback of the method. More specifically, in order to attack the second-type problem, general method suggests a "geometric similarity," that is, it assumes that the shape of the integrand (of the second integral of Equation 2.24) versus time curve during cooling is geometrically the same, irrespective of the total heating time. This is not true in general. An example of using the general method for heating time calculations is given by Stoforos and Taoukis (2006). The process F value for the product time–temperature data presented in Figure 2.4, calculated by the general method, is equal to 6.9 min.

A question yet to be addressed in relation to Equation 2.21 (or Equation 2.24) is, at which point inside the product are temperatures to be taken. When product temperature is not uniform, as with conduction heating products, each point will possess a unique $F_{process}$ value, which means that each point will be characterized by a different microbial (log) reduction. The point that receives the least effects of the heat treatment, in terms of microbial destruction, is termed "critical point." It is located at the geometric center of conduction-heated foods in cylindrical cans, or more precisely, at two doughnut-shaped regions located symmetrically along the vertical axis, slightly away from the geometric center (Flambert and Deltour, 1972) and toward the bottom of the container for natural convection-heated foods (Stoforos, 1995). Using computational fluid dynamics, the location of the slowest heating zone and the critical point within the product were assessed for several cases during thermal processing of table olives in still cans (Dimou et al., 2013). Some further discussion on this issue can be found, among others, in the NCA (1968), Holdsworth and Simpson (2008), and Tucker and Featherstone (2011) books.

If the critical point achieves the target microbial reduction, then the whole product will meet process requirements. Thus, an $F_{process}$ value can be based on time–temperature data at the critical point of the product. Such F values are single-point F values and sometimes are symbolized with F_c. On the other hand, design criteria can be based on the whole product. For this purpose, one must evaluate the surviving microbial population at each point in the product and by appropriately

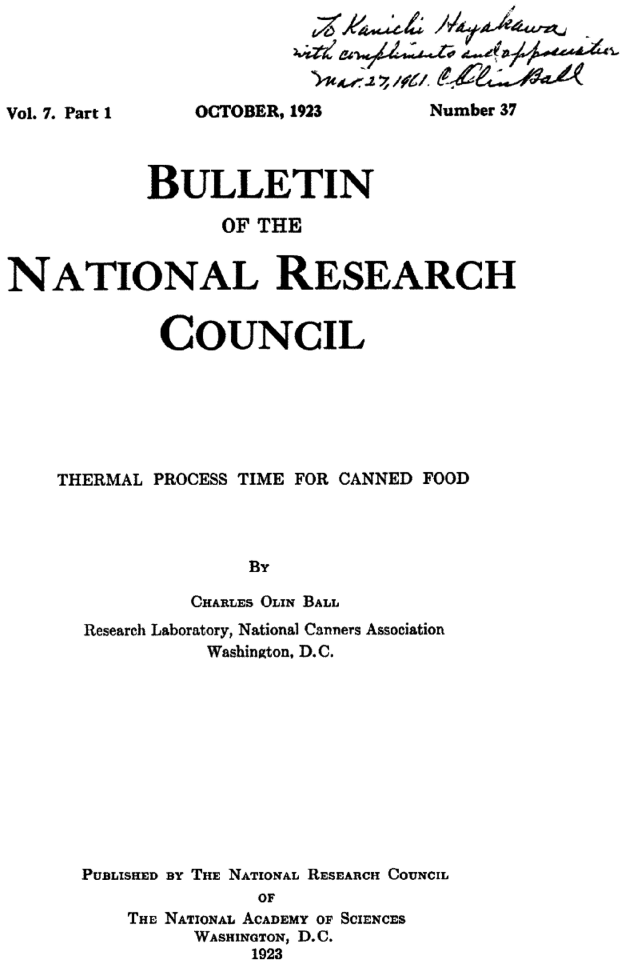
integrating such results, assess the microbial reduction over the whole product volume. Such F values are integrated F values, sometimes symbolized with F_s. While there is a preference for the single-point F_c value approach when microbial reduction (safety) is concerned, integrated F_s values are the only choice for most quality calculations cases. For example, the remaining vitamin content at the geometric center of a conduction-heated product is not representative of the vitamin content of the whole product; vitamin retention away from the geometric center, where the product is exposed to higher temperatures, will be much less compared to the center of the product. More discussion and a number of references on this issue are given by Stoforos (1995). Calculations based on F_c values constitute the most common approach for thermal process calculations and will be further discussed.

