ACIDIFIED VS. CONVENTIONAL THERMAL PROCESSING OF LOW-ACID VEGETABLES: INFLUENCE OF RECIPROCATING AGITATION ON PROCESS TIME AND PRODUCT QUALITY

By

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DEDICATED TO MY MOTHER

ABSTRACT

Thermal processing schedule for low acid foods (LAF) is more severe than that for acid or high acid foods (HAF) because of the effectiveness of pH (pH < 4.5) associated with HAF to control the growth and activity of microbial spore forming bacteria. Hence, the hypothesis that if the LAF can be acidified (ALAF) to bring their pH to below 4.5, they can be processed like HAF. This permits the processing of ALAF under pasteurization conditions providing the opportunities for milder processing. The main objective of this study was to evaluate the quality advantages of acidified low acid food thermal processing (ALAFTP) in comparison to the conventional thermal processing of low acid foods (LAFTP). An additional objective of this investigation was to study the combined effect of ALAFTP and reciprocating agitation thermal processing (RATP) on the process time and product quality. The thermal processes were given to low acid food packed in glass jars to evaluate the influence of ALAFTP and RATP on the heating rate index, heating lag factor and the resulting processing times for both, LAFTP and ALAFTP, followed by quality retention associated with each processing condition. LAFTP was established to achieve commercial sterilization (Fo value of 5.0 min at 121 °C). Whereas ALAFTP was set to attain an equivalent pasteurization process (Fo value of 10.0 min at 90 °C). The low acid foods used in this study were mushrooms and chickpeas. Processing conditions included three processing temperatures (115, 120, 125 °C for LAFTP and 90, 95 and 100 °C for ALAFTP) and three reciprocating agitation frequencies (0, 1.0 and 2.0 Hz).

As expected, it was found that the rate of heat penetration increased as the frequency of agitation augmented. The results showed a similar advantage as the processing temperature increased. The tested quality parameters (color, texture and antioxidant activity) retained by ALAFTP were substantially higher than that of LAFTP. The most significant advantage was realized when ALAFTP and RATP were combined. In this combination, the optimum processing temperature and reciprocating frequency for maximum quality retention were 100 °C and 1 Hz, respectively. It was noted that the application of 2 Hz of reciprocation frequency damaged the product quality due to an excessive collision rate of food particles in the jar. To our knowledge, this is the first study that combined ALAFTP and RATP.

RÉSUMÉ

Le programme de traitement thermique des aliments peu acides (LAF) est plus sévère que celui des aliments acides ou très acides (HAF) en raison de l'efficacité du pH (pH < 4,5) associé au HAF pour contrôler la croissance et l'activité des bactéries microbiennes sporulées. D'où l'hypothèse que si les LAF peuvent être acidifiés (ALAF) pour amener leur pH en dessous de 4,5, ils peuvent être traités comme les HAF. Cela permet le traitement de l'ALAF dans des conditions de pasteurisation offrant des possibilités de traitement plus doux. L'objectif principal de cette étude était d'évaluer les avantages qualitatifs du traitement thermique des aliments peu acides acidifiés (ALAFTP) par rapport au traitement thermique conventionnel des aliments peu acides (LAFTP). Un objectif supplémentaire de cette enquête était d'étudier l'effet combiné de l'ALAFTP et du traitement thermique par d'agitation réciproque (RATP) sur le temps de traitement et la qualité du produit. Les processus thermiques ont été appliqués à des aliments peu acides emballés dans des bocaux en verre pour évaluer l'influence de l'ALAFTP et de la RATP sur l'indice de vitesse de chauffage, le facteur de retard de chauffage et les temps de traitement résultants pour LAFTP et ALAFTP, suivis de la rétention de qualité associée à chaque condition de traitement. LAFTP a été créé pour obtenir une stérilisation commerciale (valeur Fo de 5,0 min à 121 ° C). Alors que ALAFTP a été réglé pour atteindre un processus de pasteurisation équivalent (valeur Fo de 10,0 min à 90 °C). Les aliments peu acides utilisés dans cette étude étaient les champignons et les pois chiches. Les conditions de traitement comprenaient trois températures de traitement (115, 120, 125 °C pour LAFTP et 90, 95 et 100 °C pour ALAFTP) et trois fréquences d'agitation réciproque (0, 1,0 et 2,0 Hz).

Comme on pouvait s'y attendre, on a trouvé que la vitesse de pénétration de la chaleur augmentait à mesure que la fréquence d'agitation réciproque augmentait. Les résultats ont montré un avantage similaire à mesure que la température de traitement augmentait. Les paramètres de qualité testés (couleur, texture et activité antioxydante) retenus par l'ALAFTP étaient nettement supérieurs à celui du LAFTP. L'avantage le plus significatif a été réalisé lors de la fusion de l'ALAFTP et de la RATP. Dans cette combinaison, la température de traitement optimale et la fréquence de réciproque pour une rétention maximale de la qualité étaient respectivement de 100 °C et 1 Hz. Il a été noté que l'application de 2 Hz de fréquence de réciproque endommageait la

qualité du produit en raison d'un taux de collision excessif des particules alimentaires dans le bocal en verre. A notre connaissance, il s'agit de la première étude qui associe ALAFTP et RATP.

CONTRIBUTION OF AUTHORS

Parts of this research have been presented as a poster in 2022 at the Northeast Agricultural and Biological Engineering Conference (NABEC), Maryland, USA. Some parts were also submitted as a manuscript to the Institute of Thermal Processing Specialists (IFTPS) Charles R. Stumbo Student Paper Competition, 2023. The manuscript was titled 'Acidified vs. conventional thermal processing of chickpeas and mushrooms: quality retention under the influence of reciprocating agitation' and was awarded 2nd place winner. Three authors have contributed towards this research and their contributions are as follows:

Mr. Ali Asgar Rampurwala is the M.Sc. candidate who is a student at McGill University, pursuing the program 'Food Science and Agricultural Chemistry'. He conducted experiments, gathered and analyzed data, and represented result under the guidance of his supervisor. He drafted the thesis, poster and manuscripts for scientific conferences and publications.

Dr. Hosahalli S. Ramaswamy is the supervisor under whose guidance the research was conducted. He guided the M.Sc. candidate throughout the research by providing funding for the research, providing the special processing equipment, supervising the experiments, reviewing the results, and final editing the thesis. He also supported in editing the poster and manuscripts prepared for conferences and publications.

Dr Ali R. Taherian is the research associate working at the laboratory used by the M.Sc. candidate. He supported the M.Sc. candidate by providing help with experimentation methods, reviewing results, and editing the thesis. He also guided the candidate in editing the poster and manuscripts prepared for conferences and publications.

LIST OF PUBLICATIONS AND PRESENTATIONS

Part of this thesis has been presented / submitted as a poster at the following scientific conferences:

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NOMENCLATURE

A	Absorbance
a*	Redness or greenness
b*	Blueness or yellowness
E	Total color difference
F_h	Heating rate index, min
Fo	Process lethality, min
j_{ch}	Heating lag factor
L*	Lightness
T	Temperature, °C
U	Overall heat transfer coefficient, W / (m^2 °C)
w	Weight, (kg m) / s^2

Subscripts

ih	Initial heating
o	Reference
pih	Pseudo-initial heating
R	Retort
s	Sample

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CHAPTER 1

INTRODUCTION

Thermal processing is an extensively used method for processing of food. It has proven to be a highly effective preservation technique, as well as a solution to make food safe for consumption. This process was introduced in 1810 by Nicolas Appert, a French inventor, and was referred to using various terms like ‘canning’ and ‘appertization’. Appert simply sealed food in glass jars and placed it in boiling water for a certain duration. Due to its simplicity, this method was adopted by many to preserve their food. However, the reason behind the success of this method could not be explained until 50 years later when Louis Pasteur, a French chemist and microbiologist, reported that this heat treatment inactivated microorganisms that spoiled food. In 1920, Bigelow categorized microbial spores according to the optimum pH for their growth, and reported that they could withstand only a specific amount of heat until inactivated. This concept was further developed in the following years by researchers all over the world. Like every food processing technique, thermal processing comes with its drawbacks – heat treatment usually softens the food commodity and brings undesirable changes to its color. Nevertheless, the side-effects of thermal processing can be controlled and minimized to a significant extent, making this method the most popular over a large variety of food items.

There are several methods of heat treatments that vary according to the requirements of the product. These methods include pasteurization, commercial sterilization, cooking, and blanching. Pasteurization is a process where the food commodity is held at a high temperature (< 100 °C) for a duration of time to inactivate harmful microorganisms, then cooled immediately. As spores are not inactivated, low-acid pasteurized foods are stored at refrigerated conditions to avoid spoilage by almost entirely preventing germination of most spores. Whereas high-acid pasteurized foods are shelf-stable as the high-acid environment prohibits the activity of most spores. Food products like milk, fruit juice and eggs are pasteurized. For commercial sterilization, the product is exposed to a much higher temperature (> 110 °C) and held for a predetermined amount of time to destroy all spoilage and disease-causing microorganisms and their spores. Foods that are commercially sterilized include all canned food products like

vegetables, meat, poultry, egg and fish. The primary focus of cooking is to improve the taste, texture and color of food by heating it to a high temperature. Blanching is another heat treatment that mainly aims to inactivate enzymes present in a food sample. This is also an important pre-treatment used in canning of food as it provides several benefits other than inactivating enzymes. While all these methods are heat treatments, thermal processing generally refers to pasteurization and commercial sterilization only, as its primary objective is to inactivate microorganisms in food to preserve it and improve its safety.

Being the most threatful bacteria concerning food safety in canned food, *Clostridium botulinum* is designated to be the target bacteria in thermal processing (Esty and Meyer, 1922). While commercial sterilization inactivates spores of this bacteria, it makes use of high temperatures that degrade the quality of the product. However, the same spores remain inactive in high-acid conditions ($pH \leq 4.6$) (Tola, 2014; Tola and Ramaswamy, 2018). Thus, acidified thermal processing aims to convert low-acid foods to high-acid foods by acidification, resulting in inhibition of the activity of bacterial spores. The remaining vegetative microorganisms are inactivated by a milder process called pasteurization, which uses lower temperatures than commercial sterilization and retains much more quality of the product.

There are several steps involved in the present method of thermal processing. Initially, the food commodity is washed to remove dirt and chemicals like pesticides and fertilizers from its surface. After washing the food item, it is blanched to inactivate enzymes, remove air from its tissues and to achieve many more of such benefits. As blanching offers multiple advantages (enzyme inactivation, expelling intracellular gases, compacting, cleansing, etc.), it is an important step in thermal processing. The blanched products are filled into containers and covered with an appropriate liquid as a heat transfer medium. For low-acid foods, generally, the canning liquid is a weak sugar-salt solution. Whereas a sugar solution is used for high-acid foods such as fruits. The canning liquid is poured into the container over the blanched food pieces while the liquid is hot. This is known as hot fill. The cans are then sent through a conveyor steam box (exhaust box) which pushes out air from the container, after which the container is sealed instantly to block air from entering back into the container. The container is then treated at a

specific retort process temperature for a specific duration to kill the target microorganisms. Once treated, the containers are immediately cooled to avoid any extra heat treatment.

While thermal processing is necessary for food safety and preservation, it is important to realise its drawbacks. Many studies have reported that this process is generally destructive to the quality of food as heat can bring changes in certain compounds that are responsible for the product's structure, appearance and nutritional content (Taherian and Ramaswamy, 2009; Rodriguez-Amaya, 2019). The texture is degraded as pectic structures are broken down and other constituents like starch and proteins undergo a change in their structures. The color of processed food changes as color-imparting pigments are deteriorated. The overall nutritional content of food also changes because of the breaking down heat-sensitive nutrients like vitamin C and vitamin B1 (thiamine).

The convenience of canned food offered to consumers has increased its demand and has motivated the industry towards rapid and notable developments in thermal processing. Naturally, the consumers prefer having better quality of food, along with the primary safety goal of this process. As heat treatment degrades the quality of food in terms of its texture, color and nutritional content, the food industry now shifts its focus on optimizing the process to better retain the quality parameters of thermally processed foods. As nutrients are less sensitive to heat than microorganisms, the concept of high temperature short time (HTST) was favored as a means of producing high quality processed food (Holdsworth, 1985; Ramaswamy and Marcotte, 2006). This method aims to inactivate the microorganisms rapidly by holding the container at a high temperature for a short time, while affecting the nutrients the least. Another technique that is similar to HTST is ultra-high temperature (UHT). This method uses a temperature even higher than HTST and the product is held at that temperature for a shorter duration. However, UHT produces commercially sterile food that has lower quality than HTST (pasteurized) food due to the treatment's severity.

In order to reduce the processing time, several methods of agitation have proven to increase forced convection in the containers and consequently, increase the rate of heat transfer (Rattan and Ramaswamy, 2014). Agitation methods include fixed-axial, biaxial, end-over-end and

reciprocating agitation. It was reported that the overall heat transfer coefficient for reciprocating agitation increased with the highest proportion when the rate of agitation was increased, as compared to other methods of agitation (Singh et al., 2018). Therefore, a part of this study focuses on analysing the effect of reciprocating agitation on processing time and the corresponding product quality retained. In combination with reciprocating agitation, this study also focuses on higher retention of the product's quality by using acidified thermal processing.

Several studies have evaluated the effect of end-over-end and axial agitation on thermal processing of low acid foods like potatoes, carrots, tomato puree, radishes and green beans (Abbatemarco and Ramaswamy, 1994; Dwivedi and Ramaswamy, 2010; You et al., 2016). Reciprocation agitation is relatively more recent. Singh and Ramaswamy (2015), Singh et al. (2015a), Singh et al. (2015b), Singh and Ramaswamy (2016) and Singh et al. (2016) have evaluated RATP processes and demonstrated it to offer significant advantage for quality factor retention as compared to other methods of agitation processing. Research on reciprocating agitation and acidified thermal processing of mushrooms and chickpeas is scarce. Further, the combination of these two processes has not been studied. Therefore, the general objectives of this research are:

1. To evaluate the influence of reciprocating agitation on heat penetration characteristics of mushrooms and chickpeas.
2. To study and compare the effect of acidified thermal processing with the conventional method of thermal processing, in presence and absence of reciprocating agitation, in terms of processing time and product quality of mushrooms and chickpeas.