2.3.3 Ball's Formula Method

Due to the limitations of the general method, a number of thermal process calculation methodologies appeared in the literature (Stoforos et al., 1997). The common characteristic of these methodologies, termed *formula methods*, was the incorporation of an equation, *a formula*, to relate product temperature with time, so that one could transform time–temperature data to different conditions. Charles Olin Ball was a pioneer in this approach (1893–1970); while in graduate school at George Washington University (1919–1922), he did research on sterilization of canned foods for the National Canners Association (Valigra, 2011b). Soon after the introduction of the general method, Ball developed his method (Ball, 1923), which became the most widely used method in the United States for establishing thermal processes and the basis for all subsequently developed formula methods. Figure 2.6 is a scanned copy of a cover of the original publication being in the possession of the present author since 1996, courtesy of Kan-Ichi Hayakawa (1931–2009), a food engineering professor and a major contributor to the thermal processing literature. In fact, the product temperature profile depicted in Figure 2.4 was created using the empirical equations developed by Hayakawa (1970), based on experimental time–temperature data, to describe the product center temperature during the heating and the cooling cycles of a thermal process. A number of publications dealt with Ball's formula method (Merson et al., 1978; Stoforos, 1991, 2010). A brief working presentation of the method will be given in the next paragraphs.

Ball (1923) used the empirical parameters f and j to describe the time–temperature curves of any product during thermal processing. A rather extensive discussion on these parameters as well as their theoretical correlation to product properties and process conditions for a number of practical cases was made in Chapter 4 of the present Handbook (Kookos and Stoforos, 2014). The parameters f and j are related to the slope and the intercept of the heat penetration curves. When the difference between medium and product temperature is plotted, in the logarithmic scale of a semilogarithmic paper, versus time, both heating and cooling curves could be approximated by a straight line. Conventionally, medium temperature during the heating cycle is called retort temperature, symbolized by T_{RT}, whereas during cooling it is called cooling water temperature and is symbolized with T_{CW}. Traditionally, the heating curve ($T_{RT} - T$ vs. heating time) is plotted on a reversed logarithmic paper, with two y-axis scales, as shown in Figure 2.7. A similar plot is used for the cooling curve, where $T - T_{CW}$ versus cooling time data are used (Figure 2.8). The parameter f (f_h for heating and f_c for cooling) is defined as the time needed for the straight-line heating or cooling curve to traverse through a logarithmic cycle. The parameter j, a dimensionless correction factor, is related to the intercept of the straight-line heating or cooling curve. The j_h value is defined as

$$j_h = \frac{T_{RT} - T_A}{T_{RT} - T_{IT}} \tag{2.25}$$


To Kanichi Hayakawa
with compliments and appreciation
Mar. 27, 1961. C. Olin Ball

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BULLETIN
OF THE
NATIONAL RESEARCH
COUNCIL

THERMAL PROCESS TIME FOR CANNED FOOD

By

Charles Olin Ball

Research Laboratory, National Canners Association
Washington, D.C.

Published by The National Research Council
of
The National Academy of Sciences
Washington, D.C.
1923

FIGURE 2.6 Copy of a cover of the original publication of Ball's method (Ball, 1923) with Ball's hand writing.

with T_A being an extrapolated pseudo-initial product temperature at the beginning of heating defined as the intercept, with the temperature axis at time zero, of the straight-line heating curve, and T_{IT} is the initial product temperature (Figure 2.7). Similarly, j_c is defined as

$$j_c = \frac{T_B - T_{CW}}{T_g - T_{CW}} \tag{2.26}$$

with T_B being the extrapolated pseudo-initial product temperature at the beginning of cooling, and T_g is the actual product temperature at the beginning of cooling (equal to the product temperature at the end of heating) (Figure 2.8).

Based on the definitions given earlier, the equation for the straight-line portion of the heating curve becomes

$$\frac{T_{RT} - T}{T_{RT} - T_{IT}} = j_h 10^{-t/f_h} \tag{2.27}$$

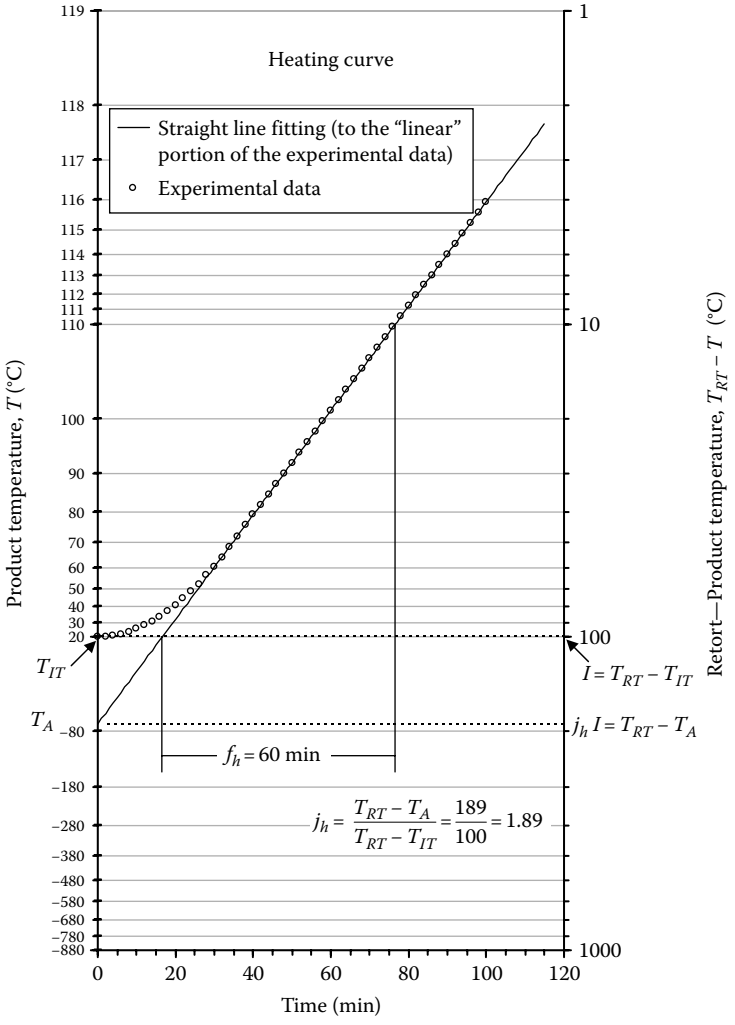

FIGURE 2.7 Typical heating curve, as traditionally plotted, based on heat penetration data presented in Figure 2.4 ($T_{RT} = 120°C$).

The reader should recognize Equation 2.27 based on similar equations presented in Chapter 4 of the present Handbook (Kookos and Stoforos, 2014). Equation 2.27 can be explicitly solved for product temperature to give

$$T = T_{RT} - j_h(T_{RT} - T_{IT})10^{-t/f_h} \tag{2.28}$$

Equation 2.27 (or 2.28) describes only the linear portion of the heating curve, that is, it approximates the heating curve only after some initial time lag. However, Ball (as well as all other investigators that proposed formula methods) used this equation to describe the entire heating curve since the thermal destruction taking place at the beginning of heating, where, under common commercial practices the temperature of the product has not yet reached lethal temperatures, is negligible.