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CHAPTER 2

LITERATURE REVIEW

2.1 Thermal processing

2.1.1 General overview

Thermal processing is one of the most common methods of microbial inactivation of food. It involves the heating of food in a closed system for a specific duration of time. This process is also called as ‘canning’ as it is carried out in hermetically sealed containers like metal cans and glass jars. This closed system defends processed food against recontamination during storage. Thermally processed food is called as ‘commercially sterile’, which means that there is no viable microorganism present in the product that can grow at room temperature. Thermal processing does not inactivate all microorganisms – it only inactivates the ones that can potentially contaminate food at commercial storage condition (Owusu-Apenten and Vieira, 2022). These microorganisms involve mesophilic microorganisms that can spoil food or harm our health on consumption. As canned food is commercially stored on shelves at room temperature, mesophilic microorganisms are the primary target.

The cans / jars contain a particle-in-fluid phase, where solid pieces of food are suspended in a solution called the canning liquid. A small volume of the container is left empty at a vacuum condition to provide headspace for expansion of contents and to facilitate product agitation. This is because air is removed to avoid any oxidation reactions and any growth of aerobic microorganisms. Thus, anaerobic microorganisms can still grow and need to be focused upon. The most dangerous anaerobic bacterium is *Clostridium botulinum*, which is a spore-forming, gram positive bacteria that produces a neurotoxin that leads to botulism, a fatal disease (Lund and Peck, 2013). *Clostridium botulinum* which is a mesophilic, anaerobic bacterium has an appropriate environment to thrive in the containers used for thermal processing.

2.1.2 History of thermal processing

Over the past years, terms such as canning, sterilization and preservation were used to describe the process of microbial inactivation of food in sealed containers, although other containers like glass jars, retortable pouches, semi-rigid plastic containers have all been included in the same context. As time passed, the use of a more appropriate and general term was imperative, and this process is now known as thermal processing.

The process was discovered in 1810 by Nicolas Appert, a French inventor. This was done in response to the government calling out for methods to preserve food for the country's military use. Appert used a glass jar in which he kept food and tightly sealed the lid. The sealed jar was heated to a specific temperature, held at that temperature for a certain duration and kept sealed until use. This method was widespread and began to be used ever since due to its simplicity. However, the reason behind the success of this method was unknown until 1864 when Louis Pasteur, a French chemist and microbiologist, showed that heat inactivated microorganisms that contaminated food. The next major discovery was made by Bigelow and Esty (1920), who categorized microbial spores according to the pH level they grow at and the amount of heat they can withstand. In 1920, Bigelow and Ball developed a method to calculate the minimum sterilization required to process food. Collin Ball further developed the method in 1923. After few more developments to this method, Stumbo improved Ball's formula method and made it more adaptable and accurate in the 1950s. This concept has been refined over the past few years to make it more efficient.

In the last 3 decades, thermal processing has evolved immensely. The concept of agitated thermal processing has been studied in depth with various modes of agitation, including end-over end, axial and reciprocating motions (Singh et al., 2018). Furthermore, each mode of agitation has been uniquely developed to achieve higher rates of heat transfer and lower quality loss. For example, effects of reciprocating agitation had been studied for different Can orientations (Singh and Ramaswamy, 2015) and fixed axial agitation was modified to free axial (bi-axial) agitation (Dwivedi and Ramaswamy, 2010) to provide a higher rate of heat transfer and prevent clumping of particles on container walls.

2.1.3 Steps involved in thermal processing

2.1.3.1 Washing

Raw samples obtained from the farmers are usually not processed at all. In addition to that, some samples are not directly sold after being harvested, they could rather be stored for a long duration to balance the market's demand and supply, or it could be stored for transportation purposes to increase the reach of selling a product. Due to time spent in storage and handling, the food item gets dirty by being exposed to the environment. Another reason for the product to be externally contaminated could be its production method. The use of pesticides and fertilizers could potentially remain on the products body and cause harm to humans on consumption. Many studies have reported the risks of cancer due to consumption of pesticides. In fact, this has been associated to breast, liver, prostate, esophageal, lung and skin cancer (Gilden et al., 2010; Mostafalou and Abdollahi, 2013). Long exposure to pesticides has also proven to disrupt the reproductive system as they have been found to act as endocrine-disrupting chemicals (Zlatnik, 2016). Extensive exposure to nitrates and nitrites through food items due to the use of chemical fertilizers has also been associated with higher risks of Alzheimer's disease and diabetes mellitus (Anushree et al., 2022).

For all these health hazards, washing the sample before any other step involved in thermal processing is highly essential. Washing or soaking with water or other solutions of chlorine, ozone, acetic acid and brine extract such harmful chemicals and reduce its toxicity (Bajwa and Sandhu, 2014). It must be noted that soaking of sample could also have another usage – it could be done for hydration of the sample too. Washing and soaking could be done for various durations of time depending on the type of sample, method of production and its originating location. These raw food items are usually cover with mud, which carries pesticides and fertilizers. Thus, washing off the dirt in the first place is an efficient way to get rid of these dangerous chemicals. Lozowicka et al. (2016) have shown how a large number of pesticides used in strawberry production could be removed using ozonated water.

2.1.3.2 Blanching

One of the most important steps of thermal processing is blanching. It offers several benefits and therefore, it is a mandatory process. The advantages offered by blanching are as follows:

i. Inactivation of enzymes

The primary goal of blanching is to inactivate enzymes that could spoil food in several ways. Enzymatic browning leads to degradation in the quality of food during transportation, storage and heat treatment. It also leads to off-flavors, off-odors and unwanted changes in the color and texture. Blanching also inactivates enzymes that could damage the food item through other spoilage reactions. Another advantage offer by blanching is that it inactivates some of the microbial contaminants. A study showed that the carotenoid content of processed paprika and carrots was significantly higher as compared to the ones dried without blanching (Ramesh et al., 1999). Another study reported that frozen carrots that were not blanched had an undesirable taste that was caused by enzymatic activity (Kidmose and Martens, 1999).

ii. Removal of air from the tissues

As we aim to remove oxygen completely from the containers, we must ensure that air trapped in the tissues of food is forced out. If this is not done, air would be released into the container during thermal processing and remain trapped in the container, disturbing the anaerobic condition. Further, air is a strong insulator and it would reduce the rate of heat transfer during heat treatment. Therefore, removing air from tissues of food is extremely important. This would also avoid any oxidation reactions of food during storage, production of any deformed containers, and corrosion of material if metallic cans are used (Xiao et al., 2017).

Another reason to remove air from the sample is to consider the initial size reduction on heat treatment. If the air is not removed, the size of the sample would reduce during heat

treatment in the sealed container and most of the container's volume would be filled with air and the canning solution, rather than food particles. Thus, removal of air would account for the initial size reduction and allow one to fit more food particles in the container.

iii. Reduction in the rate of browning reactions

Enzymatic browning reactions are reduced by the inactivation of enzymes. However, non-enzymatic browning reactions (Maillard reaction and caramelization) could still take place and bring unwanted changes to the product (Jaeger et al., 2010). These non-enzymatic browning reactions are possible in the presence of reducing sugars only. The rate of these reactions is controlled by the reducing sugar content in the food item. Blanching reduces the reducing sugar content in food and consequently, reduces the rate of non-enzymatic browning reactions. Mestdagh et al. (2008) reported that blanching reduced the reducing sugar content in potatoes and acrylamide formation in fried potatoes was reduced as a result. This reduced the formation of off-colors and reduced the carcinogenic threat caused by acrylamide.

iv. Removal of toxic residues and antinutritional content

It is common for farmers to use toxic chemicals in the production of food to obtain a better crop yield and better quality of products too. These chemicals include pesticides and fertilizers. While washing the food item could remove some of these toxic residues, blanching helps in further removal or disintegration of these contaminants (Chung, 2018). Since blanching commonly makes use heat, these contaminants are also degraded due to mild heat treatment. The heat could also increase the solubility of such contaminants in the blanching solution. In addition to residues of pesticides and fertilizers, blanching also assists in the removal of the antinutrient content of some foods (Dagostin, 2017). Mozzoni et al (2009) reported that 5 minutes of blanching reduced the trypsin inhibitory activity by 88%. Another study also showed that trypsin inhibitors in soybean milk were reduced by blanching (Yuan et al., 2008). Chung et al. (2011) reported that the nitrate and

nitrite contents of cabbage, spinach and celery were reduced considerably after blanching.

v. Other advantages of blanching

Blanching also offers minor benefits such as cleaning the surface of food, inactivating parasites and their eggs and separating damaged food pieces and foreign material by floating or drowning. It also reduces the microbial load by acting as a mild heat treatment, and aids in peeling of certain foods like tomatoes, potatoes and peanuts.

Blanching is done using several methods with each method providing unique benefits in addition to the general advantages it offers. The methods of blanching are listed as follows (Xiao et al., 2017; Wang et al., 2017):

i. Hot water blanching

Hot water blanching is one of the most commonly used methods for blanching food. It is a simple and efficient blanching method. In a typical hot water blanching process, food pieces are submerged into water (or the blanching solution) and held like that for several minutes. The temperature of the blanching solution is generally between 70 °C and 100 °C. While hot water blanching is a simple method, it generates a lot of wastewater as nutrients from food are diffused into the blanching solution, which needs to be changed after few uses or each use. It was reported that more than 10% potato solids were lost after 2 minutes and 9 seconds of hot water blanching at boiling temperature. (Mukherjee and Chattopadhyay, 2007). Replenishing the blanching solution ensures that each batch of food is blanched uniformly.

Although hot water blanching offers several benefits, it has some disadvantages too. It can lead to the degradation of some heat-sensitive substances like aroma and flavor compounds (Xiao et al., 2017). It also results in wastewater that has a high concentration of sugars, proteins, carbohydrates, soluble solids and water-soluble minerals. If not

treated before discharging it, this wastewater could cause environmental pollution. Thus, treatment of used blanched solution is required after hot water blanching.

ii. Steam blanching

Steam blanching makes use of superheated steam to blanch food. Initially, the pieces of food are at a temperature lower than steam. This causes steam to condense on the surface of food and a large amount of latent heat is absorbed by this layer of condensation. The temperature of food then increases steadily due to the heat transferred by steam, and the effects of blanching take place.

When compared to hot water blanching, steam blanching is inexpensive. Roy et al. (2009) reported that it also retains most of the water-soluble content of food as there is no leaching effect. The rate of heat transfer during steam blanching is lower than hot water blanching because of the condensation layer formed on food. This forces steam blanching to use a much higher blanching time, which degrades the texture of food because of softening of its tissues.

iii. High-humidity hot air impingement blanching

High-humidity hot air impingement blanching (HHAIB) is a relatively new method of blanching. It combines the advantages of steam blanching and impingement technology. This combination offers multiple benefits such as low loss of solids and a highly efficient and rapid blanching treatment. HHAIB involves the impingement of a jet of high-humidity hot air on the surface of food at a high velocity, resulting in a high rate of heat transfer. Like steam blanching, in HHAIB, the product is heated by superheated steam or high-humidity hot air, rather than being immersed in water. Thus, loss of solids is lowered as the effect of leaching is minimized. Bai et al. (2013) reported that a substantial amount of vitamin C was retained when apple pieces were blanched using HHAIB to completely inactivate polyphenol oxidase.

iv. Other methods of blanching

Several other blanching methods include microwave-assisted blanching, radio frequency blanching, ohmic blanching and infrared blanching. Microwave-assisted blanching (MAB) makes use of microwaves to provide heat into food commodities. Benefits of MAB include reduction in blanching time, lower energy requirements, retention of more nutrients and bioactive compounds, lower solid loss and higher rates of heat transfer due to deep penetration of heat into the food commodity (Dorantes-Alvarez et al., 2017). Radio frequency blanching also offers higher penetration depth and faster rates of heat transfer. Ohmic blanching is based on the passage of electrical current through the food commodity, which acts as an electrical resistance (Icier, 2003). This blanching technique also offers rapid heat transfer and minimal solid loss as compared to the conventional hot water blanching (Icier et al., 2006). Infrared blanching makes use of infrared rays to provide the required heat treatment for blanching. This employs fairly simple equipment, making it a simple blanching method itself (Bingol et al., 2014).

2.1.3.3 Hot fill

Once the blanched samples are placed into the container, it must be covered with the canning solution. Before filling the container, the canning liquid is heated up to 85 – 95 °C. This ensures that the liquid is steaming when poured into the container. The steam forces out any air in the container and keeps it free of air when sealed and cooled. When the container is cooled, the steam condenses and leaves a certain volume of vacuum in the container, known as headspace. One must ensure that the container must be sealed before the canning solution's temperature drops. It is generally a good idea to heat the liquid about 5 °C higher than required to make sure that it does not cool before the container is sealed (McGlynn, 2003). If it cools down before sealing, the air forced out would enter the container once again, defeating the purpose of hot filling.

2.1.3.4 Heat treatment

The main objective of thermal processing is to inactivate spoilage-causing and pathogenic microorganisms through heat treatment. Usually, the sealed containers are heated using steam or a mixture of steam and air inside a retort. The heat treatment could vary by the temperature and duration of holding time. Every heat treatment is established to achieve a minimum thermal process to inactivate the target microorganisms. This degree of heat treatment is referred to as 'lethality'. As many parameters affect the rate of heat transfer from the heating source to the food pieces, it is essential to understand the heating behaviour. There are several methods to record time-temperature data during the heat treatment, such as using thermocouples, wireless sensors, thermochromic liquid crystals (TLC), melting point indicators (MPI), biological indicator, chemical and biochemical indicators, magnetic thermometry and magnetic resonance imaging (MRI) techniques (Singh et al., 2017).

A thermocouple consists of two different metals joined together to form a junction. A small voltage is created when this junction is heated or cooled, allowing an electrical circuit to correspond the magnitude of this voltage to a certain temperature. Thermocouple wires could be rigid, flexible or thin wired, and depending on the combination of metals used, they could be Type T, Type K, Type J and so on. Each of these thermocouple types have different temperature ranges that it can measure.

While thermocouple wires are simple to use, their use in setups that involve rotation is not possible as these wires will entangle and eventually break. Thus, the use of wireless sensors, like wireless thermocouples, in such cases would be imperative. These devices gather temperature data and send it to a computer through signals. Another benefit of using wireless sensors is that lower wiring costs are associated. However, these devices are relatively big and occupy space, and absorb some heat themselves. Hence, there is always a slight deviation from the actual temperature (Awuah et al., 2007a; Khurana et al., 2009). Thermochromic liquid crystals are chemical compounds that change their color with change in their surface temperature. These color changes are recorded as a video and its image analysis provides the required data. One

major limitation of using TLCs is that they can only be used in optically transparent liquids (Abdullah et al., 2010).