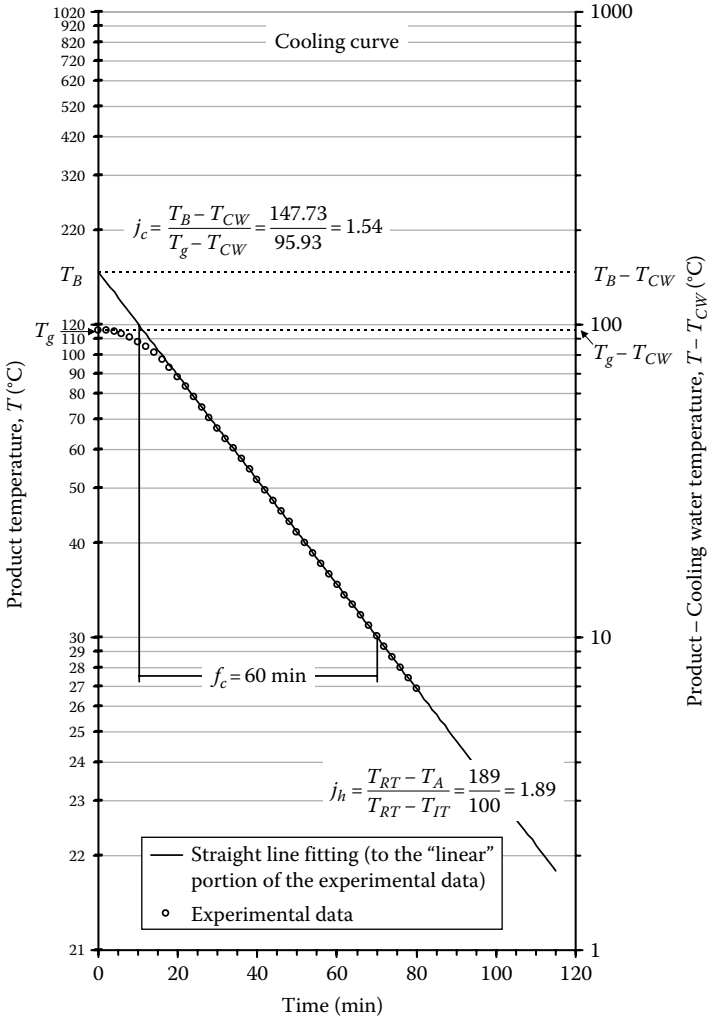

FIGURE 2.8 Typical cooling curve, as traditionally plotted, based on heat penetration data presented in Figure 2.4 ($T_{CW} = 20$°C).

In fact, Ball assumed that no microbial destruction takes place if the product temperature is more than 80°F lower than the retort temperature.

Solving Equation 2.28 for heating time, we obtain

$$t = f_h(\log(j_h(T_{RT} - T_{IT})) - \log(T_{RT} - T)) \tag{2.29}$$

Ball used the symbol B for the time at the end of heating, the symbol I for the initial temperature difference, that is,

$$I = T_{RT} - T_{IT} \tag{2.30}$$

and the symbol g for the temperature difference at the end of heating, that is,

$$g = T_{RT} - T_g \tag{2.31}$$

Under the definitions given earlier, at the end of heating, Equation 2.29 gives

$$B = f_h(\log(j_h I) - \log(g)) \tag{2.32}$$

Thus, from Equation 2.32, one can calculate the (required) heating time if the temperature difference (retort – product temperature) at the end of heating is known.

A similar, to Equation 2.28, equation was used to describe the linear portion of the cooling curve:

$$T = T_{CW} + j_c(T - T_{CW})10^{-t_c/f_c} \tag{2.33}$$

where cooling time, t_c, is used instead of processing time, t. Note that the cooling time is zero at the beginning of cooling, and with the definitions used throughout the chapter:

$$t_c = t - t_g \quad \text{or} \quad t_c = t - B \tag{2.34}$$

Contrary to the heating curve, the initial curvilinear part of the cooling curve, where the product is in the lethal temperature range, cannot be approximated by Equation 2.33, but it needs to be precisely evaluated. In fact, the main difference of the various proposed formula methods for thermal process calculations is based on the way they approach the initial part of the cooling curve (Stoforos et al., 1997). Ball used a hyperbola for the initial curvilinear portion of the cooling curve. For $0 \le t_c \le f_c \times \log(j_c/0.657)$, he used the following expression:

$$T = T_g + 0.3\,(T_g - T_{CW})\left[1 - \sqrt{1 + \left(\frac{1}{0.5275\log(j_c/0.657)}\right)^2\left(\frac{t_c}{f_c}\right)^2}\right] \tag{2.35}$$