Like TLCs, melting point indicators also change their color according to their surface temperature and melting point, and can only be used with transparent liquids. Biological indicators make use of tubes filled with spores of certain bacteria. The heat treatment is directly related to the inactivation these spores. Chemical and biochemical indicators work like biological indicators, however, they make use of chemical and biochemical compounds like anthocyanins, thiamine, etc. Hassan and Ramaswamy (2013) used a biological indicator to compute the process lethality of a certain heat treatment of carrot and meat alginate spheres. Weng et al. (1992) used immobilized peroxidase as a chemical indicator to record the temperature data of particles in a pasteurization process. Magnetic thermometry uses a quartz crystal that resonates at a frequency according to the temperature and produces a magnetic signal. This signal is received by a receiver and converts it to meaningful temperature data. In magnetic resonance techniques, the change in temperature is recorded as the change in the magnetization of a magnetic particle.

2.1.3.5 Cooling

After the required heat treatment is achieved, the container must be cooled down immediately to avoid further heating or cooking. Any extra heating would degrade the quality of the product. It is important to keep the product as raw as possible, thus, any cooking that takes place post-processing must be avoided by cooling down the product as soon as possible. While metallic cans can withstand sudden pressure changes, glass jars need to be pressure cooled to avoid the jar's explosion. When the content of the jar is processed, it is at a high temperature. If cold that hot jar is submerged in cold water, the pressure inside the jar would increase rapidly due to the sudden change in temperature. This phenomenon could cause the jar to explode.

Cooling is considered to be somewhat irregular due to multiple parameters involved that are difficult to control. These include internal boiling and random mixing of the content inside the container (Cleland and Gesterkamp, 1983). For this reason, the lethality contributed by the cooling phase is regarded as a safety margin.

2.1.4 Principles of thermal processing

Inactivation of a microorganism requires a certain duration of thermal processing for every processing temperature. These time-temperature combinations represent the degree of heat treatment and are quantified as 'lethality'. It corresponds to the equivalent heating time of the complete process expressed as minutes at the reference temperature, and is calculated by the following Equation:

$$Fo = \int 10^{\frac{(T - To)}{10}} \, dt \qquad \textbf{2.1}$$

where T is the sample temperature, T_o is the reference temperature and t is time. The reference temperature for commercial sterilization is 121.1 °C. The time required to inactivate one log cycle of the initial count of a microorganism, or 90% of it, is called the thermal death time (D). Thus, the D-value is unique for every temperature. The temperature difference that corresponds to one log cycle of change in the D-value is known as thermal sensitivity indicator or z-value. Graphically, D-value and z-value are obtained as shown in Figure 2.1 and Figure 2.2, respectively. Microbial vegetative forms have a z-value around 5 - 8 °C, microbial spores have a z-value of 10 – 15 °C and nutrients in food have a z-value of 30 - 35 °C (Holdsworth, 1985; Ramaswamy and Marcotte, 2006; You, 2015). From Equation 2.1, we can see that a higher Z-value would mean that a lower amount of lethality has been achieved in a certain period of time. Therefore, nutrients in food experience a lower lethality as compared to vegetative microorganisms and microbial spores for the same heat treatment. As microorganisms present in food are more sensitive to a change in temperature, thermal processing allows one to quickly inactivate these microorganisms while retaining most of the product's nutrients. This implies that a higher processing temperature and lower processing time would maintain most of the product's quality, and this concept is known as High Temperature Short Time (HTST).

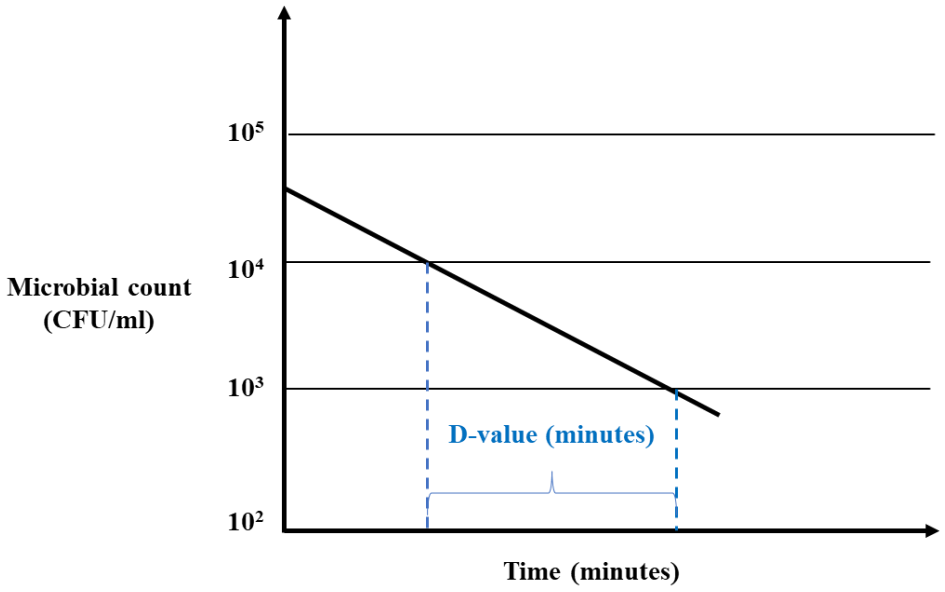

Figure 2.1. Microbial inactivation survivor curve.

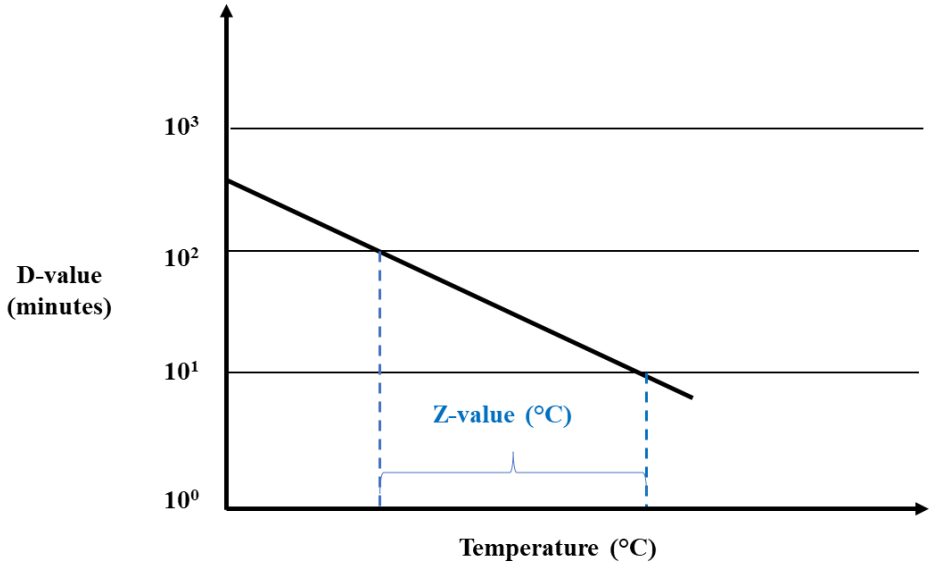

Figure 2.2. D-value vs Temperature curve.

As described in Figure 2.3, foods are divided into 2 groups based on their pH level. Low-acid foods have pH > 4.6, and acid and high-acid foods have pH ≤ 4.6. The target microorganisms in food include vegetative pathogens, which require a lower heat treatment for inactivation, and bacterial spores, which are more heat-resistant but remain inactive in high-acid conditions. When

we deal with low-acid foods, we must use a higher temperature as both, vegetative pathogens and bacterial spores, need to be inactivated. This process is called 'commercial sterilization' and requires a lethality of $F_{121.1}$ = 5 min. This value of lethality ensures that the initial count of *Clostridium botulinum* reduces by 12 log reductions to statistically reduce the survivor probability to 1 in 10^{12}. Inactivation of *Clostridium botulinum* by 12 log reductions is known as 'Bot-cook'. High-acid foods need a milder process, called 'pasteurization', as only vegetative pathogenic and spoilage-causing microorganisms need to be inactivated. The high-acid environment inhibits the activity of bacterial spores. The target lethality for pasteurization is F_{90} = 10 min (Odlaug and Pflug, 1977a,b; Breidt et al., 2014). The incomplete destruction of bacterial spores in acidified thermal processing could cause a serious threat. Surviving spores of *Bacillus Licheniformis* could multiply, even under high-acid conditions, and its activity could potentially increase the pH level (Rodriguez et al., 1993). This phenomenon could aid in the growth of *Clostridium botulinum*. Thus, the target lethality for acidified thermal processing is set to avoid such threats by inactivating spores of *Bacillus Licheniformis* (Tola and Ramaswamy, 2014a,b). Low-acid food can also be pasteurized to obtain a shorter shelf-life of two to six weeks. However, it must be stored under refrigerated conditions. In such cases, the heat treatment inactivates vegetative microorganisms, and the activity of bacterial spores is inhibited by keeping the temperature below 4 °C.

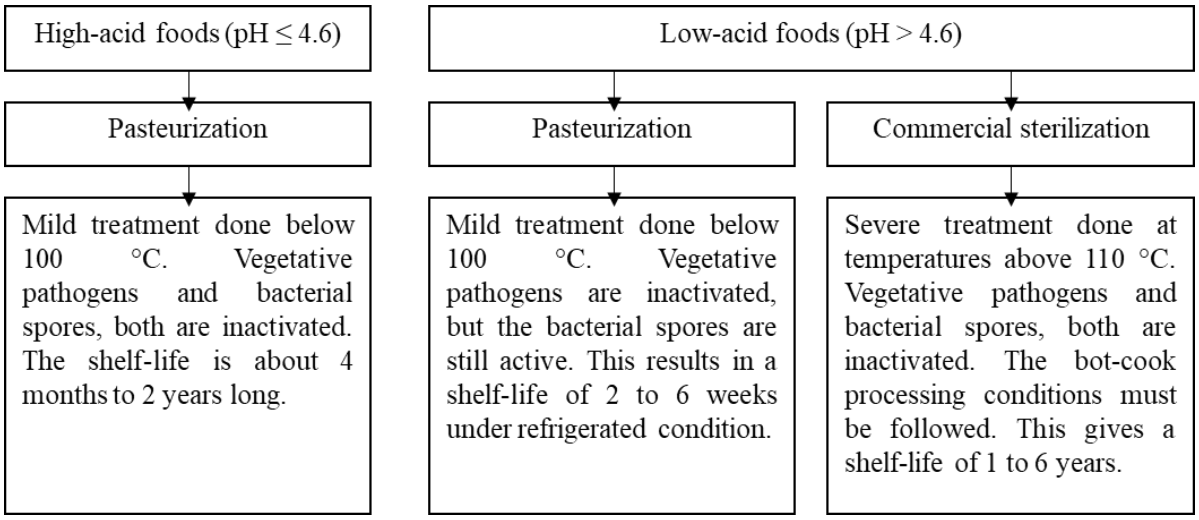

Figure 2.3. Schematic diagram of thermal processing.

2.1.5 Rate of heat transfer during thermal processing

The rate of heat transfer of a particular process is understood by calculating the heating rate index (f_h) and heating lag factor (j_{ch}). The heating rate index is a prominent indicator of the rate of heat transfer, but does not measure the rate of heat transfer directly. It is defined as the time required to pass one log cycle for the logarithmic temperature difference between the retort and the sample vs time curve. Thus, a lower f_h value means that the rate of heat transfer is higher. This would result in quicker attainment of the target lethality and consequently, a lower processing time, retaining more quality of the product. Figure 2.4 shows a typical heating curve diagram, where the slope of Line 1 gives the heating rate index. Another important indicator of the heat penetration characteristics is the heating lag factor, which measures the delay in achieving steady phase heating. A lower value of the heating lag factor corresponds to a shorter duration to achieve steady phase heating. Like the heating rate index, a lower value of the heating lag factor also suggests that the rate of heat transfer is higher. From Figure 2.4, we obtain the values of $\text{Log}(T_R - T_{pih})$ and $\text{Log}(T_R - T_{ih})$. The ratio of $(T_R - T_{pih})$ to $(T_R - T_{ih})$ gives the heating lag factor.

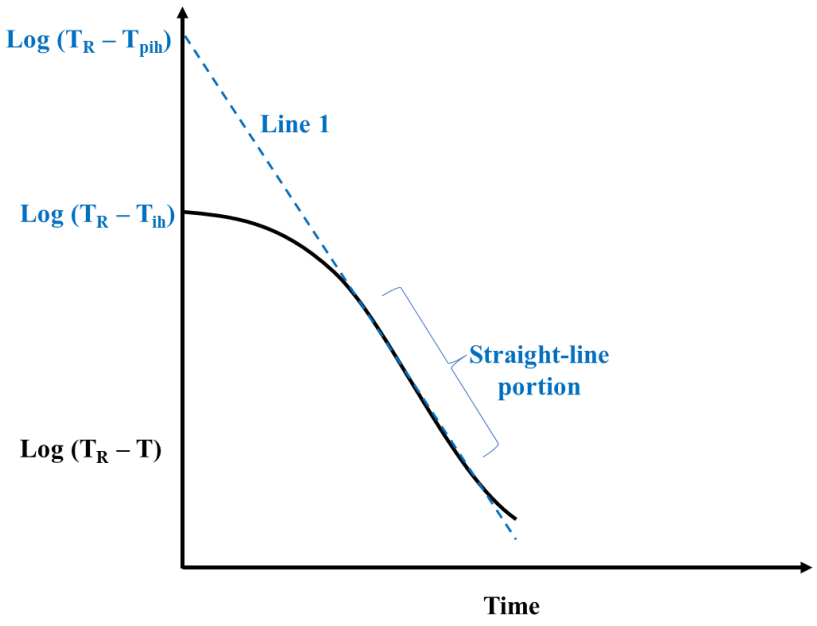

Figure 2.4. Thermal processing heating curve diagram.

To reduce the processing time, the rate of heat penetration into the food item must be increased. Many studies have suggested ways of increasing the rate of heat transfer by providing agitation into the system during thermal processing. This induces turbulence in the containers and increases forced convection, allowing the canning liquid to absorb heat quicker. Consequently, the food particles heat up quicker. Abbatemarco and Ramaswamy (1994) reported that increasing the rate of agitation during end-over-end rotation thermal processing decreases the processing time for potatoes, carrots and green beans. Dwivedi (2008) showed similar results for fixed-axial and free-axial modes of agitation. Pratap Singh et al. (2017) also showed that reciprocating agitation increases the rate of heat transfer for tomato puree as the frequency of agitation was stepped up. Another study on the effect of reciprocating agitation on processing shrimps showed similar results (Dixon et al., 2020).

2.2 Types of thermal processing

2.2.1 Based on the method of agitation

2.2.1.1 End-over-end agitation

The containers are rotated such that the container is flipped lengthwise, switching one end of the container with the other. This motion is well-explained in Figure 2.5. Usually, the containers are placed in cages and the entire cage is rotated end over end. This forces the containers to be processed in slightly variable manners as the central container would spin around its central horizontal axis, whereas the containers placed on the ends of the cage would cover the largest circumference than the others.

2.2.1.2 Fixed-axial agitation

The containers are rotated about their vertical axis. This differs by end-over-end agitation only by the orientation of the containers. Like end-over-end agitation, free axial agitation also faces some variability. The particles in the particle-in-fluid phase would experience a greater centrifugal force, resulting in clumping of particles on the container wall. This reduces the

overall rate of heat transfer in the fluid due to lower mixing and thermal resistance created by the clumps.

2.2.1.3 Free-axial / biaxial agitation

The containers are oriented and rotated like the ones in free axial agitation. As shown in Figure 2.5, the only difference is that the rotation is not a complete 360° rotation. Instead, the cage is allowed to rotate a fixed angle, after which the containers are allowed to roll over their lateral surface for the rest of rotation. Due to the existence of gravitational force, the containers are allowed to roll over their surface only during the bottom section of rotation. This change in mode of rotation allows the container to rotate in the opposite direction, avoiding any formation of clumps on the walls. This is also called as biaxial rotation as the containers change their direction of rotation twice in every complete rotation.

2.2.1.4 Reciprocating agitation

The containers are agitated in a back-and-forth manner, allowing all containers to be treated equally. This type of agitation is described in Figure 2.5. Depending on the orientation of the containers, reciprocating agitation thermal processing (RATP) could be done in multiple ways. The containers could be kept such that their long axis is perpendicular, parallel or angled to the direction of agitation. When placed perpendicularly, the containers could further be oriented in two ways – the container's long axis could be perpendicular or parallel to the direction of gravity. Singh and Ramaswamy (2015) showed how the container's orientation affected the rate of heat transfer during RATP. Also, Singh et al. (2018) reported that the overall rate of heat transfer for reciprocating agitation increased with the highest proportion when the rate of agitation was increased. This implies that this mode of agitation is the best agitation method to increase the rate of heat transfer.

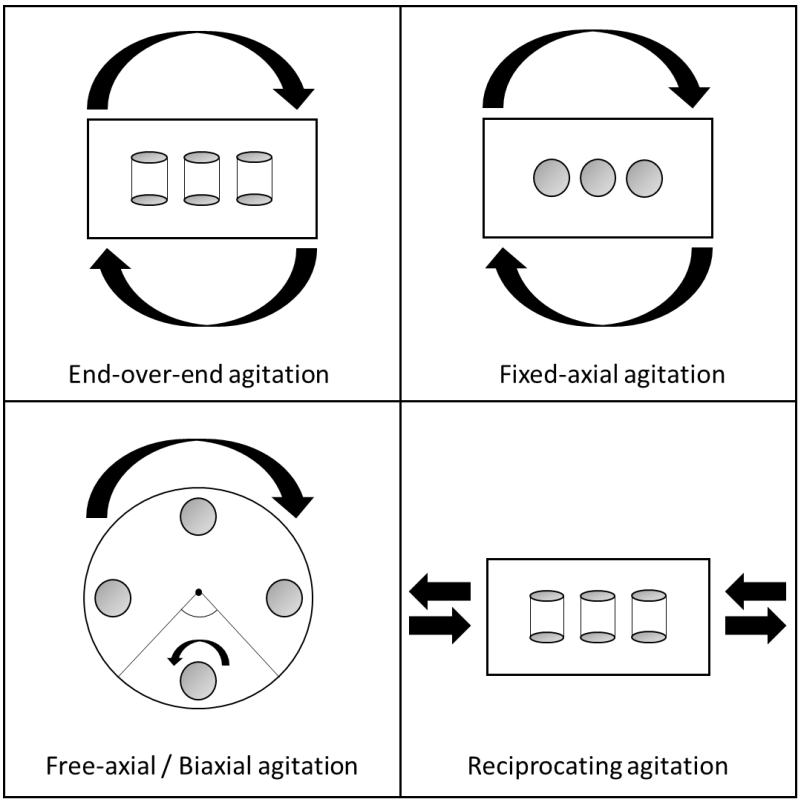

Figure 2.5. Agitation methods for thermal processing.

2.2.2 Methods of processing

2.2.2.1 Conventional thermal processing

Low-acid foods are processed to achieve a lethality of F_{121} = 5 minutes. This ensures that the initial count of *Clostridium botulinum* is reduced by 12 log reductions. The processing temperature is above 110 °C, which makes this a harsh treatment. The processed products are considered to commercially sterile and last for one to six years. Low-acid foods include most of the vegetables.

2.2.2.2 Acidified thermal processing

Low-acid foods are acidified to high-acid foods by using food-grade acids like citric acid, acetic acid, tartaric acid and so on. A noticeably milder acid is glucono-d-lactone, which does not

impart a very sour taste to food (Tola and Ramaswamy, 2018). With acidification to low-acid foods to pH $\leq$ 4.6, acidified thermal processing (ATP) offers the benefits of pasteurizing the food, rather than commercially sterilizing it, as the activity of bacterial spores is already inhibited due to the high-acid environment. Pasteurization makes use of process temperatures below 100 °C, making it a milder process than the conventional method. The lethality to attain is F_{90} = 10 min. The targeted microorganisms include vegetative pathogens like *Escherichia coli*, *Listeria monocytogenes*, fungal spores and spores of *Bacillus licheniformis*. Due to the milder processing temperatures, it is expected that ALAFTP results in more retainment of product quality than the conventional method.

2.3 Factors influencing the rate heat penetration

Several researchers have evaluated the parameters that affect the rate of heat penetration into food particles in a particle-in-fluid phase during thermal processing. The main objective of studying these parameters was to understand their potential in increasing the rate of heat transfer and consequently, decreasing the processing time. A lower processing time would retain more quality. Thus, these parameters influence the quality of the product. Most of the studies revealed that the mode and speed of agitation, fluid viscosity, container's headspace and the food particles' size, shape and density influenced the rate of heat penetration into the food particles the most (Lenz and Lund, 1978; Deniston et al., 1987; Fernandez et al., 1988; Sablani, 1996; Sablani et al., 1997; Sablani and Ramaswamy 1995, 1996, 1997,1998; Ramaswamy and Sablani, 1997, 1999). The influence of these factors are generally studied on the basis of their effect on the overall heat transfer coefficient (U). To avoid variations caused by the biological system of food, some of these studies used particles of various materials like nylon, aluminum, lead, and so on. Whereas others used real food. The factors that influence the rate of heat penetration have been discussed below.

2.3.1 Agitation method

Different modes of agitation have different effects on the rate of heat transfer. Singh et al. (2018) reported that the overall heat transfer coefficient was the highest for reciprocating

agitation. After that comes biaxial agitation, end-over-end agitation and fixed-axial agitation, which has the lowest. The still mode of processing has an overall heat transfer coefficient much lower than any agitated mode of processing. Quast and Siozawa (1974) observed that the rate of heat transfer for fixed axial rotation was two to four times higher than that of still processing. It was also reported that the heat transfer coefficient for end-over-end agitation was two to three times higher than that of fixed axial rotation (Naveh and Kopelman, 1980). Dwiwedi and Ramaswamy (2010) and Rattan and Ramaswamy (2014) further explain the effect of different mode of agitation on the rate of heat transfer. Dwivedi (2008) reported that these differences are more predominant in the early stages of processing, when the temperature difference between the sample and heating source is high.

2.3.2 Rate of agitation

Many studies have reported that the rate of heat transfer is directly proportional to the rate of agitation (Van Loey et al., 1994; Sablani and Ramaswamy, 1996; Dwivedi and Ramaswamy, 2010; Singh et al., 2015b). Abbatemarco and Ramaswamy (1994) showed that the heating rate index reduced as the end-over-end rotational speed was increased from 0 to 20 RPM. You et al. (2016) revealed that the heating rate index lowered as the reciprocation frequency increased from 0 to 3 Hz while processing potatoes and radishes. Stoforos (1988) explained the influence of the rate of agitation on the heating rate index during axial agitation thermal processing. Also, Lekwauwa and Hayakawa (1986) found out the fluid to particle heat transfer coefficient for potato pieces in water during end-over-end agitation.

2.3.3 Viscosity of canning liquid

It has been observed that increasing the viscosity of the canning liquid decreased the rate of heat transfer (Hassan, 1984). A study that compared the rate of heat transfer between water and a 60% sucrose solution concluded that water, being a more viscous fluid, contributed towards a higher rate of heat transfer (Lenz and Lund, 1978). Similarly, Sablani (1996) reported that the overall heat transfer coefficient was higher for a canning liquid of water as compared to that of oil. This study was done using Nylon spheres as food particles. These studies suggest that the rate of heat transfer is higher in lower viscosity canning liquids as the

relative speed of particles is higher in such cases. This contributes towards more turbulence, increasing the overall rate of heat transfer.

2.3.4 Food-particle concentration

The concentration of particles in the particle-in-fluid phase greatly influences the rate of heat transfer between the canning liquid and the particles. The number of particles inside the container affects the flow pattern of the canning liquid. In addition to that, these particles are responsible for creating secondary agitation and distribute the heat evenly. Studies revealed that as the particle concentration increases, the rate of heat transfer also increases (Hassan, 1984). As the particle concentration increases further, at one point the rate of heat transfer begins to drop sharply. Therefore, optimization of the particle concentration is essential for an efficient process. Deniston et al. (1987) reported that for high food-particle concentrations, the rate of heat transfer reduced as the particles were tightly packed and no space for movement was allowed. This reduces the secondary agitation created by particles and consequently, reduces the rate of heat transfer.

2.3.5 Food-particle size

Several studies have worked on finding a relation between the food-particle size and the rate of heat transfer, however, many contradictory results were achieved. It was reported that the rate of heat transfer decreased as the diameter of potato spheres increased from 2.22 cm to 3.49 cm. Also, Sablani and Ramaswamy (1997) showed that the rate of heat transfer decreased as the size of Nylon particles increased from 19.05 mm to 25 mm. On the other hand, Lenz and Lund (1978) reported that the overall rate of heat transfer increased as the particle size increased. The rate of heat transfer decreases with an increase in particle size because the surface area to volume ratio of these particles decreases. However, when the particle size is too small, the particles clump together during agitation and the rate of heat transfer reduces.

2.3.6 Food-particle shape

Sablani and Ramaswamy (1997) used Nylon particles shaped as cylinders, cubes and spheres to understand the effect of particle shape on the rate of heat transfer. They revealed that the rate of heat transfer was lower for cubical particles as compared to cylindrical and spherical particles. Different shapes produced various empty spaces between the particles, enabling various degrees of mixing inside the can. Åström and Bark (1994) explained that cubical particles have the lowest rate of heat transfer as cubical particles behave like highly rough particles, whereas spherical particles had the highest. The shape influences the way these particles interlock with each other, which consequently affects the rate of heat penetration.

2.3.7 Food-particle density

The heat transfer coefficient can be impacted by the particle density, which can change the pattern of fluid motion for the particles inside the container. Sablan (1996) reported that the particle density significantly affected the rate of heat transfer – particles of higher density settled in the container quicker, creating more movement in the fluid and increasing the convection. Meng and Ramaswamy (2007) also reported that the rate of heat transfer increased as the particle density increased.

2.3.8 Container headspace

Up until a certain point, the container's headspace was observed to enhance the rate of heat transfer (Mohamed, 2007). This is because faster heating rates are caused by quickly heating up water's surface (Singh and Ramaswamy, 2016). However, if the can headspace is very large, it begins to act as an insulation, reducing the heating rate (Singh et al., 2018).

2.4 Quality loss during thermal processing

While thermal processing offers several advantages in the preservation and safety aspects of food, it compromises the quality of processed product. Heat treatment degrades the texture, color and nutritional content of food. It also alters the odor and flavor of food, which could be an

undesirable change for most of the times. The nutritional content that is vulnerable to change during thermal processing include proteins, lipids, vitamins and antioxidants.

2.4.1 Texture

Thermal processing of food usually softens the processed products as the pectic structures in the cell wall and interlamellar region are broken down (Taherian and Ramaswamy, 2009). This happens from enzymatic and non-enzymatic reactions of pectin (Greve et al., 1994; Anthon et al., 2005). Starch gelatinization also plays an important part during heat treatment to change the product's texture (Kadam et al., 2015). The instrument used for measuring texture parameters is known as 'texturometer', which measures all parameters using two compression-decompression cycles on a force vs distance graph. These two cycles mimic two bites. The part of the equipment that is in direct contact with the product is called as the probe. The variables that need to be adjusted for analysing the texture of different types of products include the type of probe, the pre-test, test and post-test speeds of the probe and the degree of compression, which is represented as a fraction (in percentage) of the product's height. The entire test is known as Texture Profile Analysis (TPA).

The texture parameters that are affected due to heat treatment are hardness, fracturability, cohesiveness, springiness, gumminess, chewiness and resilience. Hardness is measured as the maximum force of the first compression. It need not be at the first significant peak, but it is the case for most products. Not all products fracture, but when it does, the fracturability is the force at the first significant peak. When fracturability of a product exists, it is understood that its hardness is measured at the first peak, rather than the first significant peak. Cohesiveness is calculated as the ratio of work done during the second compression cycle to that of the first compression cycle. It represents how well a product can withstand the second compression relative to its first one. Springiness shows the ability of a product to spring back to its original height after a compression. It is computed as the ratio of heights detected by the probe at the second compression to the first one, and is expressed as a percentage of the original height. Gumminess represents how gummy a product is, and it is measure only for semi-solid products. It is calculated as the product of hardness and cohesiveness. If the product is solid, we measure

its chewiness instead of its gumminess. Thus, these two parameters are mutually exclusive. Chewiness is measured as the product of hardness, cohesiveness and springiness. It corresponds to the energy required to chew the product. Lastly, resilience represents the ability of a product to fight against the probe to recover back to its original height. It is calculated as the ratio of upstroke energy of the first compression to the downstroke energy of the same.

There is another texture parameter that exists, which is known as adhesiveness. However, it is considered to be secondary parameter sometimes as there are better methods of computing this parameter. It is measured as the negative work done between the two compressions. For adhesiveness to be measured, the product must stick to the probe after the first compression, and be lifted up along with the probe. It is not necessary for the product to remain attached throughout the probe's movement.