Ball proceeded by substituting Equations 2.28, 2.33, and 2.35 into 2.24 and obtained a relationship between the F value and the heating time. Given the complexity of Equation 2.35, he evaluated the resulting integrals numerically. Before proceeding to the solution of the resulting equation, he did some conservative simplifying assumptions, the most important being the use of a fixed value of 1.41 for j_c and the use of $f_c = f_h$. He presented his results in a tabulated or graphical form (Ball, 1923, 1957; NCA, 1968). Instead of giving F versus B values, in order to significantly reduce the number of figures or tables involved, Ball gave f_h/U versus g or $\log(g)$ data, where U was defined as

$$U = F^z_{T_{ref}} F_i \tag{2.36}$$

for

$$F_i = 10^{((T_{ref} - T_{RT})/z)} \tag{2.37}$$

that is, $U = F^z_{T_{RT}}$, which means that Ball used T_{RT} as T_{ref}, in order to reduce the number of parameters involved. The only additional parameters used were the z value and the $T_{RT} - T_{CW}$ temperature difference, or $m + g$ according to Ball's nomenclature. For m defined as

$$m = T_g - T_{CW} \tag{2.38}$$

then

$$m + g = T_{RT} - T_{CW} \tag{2.39}$$

The final working f_h/U versus $\log(g)$ figures associated with Ball's method (NCA, 1968) are three figures for $m + g$ equal to 130°F, 160°F, and 180°F, each one having eight curves for eight different z values: 10°F, 12°F, 14°F, 16°F, 18°F, 20°F, 22°F, and 24°F. Note that since safety (instead of quality) was Ball's intention, the z values used were adequately covering the range of z values involved in microbial destruction calculations.

Corrections for cases where the retort temperature does not instantaneously reach the processing temperature, or when $f_c \neq f_h$, or when a straight line does not adequately describe the heating curve have been addressed by Ball (1923), but they are not considered within the scope of this chapter, and therefore, they will not be presented here. However, they have been discussed elsewhere (Stoforos, 2010).

The steps for solving *first-type problem*s (i.e., when looking for the F value of a given process) with Ball's method (or, in fact, any formula method) are

1. Given the heating time, B, calculate $\log(g)$ from Equation 2.32.
2. From Ball's figures for the $\log(g)$ value calculated in step 1, find f_h/U (for the appropriate z and $m + g$ values).
3. From the f_h/U value calculated in step 2, calculate the $F_{process}$ from the following equation (based on Equation 2.36):

$$F_{T_{ref}}^{z} = \frac{f_h}{(f_h/U)F_i} \tag{2.40}$$

The reverse procedure is followed for solving s*econd-type problem*s (i.e., when looking for the required heating time, B, for a given $F_{required}$ value). Giving explicitly, the steps involved

1. Based on the given required F value, calculate f_h/U from the following equation:

$$\frac{f_h}{U} = \frac{f_h}{F_{T_{ref}}^{z} F_i} \tag{2.41}$$

2. From Ball's figures for the f_h/U value calculated in step 1, find $\log(g)$ (for the appropriate z and $m + g$ values).
3. From the $\log(g)$ value calculated in step 2, calculate the heating time, B, from Equation 2.32.

To facilitate calculations and make Ball's method easier for computer implementation, regression equations were developed to substitute for Ball's figures (Stoforos, 2010). Thus, for thermal processes with $g \geq 0.1$°F, the following equation was proposed to relate f_h/U with $\log(g)$:

$$\log\left(\frac{f_h}{U}\right) = \frac{a_1}{1 + a_2 e^{-a_3(\log(g/z) - z/z_c)}} + \frac{a_4}{1 + a_5 e^{-a_6(\log(g/z) - z/z_c)}} + a_7 \tag{2.42}$$

for the values of the regression parameters a_1 to a_7 and z_c given in Table 2.1.