Several studies have been carried out to understand the softening of food during heat treatment. Cheng et al. (1979) studied the effect of thermal processing on the texture of minced fish gel. Zivanovic and Buescher (2004) investigated how mushroom's texture was affected by thermal processing. Similarly, Borowski et al. (2015) studied the effect of thermal processing on broccoli and Mallidis and Katsaboxakis (2002) did the same for apricots.

2.4.2 Color

The appearance of a product is the first criterion that a consumer would consider before inspecting the rest of it. Thus, maintaining the appropriate color of a processed product is extremely important. Like texture, heat treatment of food also degrades its color due to various reactions. This generally include the degradation of color-imparting pigments like carotenoids, anthocyanins, betanin and chlorophylls (Rodriguez-Amaya, 2019). Chlorophyll gives the green color, carotenoids give yellow, orange and red shades, anthocyanins are responsible for the red, blue and purple shades and betanin gives the red color. Much attention has been given to chlorophyll as it is present in many vegetables, and is highly susceptible to lose its greenness on heat treatment. Gaur et al. (2007) reported that chlorophyll is converted to pheophytins on heat

treatment as it undergoes a series of reactions that forces it to lose its central magnesium ion. This changes chlorophyll's fresh green color to an undesirable shade of brown.

The instrument used for measuring color parameters of food is called a colorimeter. The three parameters of color that are measures by the colorimeter are lightness (L*), redness or greenness (a*) and blueness or yellowness (b*). Lightness is measured on scale of 1 to 100, 100 being the lightest / brightest. Redness is measured from +a to -a, +a being redder. Whereas blueness is measured from +b to -b, -b being bluer. The total color difference is computed as ΔE, defined by the following Equation:

$$\Delta E = \sqrt{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2} \qquad \textbf{2.2}$$

The effect of thermal processing on the color of food has been studied widely. Chutintrasri and Noomhorm (2007) studied of heat treatment affected the color of pineapple puree. Rao et al. (1981) worked on understanding the same for peas. Also, Teribia et al. (2021) carried out research on the effect of thermal processing on the color attributes of strawberry puree originating from different cultivars.

2.4.3 Antioxidant activity

Antioxidants are micronutrients that prevent or hinder the damage to cells caused by free radicals, which are unstable molecules created as by-products when cells in our body use oxygen to generate energy. Free radicals could be produced in the form of superoxide, hydroxyl, peroxyl and so on (Lim et al., 2007). Antioxidants scavenge these free radicals by quenching superoxide, reducing hydrogen peroxide and terminating chain reactions. If these free radicals are not dealt with, their threat could cause various health problems such as cardiovascular diseases, inflammatory diseases, cataract and cancer. Thus, consumption of antioxidants is crucial. Foods that are rich in antioxidants include broccoli, carrots, spinach, potatoes and berries.

Although there are many substances that act as antioxidants, the most familiar ones include vitamin C, vitamin E, phenolic compounds and carotenoids like beta-carotene. Most of them are

naturally present in food. Antioxidants are categorized as enzymatic and non-enzymatic, and are further categorized as shown in Figure 2.6.

There are many methods to quantify the antioxidant activity in food. These are mainly categorised into 3 categories – spectrometry, chromatography and electrochemical methods (Carocho and Ferreira, 2013). Common spectrometric techniques include ORAC (Oxygen Radical Absorbance Capacity), FRAP (Ferric Reducing Antioxidant Power) and DPPH (2,2-diphenyl-1-picrylhydrazyl) assays. The ORAC assay measure a fluorescent signal from a probe that is quenched in the presence of reactive oxygen species (ROS). Antioxidants absorb these ROS, allowing the fluorescence to last for a longer duration. The FRAP assay makes use of the rapid reduction of an Fe^{3+} complex by antioxidants to form a blue-colored product (Fe^{2+}) (Benzie and Strain, 1996). The concentration of Fe^{2+} in the sample is measured by using the FRAP reagent and making a standard curve by adding it to known concentrations of Fe^{2+} solutions (Payne et al., 2013). The absorbance is measured at 620 nm. DPPH is a stable organic radical that has a deep-purple color. In the presence of antioxidants, DPPH is reduced and the solution is decolorized, allowing one to measure this change in color using a spectrophotometer that reads the absorbance at 517 nm. The respective changes observed in the result of these assays are then correlated to the antioxidant activity of the sample.

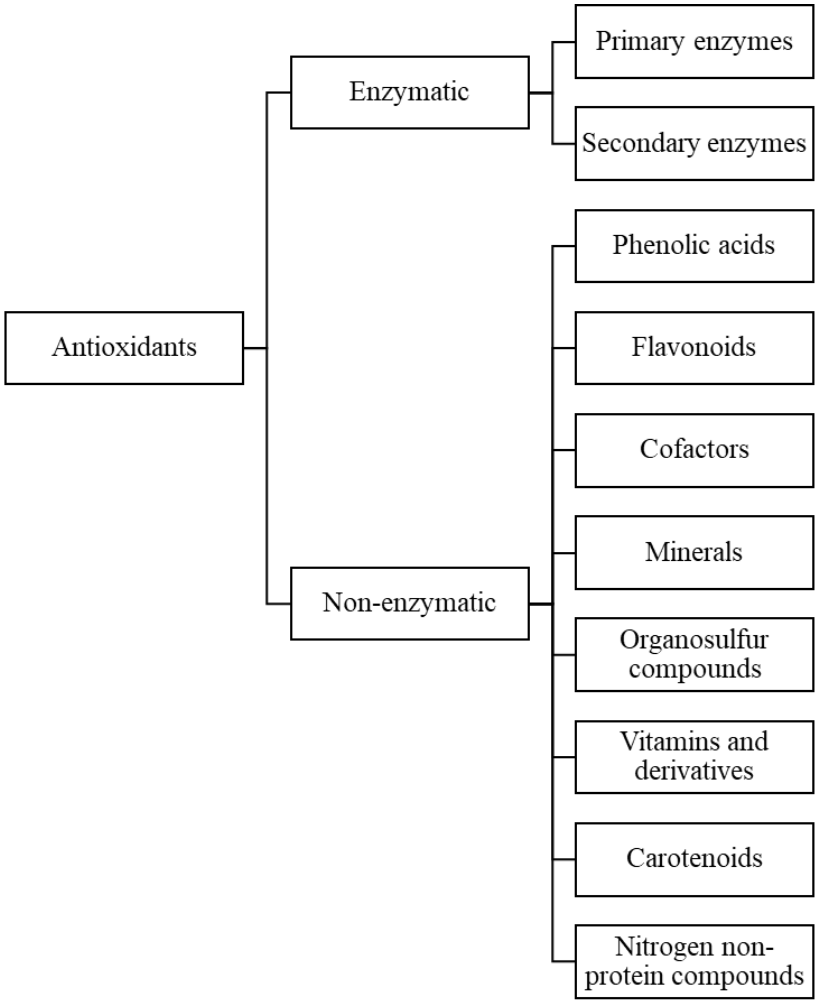

Figure 2.6. Classification of antioxidant compounds (Carocho and Ferreira, 2013; Munteanu and Apetrei, 2021).

It is expected that the antioxidant activity of food reduces on heat treatment, however, some studies have shown that it increases. Dewanto et al. (2002a) reported that the antioxidant activity of tomatoes increased after thermal processing, despite the loss of Vitamin C. Also, Dewanto et al. (2002b) showed a similar trend for sweet corn. Arkoub-Djermoune et al. (2016) showed that the phenolic and flavonol contents of eggplant increased on heat treatment.

2.5 Origin and importance of mushroom and chickpea

2.5.1 Mushroom

White mushrooms (*Agaricus bisporus*) are fungi that belong to the Agaricaceae family. These are edible mushrooms which are native to grasslands and fields of Europe, Asia and North America. However, its popularity has been increasing and is now cultivated widely over the world. It is the most cultivated type of mushroom (Cebin et al., 2018) and carries many names, including button mushroom and table mushroom. It is white in color during its immature state and turns brown when mature. In the wild, the cap is brown in color with broad, flat scales.

Although white mushrooms are low in calories, they are rich in many vitamins and minerals, especially vitamin B and potassium. They also offer many health benefits that protect against certain cancer and cardiovascular diseases. It contains a large number of compounds that are antioxidants, antibacterial, anti-inflammatory, etc. Due to their exposure to sunlight during its growth, white mushrooms are rich in vitamin D2, making it a natural, plant-based source. Similarly, it is a great plant-based source of vitamin B12 too. It has cancer-fighting properties due to its richness in antioxidant compounds, such as polyphenols, vitamin C, ergothioneine, glutathione and selenium (Kozarski et al., 2015). The vitamin C and selenium offer anticancer properties by supporting the immune system to produce cells that protect against cancer development (Chambial et al., 2013; Mehdi et al., 2013)

However, this type of mushroom has a rather short shelf life because to its high moisture content (85 – 95%) and exposed natural structure (Kumar et al., 2013). Studies have shown that white mushrooms have a shelf-life of 1 – 3 days at room temperature (20 – 25 °C), 5 – 7 days when stored between 0 – 2 °C and about 8 days at refrigerated conditions (Diamantopoulou and Philippoussis, 2015; Jiang, 2013; Xu et al., 2016). Once harvested, white mushrooms continuously lose their quality. Discoloration, moisture loss, texture changes, increase in microbial count, loss of nutrition and flavor are common effects during its postharvest stage (Zhang et al., 2018). Therefore, processing of white mushrooms to increase its shelf-stability and safety is essential.

Several studies have been pursued to process white mushrooms. Common techniques include dehydration methods such as microwave drying and freeze drying (Pei et al., 2014). Immediate postharvest cooling has been studied by (Diamantopoulou & Philippoussis, 2015). Other studies used methods like pulsed electric field (PEF) processing, washing with antimicrobial agents, packaging and coating with semi-permeable films (Flores-Lópe et al., 2016). Thermal processing of white mushrooms is very limited.

2.5.2 Chickpea

Chickpeas (*Cicer arietinum*) come from the Fabaceae family. They are widely produced all over the world, with India being the top producer by a large margin. It has various names in different countries and sometimes, within a country too. It is extremely popular in Indian, Mediterranean and Middle Eastern cuisines. Desi chickpeas have smaller and darker seeds with a rough coat. Whereas Kabuli chickpeas are larger, lighter in color and have a smoother coat.

Besides being plant-based food that is packed with protein and dietary fiber, chickpeas offer a large variety of vitamins and minerals (Cabrera et al., 2003; Kaur and Prasad, 2021). It contains a good amount of vitamin E (tocopherol) and vitamin B9 (folic acid), along with small amounts of B complex vitamins, primarily vitamin B2 (riboflavin), B5 (pantothenic acid) and B6 (pyridoxine). Regarding minerals, it has a significant amount iron, zinc, magnesium and calcium. Chickpeas contain compounds that help in the inhibition of certain types of cancer. These compounds include saponin, which prevents cancer development (Koczurkiewicz et al., 2019), and B vitamins, which are reported to lower the risk of breast and lung cancer (Peterson et al., 2020; Brasky et al., 2020). It also facilitates the production of butyrate in the body, reducing inflammation in colon cells and consequently, reducing risks of colon cancer (Wallace et al., 2016). Chickpeas are a good source of antioxidants too, containing carotenoids like beta-carotene, lutein, zeaxanthin and lycopene, as well as phenolic compounds like isoflavones biochanin A and formononetin (Jukanti et al., 2012).

While chickpeas are rich in nutrients, they contain high amounts of antinutritional content like phytic acid and tannin (Sharma et al., 2018). Phytic acid is reported to form insoluble complexes

with polyvalent cations such as Cu, Zn, Co, Mn, Fe and Ca (Roy et al., 2019). Whereas tannins bind with protein to reduce their digestibility and bioavailability (Srivastava and Srivastava, 2003). These antinutritional contents need to be extracted using methods like soaking in water before processing. Although there are some studies on processing of chickpeas using various methods (Parmar et al., 2016; Sharma et al., 2018), thermal processing of whole chickpeas is scarce and, therefore, needs attention.

2.6 References

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PREFACE TO CHAPTER 3

The principle of thermal processing is based upon achieving a certain target lethality that ensures the inactivation of harmful and spoilage-causing microorganisms. The first step of achieving this target lethality is to understand the heating characteristics of the product. This could be done with the help of the time-temperature data of the product during its heat treatment, often done using thermocouples located in to particles through the retort and the can and using a data logger to gather the time-temperature data. With this data, heat penetration parameters such as the heating rate index and heating lag factor can be calculated, and the accumulated lethality during the process can be computed. In order to expedite the thermal process, reciprocating agitation is introduced and its influence on heat penetration parameters evaluated.

The purpose of this chapter was to understand the heating behaviour of mushrooms and chickpeas in the presence and absence of reciprocating agitation, and accordingly establish a thermal process to achieve the target lethality.

Part of this research was included in a poster presented in 2022 at the Northeast Agricultural and Biological Engineering Conference (NABEC), Maryland, USA. A part has also been submitted to present at NABEC, 2023.

Rampurwala, A., Taherian, A.R., and Ramaswamy, H.S., 2022. Thermal vs Acidified Thermal Processing of White Mushrooms: Influence of Reciprocating Agitation on Process Time and Product Quality. Northeast Agricultural and Biological Engineering Conference, Maryland, USA.

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A part of this study was included in a manuscript that was submitted to the Institute of Thermal Processing Specialists (IFTPS) Charles R. Stumbo Student Paper Competition, 2023. The paper won the 2nd Place Award. The manuscript prepared was as follows:

Rampurwala, A., Taherian, A.R., and Ramaswamy, H.S., 2023. Acidified vs. conventional thermal processing of chickpeas and mushrooms: quality retention under the influence of reciprocating agitation.

CHAPTER 3

EFFECT OF RECIPROCATING AGITATION ON HEATING BEHAVIOR OF THERMALLY PROCESSED MUSHROOM AND CHICKPEA IN GLASS JARS

3.1 Abstract

This aim of this study was to investigate the effect of reciprocating agitation frequency on commercial sterilization of white mushroom (*Agaricus bisporus*) and Kabuli chickpea (*Cicer arietinum*). The first step in the process was to gather the heat penetration data and compute the required process times to achieve a target lethality. Whole white mushrooms (cap average radius: 35 mm, cap average height: 20 mm, stipe length: < 15 mm) and hydrated kabuli chickpeas (standard size) were blanched and separately filled into glass jars (volume: 500 ml, height: 13.7 cm). The glass jars were then covered with 2% NaCl solution, leaving a certain amount of headspace, and subjected to thermal processing using a pilot-scale steam retort equipped with a reciprocating agitation unit. Thermal processing was carried out at 115, 120 and 125 ºC, at different agitation frequencies of 0, 1 and 2 Hz. The rate of heat penetration was recorded in terms of time-temperature data using type-T thermocouples connected to a data logger (Agilent 34970A). The processing time (P_t) was noted as the time required to attain the target lethality, followed by the calculation of heating rate index (f_h) and heating lag factor (j_{ch}) for each run. It was revealed that higher reciprocation frequencies were associated with lower f_h and lower j_{ch} values. In most cases, increasing the reciprocating frequency by 1 Hz reduced the processing time by 15 - 20%, providing opportunities for superior quality of the processed product.