TABLE 2.1
Values for the Regression Coefficients of Equation 2.42

$m + g$ (°F)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	z_c (°F)
130	40.122199	38.533071	2.3715954	5.305832	2.8885491	0.63534158	–0.63814873	405.49832
180	22.01651	21.598294	2.4586869	38.202986	23.706331	0.49435142	–0.74859566	468.11021

From data by Stoforos (2010).

TABLE 2.2
Values for the Regression Coefficients of Equation 2.43

$m + g$ (°F)	b_1	b_2	b_3	b_4	b_5	b_6	z'_c (°F)
130	–0.088335831	–0.96375429	0.028257272	1.0711536	0.19518983	4.5699218	389.106
180	–3.3545727	–0.34453049	0.42100067	4.005721	0.13211471	3.2971998	389.48491

From data by Stoforos (2010).

Since Equation 2.42 is nonlinear, the following equation was proposed for the inverse problem, that is, to relate $\log(g)$ with f_h/U:

$$\log\left(\frac{g}{z}\right) = \frac{b_1}{1 + b_2 e^{-b_3 \log(f_h/U)}} + \frac{b_4}{1 + b_5 e^{-b_6 \log(f_h/U)}} + \frac{z}{z'_c} \tag{2.43}$$

for the values of the regression parameters b_1 to b_6 and z'_c given in Table 2.2. More details and additional information are given by Stoforos (2010).

The ratio of g/z is used in both Equations 2.42 and 2.43 following Hayakawa's (1970) approach. Note that the g and z values associated with Equations 2.42 and 2.43 were initially given in degrees Fahrenheit (see Tables 2.1 and 2.2 for the z_c and z'_c values, which are reported as initially calculated in °F), but since temperature difference ratios are used, degrees Celsius can be equally employed, as long as the z_c and z'_c values are converted to degrees Celsius. Regression coefficients for two $m + g$ values, namely 130°F (72.22°C) and 180°F (100°C), are given. For intermediate values, one can do a linear interpolation. For $m + g$ values outside the given range, one can use the closest $m + g$ value. Stumbo (1973) stated that a difference of 10°F in $m + g$ values introduces an error of the order of 1% in the F value.

2.3.3.1 Example Calculation

We will calculate the $F_{process}$ value for the data presented in Figure 2.4 and the associated f_h and j_h values from Figure 2.9, that is, for f_h = 60 min and j_h = 1.89. Further information include T_{IT} = 20°C = 68°F, T_{RT} = 120°C = 248°F, T_{CW} = 20°C = 68°F, and B = 100 min.

1. From Equation 2.32 we calculate

$$B = f_h(\log(j_h I) - log(g)) \Rightarrow \log(g) = \log(jI) - \frac{B}{f_h} \tag{2.44}$$