3.2 Introduction

Thermal processing is one of the most common methods of making food safe and shelf-stable. It does so by providing a certain degree of heat treatment that is enough to inactivate mesophilic pathogens and spoilage microorganisms (Deak, 2014). Heat, usually in the form of steam, is applied to the exterior of the sealed containers and is transferred into the interior of the container through the container's wall. This mode of heat transfer is known as conduction. Once the heat enters the interior, the canning liquid takes up the heat through another mode of heat transfer

referred to as convection. The solid food particles, that are suspended in the liquid, heat up by conduction (Britt, 2008).

While thermal processing successfully inactivates the microorganisms, the product quality is compromised due to the severity of heat treatment (Awuah et al., 2007b). This shifts our focus on retaining maximum quality while processing the product. A High Temperature Short Time (HTST) process ensures that the product is processed in a manner where the destruction of nutrients is as low as possible. This is because these vegetative microorganisms and microbial spores are more temperature sensitive (z-value = 5 to 8 °C for vegetative microorganisms and z-value = 10 to 15 °C for microbial spores) than the nutrients present in food (z-value = 30 to 35 °C) (Holdsworth, 1985; Ramaswamy and Marcotte, 2006; You, 2015). Therefore, as temperature increases, the destruction rate of these microorganisms increases much more than that of the nutrients. Whereas a shorter processing time ensures that we quickly achieve the target lethality while retaining most of the product's quality, that is, destroying a minimum amount of the product's nutrients.

Various studies have suggested methods to reduce the processing time for thermal processing, primarily by increasing the rate of heat penetration into the product through agitation (Abbatemarco and Ramaswamy, 1994; Van Loey et al., 1994; Sablani and Ramaswamy, 1996; Dwivedi, 2008; Dwivedi and Ramaswamy, 2010; Singh et al., 2015b; Singh et al., 2016). Agitation thermal processing induces turbulence into the containers and increases forced convection in the canning liquid. This allows the particle-in-fluid phase to heat up quicker, which reduces the processing time. Abbatemarco and Ramaswamy (1994) showed that increasing the RPM of end-over-end rotation during thermal processing decreases the processing time and retains higher values of texture for potatoes, carrots and green beans. A similar conclusion was drawn by Dwivedi (2008), where it was observed that the overall heat transfer coefficient (U) and heating rate index (f_h) increases as the RPM for free-axial and fixed-axial agitation increases. Pratap Singh et al. (2017) also showed that reciprocating agitation increases the rate of heat transfer for tomato puree, a fluid phase product. In comparison to static, end-over-end agitation and axial agitation, the overall rate of heat transfer for reciprocating agitation increased with the highest proportion when the rate of agitation was increased (Singh et al., 2018). This suggests

that reciprocating agitation is the best form of agitation to increase the rate of heat transfer into a container carrying products in a particle-in-fluid phase.

Ko et al. (2007) studied the kinetic change in the texture of winter mushroom stipes and caps that were processed at different heat treatments. Some studies focused on the nutritional and anti-nutritional changes in thermally process chickpeas (Parmar et al., 2016; Sharma et al., 2018). However, study on the effect of reciprocating agitation on thermal processing of mushroom and chickpea are infrequent. Therefore, this study focuses on establishing the process time for static and reciprocating agitation thermal processing of white mushroom and chickpea to achieve the required lethality. Furthermore, this study focuses on comparing the effect of reciprocating agitation with static processing, in terms of the heat penetration characteristics by calculating the heating rate index and heating lag factor.

3.3 Materials and methods

3.3.1 Preparation of products and jars

White mushroom (*Agaricus bisporus*) and kabuli chickpea (*Cicer arietinum*) samples were first pretreated according to their respective requirements. Mushrooms were hand-washed for a minute to remove dirt from its surface and blanched for 3 min at 96 - 98 °C in a blanching solution of 0.5% Citric acid and 0.1% ascorbic acid (Jaworska et al., 2012). The blanching ensured that no enzymatic browning took place during the handling of mushrooms. Mushrooms (300 g) were blanched in 4 L of solution to provide enough space for each mushroom. Raw chickpeas were soaked overnight for 14 h in the ratio of 1:10 (w/w) and 250 g were blanched for 4 min at 70 °C in 4 L of water (Arganosa, 1998). Both samples were then dried to remove surface moisture using paper towels.

Later, the pretreated samples were separately filled into 500 ml jars. A flexible type-T thermocouple was attached into the center of a mushroom, which was placed in the geometric center of the jar as that is considered to be the coldest spot in this fluid-in-particle phase (Singh et al., 2015a). Whereas a rigid type-T thermocouple was inserted into the jar of chickpeas with

its end placed in the center of the jar. In both cases, the thermocouple entered the jar through the lid, keeping the hole sealed with gaskets. The jars were then hot-filled with a 2% NaCl solution at 90 °C, leaving 5 - 8% of headspace, and the jar was tightly sealed by hand. The jars were kept in the retort's cage such that its long axis was perpendicular to the direction of reciprocation.

3.3.2 Retort setup

A pilot-scale, vertical, static retort (Loveless Manufacturing Co., Tulsa, OK) was used for conducting the experiments. This has been modified into a reciprocating agitation retort by introducing a reciprocating cage, a slider-crank assembly and a permanent magnet motor. This setup has been illustrated in Figure 3.1. The entire assembly was placed at one-third height of the retort from the top. This modification allowed the retort to hold jars in the cage and move them in a linear back-and-forth motion called reciprocating agitation.

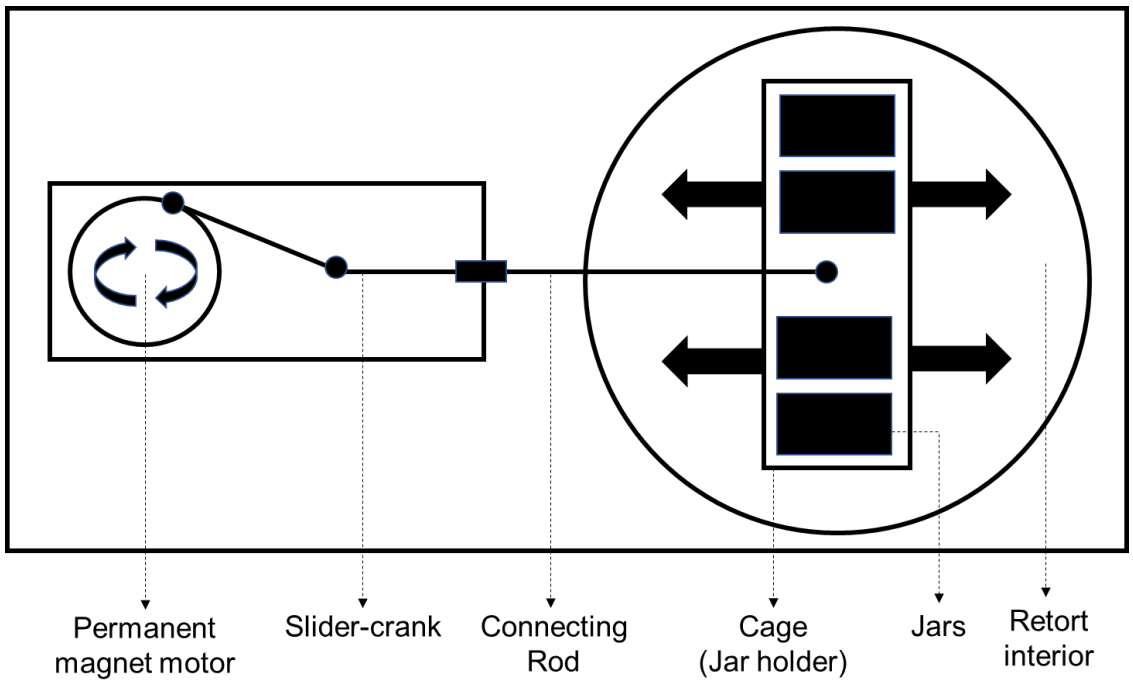

Figure 3.1. Reciprocating agitation retort assembly.

The working mechanism includes the conversion of the motor's rotating motion into a linear reciprocating motion with the help of a slider-crank with its end forced through a constriction. The amplitude of reciprocation was adjusted by varying the position of the crank and the frequency was controlled by varying the input of the magnetic motor's voltage controller. For every rotation of the rotating shaft, the cage completed one reciprocating oscillation.

The temperature in the retort was controlled by the input of steam and is determined by a pneumatic PID controller (Control & Readout Ltd., Worthing, Sussex, England). The temperature and pressure was set by the user, with a maximum of 134 °C at 308 kPa (Singh et al., 2015a). Steam entered the retort from the bottom. For cooling, cold water was introduced into the retort from the bottom.

3.3.3 Time and temperature data gathering

The time–temperature data was collected using two thermocouples (Type-T, diameter = 0.0762 mm, Omega Engineering Corp, Stamford, CT, USA) – one inside the sample that was placed in the geometric center of the jar and another one positioned inside the retort at the height as that of the cage. The other ends of these thermocouple were connected to a data logger, which was set to read the temperatures at every 5 seconds.

3.3.4 Thermal processing and processing time determination

The heat penetration tests were conducted for each sample at 0, 1 and 2 Hz of reciprocating frequency, with process temperatures of 115, 120 and 125 °C for every frequency. Each test required two runs. In the first run, the samples were over-processed to obtain time-temperature data. The lethality for every 5 s of processing was then calculated by the following formula:

$$Fo = \int L\,dt = \sum 10^{\frac{Ts-121.1}{10}}\,\frac{5}{60} \qquad \textbf{3.1}$$

where T_s represents the sample temperature. The cumulative lethality at every 5 seconds was calculated. The processing time was determined from the first run by noting the time required to achieve the target process lethality ($F_{121.1}$ = 5 min).

After obtaining the process time, samples were processed to achieve the target lethality. Once processed, the jars were cooled by introducing cold water until the temperature of the sample dropped to 80 °C, after which the jars were refrigerated for further cooling to 25 °C. A duplicate run was carried out for every test.

3.3.5 Calculation of heat penetrations parameters

A heating curve was plotted between the log of the difference of the retort and sample temperature against time. The negative reciprocal of the slope of the straight-line portion of the heating curve gives the heating rate index. Mathematically,

$$f_h = -1 / \text{slope} \qquad \textbf{3.2}$$

The heating lag factor was calculated by the following formula:

$$j_{ch} = (T_R - T_{pih}) / (T_R - T_{ih}) \qquad \textbf{3.3}$$

where T_R represents the retort temperature, T_{ih} represents the initial temperature of the sample and T_{pih} stands for the pseudo-initial temperature of the sample, which is obtained by extrapolating the straight-line portion of the heating curve and the intersection of this extrapolation with the y-axis marks the pseudo-initial temperature.

3.4 Statistical analysis

Statistical analysis of data was performed using ANOVA single factor data analysis on Microsoft Excel, followed by Bonferroni correction. The analysis of variance was carried out and the change between any two groups was concluded as significant if $p < 0.05$.

3.5 Results and discussions

3.5.1 Processing time

The processing time for each test was noted as the time required for the sample to achieve a cumulative lethality of 5 min (Eq. 3.1) at a reference temperature of 121.1 °C. Duplicate samples were tested at 115, 120 and 125 °C at a reciprocating frequency of 0 (Still), 1 and 2 Hz for each processing temperature. Table 3.1 shows the processing time obtained for mushrooms and chickpeas for the tests that were conducted. For both samples, the processing time reduced as the reciprocating frequency increased. A similar relationship between processing time and reciprocating agitation has been observed by several studies on reciprocating agitation (You, 2015; Singh et al., 2015b; Pratap Singh et al., 2017). Maximum reduction took place when the frequency was increased from 0 Hz to 1 Hz. This shows that the introduction of agitation had a stronger effect on reducing the processing time than increasing the agitation's frequency of reciprocation. On average, the processing time reduced by 17.7% from 0 to 1 Hz, as compared to 8.44% when the frequency increased from 1 to 2 Hz. However, for 115 °C, no significant decrease was observed when the frequency rose from 1 Hz to 2 Hz ($p > 0.05$). This could be supported by the fact that 115 °C is a low temperature for thermal processing (commercial sterilization) – it took more than 1.5 and 2 times longer to process than 120 °C and 125 °C, respectively, when processed at still mode (0 Hz). Nevertheless, the introduction of reciprocating agitation (0 Hz to 1 Hz) considerably reduced the processing time at 115 °C.

Table 3.1. Processing time for mushroom and chickpea at different temperatures and frequencies. Mean ± standard deviation with letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Sample	Process Temperature (°C)	0 Hz (min)	1 Hz (min)	2 Hz (min)
Mushroom	115	33.1 ± 0.6^{a}	28.8 ± 0.5^{b}	28.4 ± 0.6^{b}
	120	20.0 ± 0.4^{a}	16.4 ± 0.1^{b}	14.0 ± 0.3^{c}
	125	15.0 ± 0.3^{a}	13.1 ± 0.3^{b}	10.7 ± 0.2^{c}
Chickpea	115	32.8 ± 0.4^{a}	27.3 ± 0.5^{b}	27.1 ± 0.3^{b}
	120	18.1 ± 0.2^{a}	14.6 ± 0.3^{b}	13.6 ± 0.2^{c}
	125	14.0 ± 0.2^{a}	10.3 ± 0.2^{b}	9.40 ± 0.2^{c}

Increasing the temperature greatly lowered the processing time for each frequency of reciprocation. This is because the temperature difference between the processing temperature and reference temperature (121.1 °C) increases as the temperature is raised, which contributes a greater value towards the lethality for a given duration. Maximum difference was observed between 115 and 120 °C because 115 °C takes much longer time to process the samples. From Table 3.1, we can also see that 125 °C takes half the time for processing as compared to 115 °C. Therefore, this implies that the rate of processing the products could be doubled for the same amount of time if we increase the processing temperature of 115 °C by 10 °C.