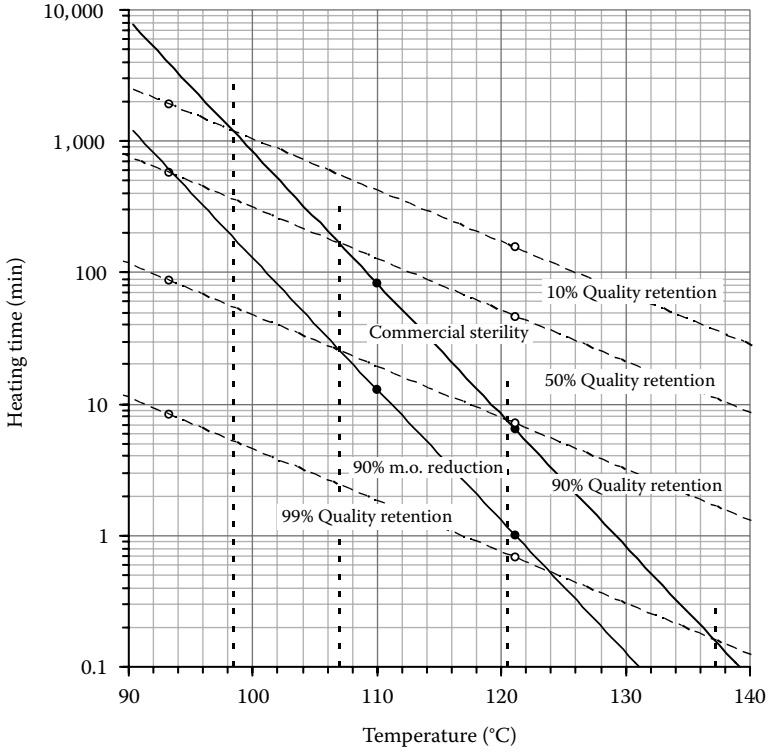

FIGURE 2.9 Time–temperature effects on quality and microbial (m.o.) destruction.

thus,

$$\log(g) = \log(1.89 \times (248 - 68)) - \frac{100}{60} \Rightarrow \log(g) = 0.8651 \Rightarrow g = 7.3294°\text{F}$$

2. From Equation 2.42, for z = 18°F and Table 2.1 coefficients for $m + g$ = 180°F (=$T_{RT} - T_{CW}$ = 248 – 68), we calculate

$$\log\left(\frac{g}{z}\right) - \frac{z}{z_c} = \log\left(\frac{7.3294}{18}\right) - \frac{18}{468.11021} \Rightarrow \log\left(\frac{g}{z}\right) - \frac{z}{z_c} = -0.4287$$

and

$$\log\left(\frac{f_h}{U}\right) = 0.8618 \Rightarrow \frac{f_h}{U} = 7.2748$$

3. From Equation 2.40, for T_{ref} = 250°F and for $F_i = 10^{(250-248)/18} = 1.2915$ (Equation 2.37), we finally calculate

$$F_{T_{250}}^{18} = \frac{f_h}{(f_h/U)F_i} \Rightarrow F_o = \frac{60}{7.2748 \times 1.2915} \Rightarrow F_o = F_{process} = 6.4 \text{ min}$$

We performed the aforementioned calculations in degrees Fahrenheit, as traditionally done in thermal process calculations literature. However, the use of the proposed Equations 2.42 and 2.43 allows direct calculations in degrees Celsius. Repeating the procedure in degrees Celsius, we have

$$\log(g) = \log(1.89 \times (120 - 20)) - \frac{100}{60} \Rightarrow \log(g) = 0.6098 \Rightarrow g = 4.0719°\text{C}$$

and for $z = 10°\text{C}$, and $z_c = 468.11021/1.8 = 260.06123°\text{C}$ we obtain

$$\log\left(\frac{g}{z}\right) - \frac{z}{z_c} = \log\left(\frac{4.0719}{10}\right) - \frac{10}{260.06123} \Rightarrow \log\left(\frac{g}{z}\right) - \frac{z}{z_c} = -0.4287$$

a value exactly the same as previously calculated, which leads to the same f_h/U and F_o values. It must be noted here that an attempt to introduce degrees Celsius for direct thermal process calculations by Shapton et al. (1971) did not receive wide acceptance.

Recall that calculations with the general method gave an $F_{process}$ value equal to 6.9 min. Thus, Ball's method calculations were close to those made by the general method (which can be considered as exact) and slightly conservative. This could be somewhat expected, given the assumptions associated with Ball's method and Hayakawa's (1970) empirical formulas. However, this conclusion should not be generalized.

2.4 THERMAL PROCESS OPTIMIZATION

So far, we presented the principles for establishing *process schedules*, that is, time–temperature combinations for thermal processing of foods. Classical publications such as the NFPA's Bulletins 26-L for metal containers (NFPA, 1982) and 30-L for glass containers (NFPA, 1984) as well as Lopez's (1987) three-volume work entitled *A Complete Course in Canning and Related Processes* suggest process schedules for a variety of products.

It is somewhat intuitively understood that what can be achieved in terms, for example, of microbial destruction, by heating a product at a certain temperature for a certain time, can also be accomplished by heating the product at a higher temperature for a shorter time. Due to differences in temperature sensitivity of quality factors compared to undesirable agents, selection of an optimum process schedule, that is, a time–temperature combination that will provide the desirable degree of safety with minimal quality degradation, is possible.

It is generally accepted that quality degradation follows first-order kinetics, and it can be described by the same kinetic parameters ($D - z$ values or $k - E_a$ parameters) as microbial destruction. Table 2.3 gives practical ranges for z, E_a, and $D_{121°\text{C}}$ values for several quality and safety factors (Lund, 1977). An extensive, comprehensive list with kinetic parameters for microbial

TABLE 2.3
Kinetics Parameters for Several Quality and Safety Factors

Constituent	z (°C)	E_a (kcal/mol)	$D_{121°\text{C}}$ (min)
Vitamins	25–31	20–30	100–1000
Color, texture, and flavor	25–45	10–30	5–500
Enzymes	7–56	12–100	1–10
Vegetative cells	5–7	100–120	0.002–0.02
Spores	7–12	53–83	0.1–5.0

From data by Lund (1977).

inactivation in a variety of products as well as for a number of quality attributes' degradation is given by Holdsworth and Simpson (2008). The high D values that characterize the majority of the quality parameters compared to the corresponding values for microorganisms (Table 2.3) lead to a high degree of quality retention for most thermally treated products. Differences in z (or, equivalently, E_a) values allow for process optimization, as it will be illustrated in the following examples.

2.4.1 Constant Product Temperature

Let us, at the moment, restrict our discussion to cases where the product temperature is constant throughout the entire thermal process, a situation that can be anticipated during aseptic processing of homogeneous liquid products. Let us further assume that the target microorganism is characterized by a z value equal to 10°C and a $D_{121.11°C}$ equal to 1 min, and commercial sterility is achieved for a required F_o value of 6.4 min. Based on these values one can plot the Phantom TDT Curve (labeled as the "90% m.o. reduction" line in Figure 2.9) and the actual TDT Curve (labeled as the "commercial sterility" line in Figure 2.9).

On the same plot, we can superimpose the retention of a quality parameter characterized by the following parameters: z = 25.56°C (46°F) and a $D_{121.11°C}$ = 154 min. Dotted (regular) lines showing different time–temperature combinations for 10%, 50%, 90%, and 99% quality retention are plotted in Figure 2.9. The intersection of the "commercial sterility" line with the quality retention lines (vertical bold dotted lines in Figure 2.9) gives time–temperature combinations that ensure safety (being on the "commercial sterility" line), but result in different percent retention of the quality parameter (Table 2.4). All calculations were performed through Equations 2.7 and 2.11 and their combination.

For these example data, it is evident (Table 2.4) that high-temperature short-time (HTST) processes preserve better product quality as compared to low-temperature long-time (LTLT) processes. Nevertheless, before generalizing one must remember that we analyzed a constant product temperature case. As a matter of fact, if product temperature is uniform (that is, there is no spatial temperature distribution within the product, although there can be time varying product temperature), the above conclusion still holds. Furthermore, we used a z value for the quality index higher than the z value of the safety parameter. HTST processes have less detrimental effect on parameters characterized with high z values, compared to LTST ones. Thus, the inactivation of a particular enzyme, characterized by a high z value, might be the aim of a HTST process.

2.4.2 Conduction-Heated Foods

If the product temperature is not uniform, one has to integrate the effects of temperature on each portion of the food in order to calculate volume average quality retention values. Mathematically

TABLE 2.4
Time–Temperature Combinations for Constant Product Temperature Thermal Processes Targeting F_o = 6.4 min

Time (min)	Temperature (°C)	Quality Retention (%)
1189.94	98.42	10
165.56	106.98	50
7.50	120.42	90
0.16	137.19	99

Quality retention is based on z = 25.56°C (46°F) and $D_{121.11°C}$ = 154 min.