3.5.2 Heating rate index (f_h)

The heating rate index is defined as the time required to pass one log cycle of the temperature difference between the retort and the sample. It is a clear indicator of the rate of heat transfer, but does not represent the heat transfer coefficient. A lower f_h value means that the process takes a lower amount of time to pass one log cycle of the temperature difference, which implies that the rate of heat transfer is higher.

Figure 3.2 illustrates the f_h values of mushrooms at various process temperature and reciprocating frequency combinations. As one would expect, the f_h values decreased as the frequency of reciprocation increased. This indicates that increasing the reciprocation frequency

increased the rate of heat transfer. The highest f_h value of 8.8 minutes was observed when there was no agitation. Whereas the lowest value was 5.9 minutes at 2 Hz. As shown in Figure 3.3, similar results were obtained for chickpeas too. However, the introduction of agitation influenced chickpeas much more than mushrooms – the heating rate index for chickpeas decreased by 40% on average from 0 to 1 Hz, as compared to 12% for mushrooms. It was also observed that the heating rate index increased with a rise in the processing temperature. As the processing temperature increased by 5 °C for 2 Hz of reciprocation, the heating rate index increased by 5.5 % on average. This experiment was done twice for a more accurate estimation of the heating rate index.

These results were in agreement with several studies that showed increasing the agitation lowered the heating rate index (Van Loey et al., 1994; Sablani and Ramaswamy, 1996; Dwivedi and Ramaswamy, 2010; Singh et al., 2015b). Earlier studies indicated that increasing the rotational speed from 0 to 20 rpm for end-over-end thermal processing decreased the f_h value for each of them (Abbatemarco and Ramaswamy, 1994). Regarding reciprocating agitation, You (2015) showed the same trend for f_h values as the reciprocation frequency increased from 0 to 3 Hz for potatoes and radishes.

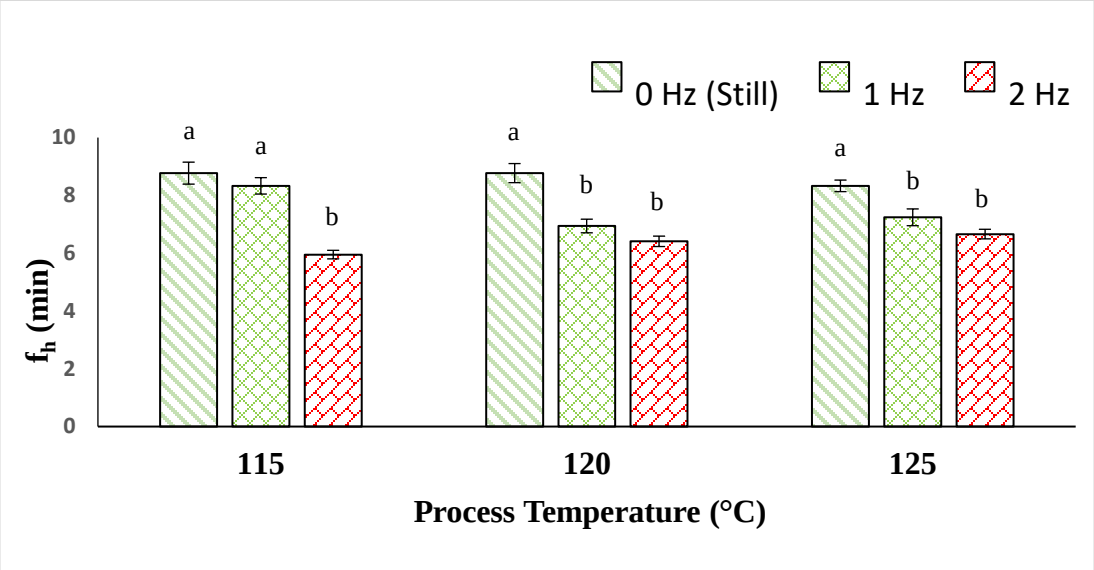

Figure 3.2. Heating rate index (f_h) of mushrooms vs process temperature at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

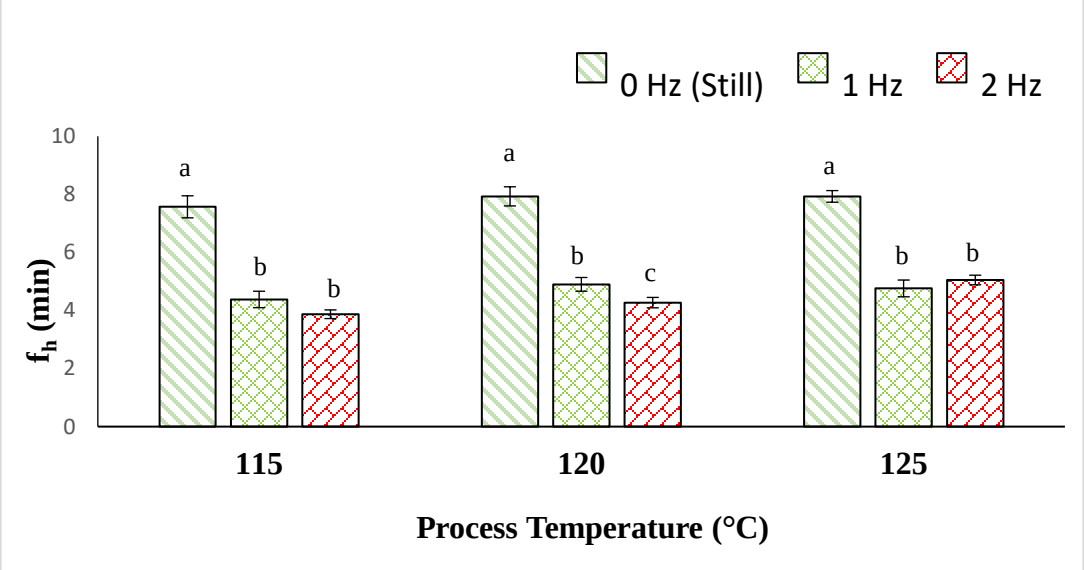

Figure 3.3. Heating rate index (f_h) of chickpeas vs process temperature at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

3.5.3 Heating lag factor (j_{ch})

While the heating rate index directly indicates a change in the rate of heat transfer, the heating lag factor represents the delay in time taken to initially reach the cold spot. Table 3.2 shows the heating lag factor of mushrooms and chickpeas processed at certain process temperature and reciprocating frequency combinations. For both samples, the j_{ch} value decreased as the reciprocation frequency was stepped up. This means that as the frequency was increased, the heating phase was achieved quicker, indicating that the rate of heat transfer increased.

For mushrooms, the heating lag factor decreased by 22.5% on average when the frequency increased from 0 Hz to 1 Hz. Whereas it reduced by 17.5% from 1 Hz to 2 Hz. When the process temperature was raised by 5 °C from 115 °C, the j_{ch} values dropped by 12.6%. It further dropped by 8.8% when the temperature was increased by another 5 °C. A similar trend was observed for chickpeas, however, the j_{ch} values for chickpeas were higher than mushrooms in each case. For 0 Hz to 1 Hz and 1 Hz to 2 Hz, the j_{ch} values for chickpeas dropped by 29.9% and 17.1%, respectively.

Table 3.2. Heating lag factor (j_{ch}) of mushrooms and chickpeas for different processing conditions. Mean ± standard deviation with letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Sample	Process Temperature (°C)	0 Hz	1 Hz	2 Hz
Mushrooms	115	2.7 ± 0.2^{a}	$2.3 \pm 0.4^{a,b}$	1.8 ± 0.1^{b}
	120	2.4 ± 0.1^{a}	1.8 ± 0.1^{b}	1.6 ± 0.1^{c}
	125	2.3 ± 0.2^{a}	1.6 ± 0.1^{b}	1.4 ± 0.2^{c}
Chickpeas	115	4.6 ± 0.2^{a}	3.2 ± 0.1^{b}	2.4 ± 0.1^{c}
	120	4.1 ± 0.3^{a}	2.9 ± 0.2^{b}	2.3 ± 0.3^{c}
	125	3.8 ± 0.2^{a}	2.7 ± 0.1^{b}	2.4 ± 0.2^{b}

3.5.4 Temperature and cumulative lethality evolution curve

Figure 3.4 explains how the processing time is determined for mushrooms processed using conventional thermal processing, respectively. The time spent to achieve the target lethality is declared as the processing time for that particular processing temperature and reciprocating frequency. It is seen that 1 Hz of reciprocating frequency results in a quicker rate of temperature build up, as well as quicker achievement of the target lethality than 0 Hz of reciprocating frequency. The same trend is followed when the processing temperature is stepped up.

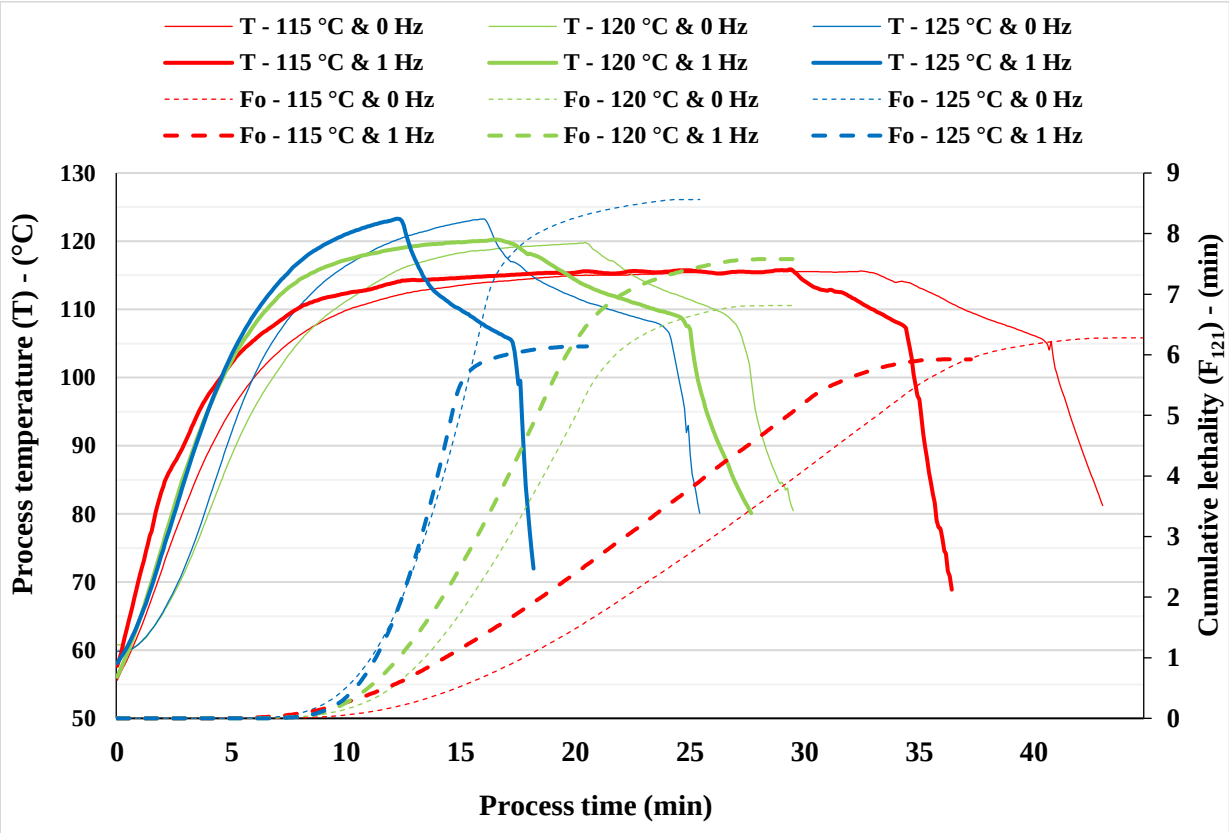

Figure 3.4. Process temperature and cumulative lethality evolution curve for mushrooms processed using conventional thermal processing at 0 Hz and 1 Hz.

3.6 Conclusions

The increment of reciprocating agitation frequency in thermal processing of mushrooms and chickpeas greatly reduced its processing time. In addition to that, the heating rate index and the heating lag factor decreased as the frequency of agitation was stepped up. This implies that the rate of heat transfer improved. More quality of the product should be retained for a lower processing time. Therefore, the best quality for mushrooms and chickpeas is expected at 125 °C and 2 Hz of reciprocating frequency as it took the least amount of time to achieve the target lethality. For mushrooms, it took 10.7 min and for chickpeas, it took 9.4 min. The results of this study could be beneficial for food processing industries to attain superior quality of commercially sterilized products.

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PREFACE TO CHAPTER 4

Thermal processing is well-established to make food safe and shelf-stable. Since this heat treatment degrades food quality, food industries have now shifted their focus on retaining more quality of the product as per the demand of consumers. Reducing the processing time by introducing reciprocating agitation is one way of doing so. Another method of retaining more quality for low-acid food is to employ an acidification process and reduce the pH to below 4.6 and process them as acidified vegetables, which makes use of lower temperatures than the conventional method and consequently, retains more product quality. This chapter focuses on comparing acidified thermal processing with the conventional method in terms of quality retention. This has been studied in the presence and absence of reciprocating agitation. The commodities used were mushrooms and chickpeas. Whereas the quality parameters included texture, color and antioxidant activity.

A part of this research was included in a poster presented in 2022 at the Northeast Agricultural and Biological Engineering Conference (NABEC), Maryland, USA. Whereas a part was submitted as a poster to present at NABEC, 2023.

Rampurwala, A., Taherian, A.R., and Ramaswamy, H.S., 2022. Thermal vs Acidified Thermal Processing of White Mushrooms: Influence of Reciprocating Agitation on Process Time and Product Quality. Northeast Agricultural and Biological Engineering Conference, Maryland, USA.

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Rampurwala, A., Taherian, A.R., and Ramaswamy, H.S., 2023. Acidified vs. conventional thermal processing of chickpeas and mushrooms: quality retention under the influence of reciprocating agitation.

CHAPTER 4

ACIDIFIED VS CONVENTIONAL THERMAL PROCESSING OF MUSHROOM AND CHICKPEA: QUALITY RETENTION UNDER THE INFLUENCE OF RECIPROCATING AGITATION

4.1 Abstract

In this study, retention of different quality parameters for conventional and acidified thermal processing of white mushroom (*Agaricus bisporus*) and Kabuli chickpea (*Cicer arietinum*), in presence or absence of reciprocating agitation, has been investigated and compared. Whole white mushrooms and Kabuli chickpeas were pre-treated and separately filled into the glass jars and covered with prepared solutions, leaving a headspace of 5 - 8%. For acidified thermal processing, a solution of 2% NaCl and 1.5% Citric acid was used. Whereas a 2% NaCl solution was used for conventional thermal processing. The jars were then processed in a pilot-scale steam retort at various temperatures and reciprocating frequencies. After thermal processing, retention of texture, color and antioxidant activity were assessed and compared.

The results revealed superior quality retention for acidified thermal processing as compared to conventional thermal processing of both, mushroom and chickpea. In addition to that, maximum quality retention was associated with acidified thermal processing at 100 ºC of processing temperature and 1 Hz of reciprocation frequency.

4.2 Introduction

Fresh low-acid foods are vulnerable to spoilage and pathogenic contamination. Canning (commercial sterilization) of such food products ensures that they have a much longer shelf-life and provide protection against the growth of mesophilic pathogens. The ease of storage of such canned products makes them convenient for consumers. With these advantages, canned products also come with undesirable changes to its quality (Awuah et al., 2007b; Ling et al., 2015). The heat treatment alters the product's texture, color and nutrient content. Hence, thermal processing

of food makes it convenient for storage, but compromises the product's quality. This shifts the food industry's attention on retaining most of the quality of processed food by making changes to the processing method. Reducing the processing time has proven to be an excellent step towards retaining more quality. Microorganisms present in food are more sensitive towards a change in temperature as compared to nutrients (Holdsworth, 1985; Ramaswamy and Marcotte, 2006; You, 2015). Therefore, a rapid treatment would destroy the microorganisms while retaining most of the quality.

Processing time is mainly reduced by providing agitation into the system during processing, which would induce forced convection into the particle-in-fluid phase and increase the rate of heat transfer (Singh et al., 2016). Reciprocating agitation increases the rate of heat transfer by the highest proportion, making it the best type of agitation for reducing processing time (Singh et al., 2018). However, high frequencies of agitation force the food particles to collide and lose its textural and visual quality. Thus, optimization of the frequency of agitation is of high importance.

Heat treatment of food softens its tissues as pectic substances present in cell walls and inter-lamellar regions are degraded (Greve et al., 1994; Vu et al., 2004; Anthon et al., 2005; Taherian and Ramaswamy, 2009). This reduces the hardness of food and affects rest of the textural parameters like springiness and chewiness. In some cases, these changes are desirable as it reduces the cooking time at the consumer's end. These foods include chickpeas, dry peas and beans. In other cases, softening of food is not preferred as it reduces the biting and chewing capacity of the food, which results in an undesirable experience for consumption. Several studies on the change in the texture of cabbage, asparagus, potatoes, whole green gram and split red gram during thermal processing have been carried out (Lau et al., 2000; Nisha et al., 2006; Jaiswal et al., 2012).

Another important parameter that is compromised during thermal processing is the product's color (Herbach et al., 2004; Patras et al., 2010). A consumer would first judge a product by its color and would usually inspect it further only if its color is right. This makes color an extremely important parameter in food processing. Pigments present in food include chlorophyll,

carotenoids, lycopene and xanthophyll (Clydesdale and Ahmed, 1978). These pigments are deteriorated when exposed to severe heat. Chlorophyll gives the fresh green color to green vegetables. Unfortunately, heat treatment causes chlorophyll to undergo a series of enzymatic and non-enzymatic reactions that turn it into a shade of brown (Gauthier-Jaques et al., 2001; Gaur et al., 2006). Gaur et al. (2007) reported that this color change is because of the conversion of chlorophyll to pheophytins on loosing its central magnesium ion when heated. Changes in color during thermal processing have also been studied on potatoes, radishes, carrots and green beans (Abbatemarco and Ramaswamy, 1994; You, 2015; Singh et al., 2015b).

Food also contains antioxidants that protect our cells from free radicals that could cause cancer and cardiovascular diseases. Antioxidants in food include anthocyanins, β-carotene, ascorbic acid, α-tocopherol and other flavonoids. While antioxidants could decay when exposed to heat, studies have shown that heating food increases its antioxidant activity (Dewanto et al., 2002a,b; Jeong et al., 2004). This contradiction is because heating food increases the extraction of bound phenolic compounds. This implies that thermal processing could potentially increase the antioxidant activity of food.

The conventional method of thermal processing (commercial sterilization) involves the inactivation of vegetative microorganisms, as well as bacterial spores that require a severe heat treatment. This forces commercial sterilization to use harsh processing temperatures of 100-130 °C. In acidified thermal processing, the low-acid foods are first acidified to create a high-acid environment (pH ≤ 4.6). This kind of environment inhibits the activity of bacterial spores, such as *Clostridium botulinum* spores, leaving only vegetative microorganisms to be inactivated (Ramaswamy and Marcotte, 2006; You et al., 2016). This requires a milder treatment called pasteurization, which is carried out at temperatures about 90 °C. The lower temperatures involved with acidified thermal processing suggest that this method would retain more quality in processed products (Tola and Ramaswamy, 2018).

However, the study of acidified thermal processing of mushrooms and chickpeas is limited. Furthermore, there is a lack of studies that evaluated the influence of reciprocating agitation on thermal processing of the mentioned commodities. Therefore, this study aimed at comparing

acidified thermal processing against the conventional method, in terms of the product's texture (hardness, springiness and chewiness), color (L*, a* and b*) and its antioxidant activity. In addition to that, the influence of reciprocating agitation during various thermal treatments was studied to find out the most suitable frequency of reciprocation for superior quality retention.

4.3 Materials and methods

4.3.1 Sample Preparation

White mushroom (*Agaricus bisporus*) and Kabuli chickpea (*Cicer arietinum*) samples were pretreated according to their respective requirements. Mushrooms (cap average radius: 35 mm, cap average height: 20 mm, stipe length: < 15 mm) were handwashed for a minute, then blanched in a solution of 0.5% Citric acid and 0.1% Ascorbic acid for 3 minutes at 96 – 98 °C. Raw chickpeas (standard size) were soaked overnight for 14 hours, then blanched for 4 minutes at 70 °C in water. Both samples were dried using paper towels to remove surface moisture. The pretreated samples were separately filled into glass jars and covered with the canning liquid, leaving a headspace of 5 – 8%. A flexible type-T thermocouple was inserted into the mushroom's center that was placed in the centre of the can. A rigid type-T thermocouple was inserted into the jar of chickpeas, placing its end in the center of the jar.

For the conventional method of thermal processing, the samples were processed in a 2% NaCl solution as the canning liquid. Whereas a solution of 2% NaCl and 1.5% Citric acid was used for acidified thermal processing. The amount of citric acid was chosen as 1.5% because this was an appropriate amount to bring down the pH of both commodities to 4.2 (± 0.1). The jars were held in the retort's cage such that its long axis was perpendicular to the direction of reciprocation. The ends of the thermocouples have been placed in the stated manner to record the temperature at the cold spot.

4.3.2 Retort Setup

A pilot-scale, vertical, static retort (Loveless Manufacturing Co., Tulsa, OK) was used for the experiment. The retort was modified into a reciprocating agitation retort by installing a slider-

crank assembly, magnetic motor and basket setup at one-third height of the retort from the top. The frequency of reciprocation was controlled by varying the motor's input voltage. The heating medium used was a combination of steam and air, and cold water was used for cooling.

4.3.3 Processing conditions

Each sample was thermally processed at reciprocating frequencies of 0, 1, and 2 Hz, with process temperatures of 115, 120, and 125 °C for conventional thermal processing and 90, 95 and 100 °C for acidified thermal processing. Two experimental runs were done for each test. The samples were over-processed in the first run to provide time-temperature data, through which the processing time was obtained. The lethality for every 5 seconds of processing was calculated by using the following Equation:

$$Fo = \int L\,dt = \sum 10^{\frac{Ts - To}{Z}}\,\frac{5}{60} \qquad \textbf{4.1}$$

where T_s represents the sample temperature and T_o stands for the reference temperature. The cumulative lethality was also calculated. The point at which the target lethality was achieved was noted as the processing time for those processing conditions. The target lethality for the conventional method of thermal processing is F_{121} = 5 minutes and for acidified thermal processing, the target lethality is F_{90} = 10 minutes. Once the processing time was obtained, the next batch of samples were processed accordingly and cooled to 80 °C using cooling water, then refrigerated for further cooling to room temperature. Duplicate runs were done for each treatment. The processed products were then subjected to assessment of different quality parameters.

4.3.4 Quality assessment

4.3.4.1 Texture profile analysis

The hardness, springiness and chewiness values of blanched and processed mushrooms and chickpeas were obtained using the TA-XT Plus Texture Analyser (Texture technologies corp., Scarsdale, NY, USA). The software used to obtain the texture parameter values is Texture

Exponent 32 software (Texture Technologies Corp., Scarsdale, NY/ Stable Micro Systems, Godalming, Surrey, UK). The stipes of processed mushrooms were sheared off using a sharp knife to obtain flat-base caps of mushrooms. The prepared sample was then double compressed up to 50% of its initial height using a 25 mm cylindrical probe at a speed of 1 mm/s. Individual chickpeas were also assessed using the same probe at a speed of 5 mm/s for 50% compression of initial height. For texture assessment, a minimum of 15 samples were tested for each commodity.

Each sample was subjected to two compression-decompression cycles that mimicked two bites. The software represents these two bites as two peaks on a Force vs Distance graph. The maximum force required to compress the sample in the first compression was noted as its hardness. Springiness was calculated as the ratio of the sample's height before each compression. It represents the ability of the sample to spring back to its original height after the first compression. Chewiness corresponds to the energy required to chew the sample. It is calculated as the product of hardness, springiness and the ratio of the area under peak 2 to the area under peak 1.

4.3.4.2 Color analysis

The equipment used for analysis of the color parameters was Minolta Tristimulus Chroma Meter (Minolta Corp., Ramsey, NJ, USA). The lightness (L*) and redness (a*) of processed samples were measured and displayed by the software (SpectraMagic, Minolta Corp., Ramsey, NJ, USA). L* is measured on a scale of lightness to darkness, 100 being the lightest and 0 being the darkest. a* is measured on a scale of redness to greenness, with +a being redder and -a being greener. Similarly, b* represents the color on a scale of yellowness to blueness, +b being yellower and -b being bluer.

4.3.4.3 Antioxidant activity analysis

The antioxidant activity was measured using the DPPH (2, 2-diphenyl-1-picrylhydrazy) method as described by Choi et al. (2006) with some modifications. DPPH is a stable radical that is deep-purple in color. In the presence of antioxidants, DPPH is reduced and the solution is decolorized, allowing one to measure the antioxidant activity using a spectrophotometer (Singh et al., 2015b).

The sample (10 g) was blended with 20 ml of Methanol (99%) for a minute. The mixture was then homogenized at 10000 rpm for 10 minutes and centrifuged at 4000 rpm for 20 minutes. The supernatant was filtered through a filter paper to obtain the extract.

In a cuvette, 1.6 ml of DPPH solution (0.2 mM solution of 99% Methanol) was added to 0.4 ml of extract and left at room temperature in the dark for 30 minutes for the reaction to proceed. The absorbance was measured by a spectrophotometer at 517 nm, along with the control (1.6 ml of DPPH solution + 0.4 ml of 99% Methanol) for each reading. This gives the sample absorbance (A_{sample}) and the control absorbance ($A_{control}$). The DPPH Radical Scavenging Activity was measured in percentage by using the following Equation:

$$\text{DPPH Radical Scavenging Activity} = (1 - (A_{sample} / A_{control})) * 100 \quad \textbf{4.2}$$

4.4 Statistical analysis

ANOVA single factor data analysis was used for the statistical analysis of the data, followed by the Bonferroni correction. The analysis was performed on Microsoft Excel. After carrying out the analysis, it was determined that a difference between any two groups was significant if $p < 0.05$. Each experiment was done twice with at least 8 samples being analysed for each test.

4.5 Results and discussion

4.5.1 Processing time

For both commodities, the processing time lowered as the frequency of reciprocation increased. This relationship is shown in Table 4.1. It clearly indicates that higher reciprocation frequencies would increase the rate of heat transfer to greater extents. Therefore, the highest processing times were observed for still processing (0 Hz) and the lowest were obtained at 2 Hz. On average, the processing time dropped by 15.3% when the frequency was stepped up from 0 Hz to 1 Hz, and 11.2% when the frequency rose from 1 Hz to 2 Hz. From the lowest to the highest frequency of reciprocation tested in this study (0 Hz to 2 Hz), the processing time reduced by 24.9%. A similar relation between processing time and frequency of agitation has also been obtained in

previous studies (Abbatemarco and Ramaswamy, 1994; Singh et al., 2016). As temperature increased, the processing time reduced drastically. This is because the difference between the reference temperature and processing temperature increases with an increment in the temperature, contributing a greater value towards the lethality. This results in a quicker target lethality achievement. It was observed that by stepping up the temperature by 5 °C, the processing time reduced by 35.3% on average. Figure 4.1 shows how the sample temperature and cumulative lethality for acidified thermal processing evolved with the passage processing time.

Table 4.1. Processing time for mushroom and chickpea treated using acidified and conventional thermal processing at various temperatures and frequencies. Mean ± standard deviation with letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Sample	Treatment	Process temperature (°C)	0 Hz (min)	1 Hz (min)	2 Hz (min)
Mushroom	Conventional thermal processing	115	33.1 ± 0.6^{a}	28.8 ± 0.5^{b}	28.4 ± 0.6^{b}
		120	20.0 ± 0.4^{a}	16.4 ± 0.1^{b}	14.0 ± 0.3^{c}
		125	15.0 ± 0.3^{a}	13.1 ± 0.3^{b}	10.7 ± 0.2^{c}
	Acidified thermal processing	90	23.3 ± 0.7^{a}	20.9 ± 0.4^{b}	18.9 ± 0.6^{c}
		95	16.4 ± 0.3^{a}	14.5 ± 0.3^{b}	10.8 ± 0.2^{c}
		100	10.3 ± 0.2^{a}	9.3 ± 0.2^{b}	7.40 ± 0.2^{c}
Chickpea	Conventional thermal processing	115	32.8 ± 0.4^{a}	27.3 ± 0.5^{b}	27.0 ± 0.3^{b}
		120	18.1 ± 0.2^{a}	14.6 ± 0.3^{b}	13.6 ± 0.2^{c}
		125	14.0 ± 0.2^{a}	10.3 ± 0.2^{b}	9.40 ± 0.2^{c}
	Acidified thermal processing	90	21.8 ± 0.3^{a}	18.7 ± 0.4^{b}	17.0 ± 0.5^{c}
		95	13.6 ± 0.6^{a}	11.3 ± 0.1^{b}	9.80 ± 0.3^{c}
		100	8.90 ± 0.2^{a}	7.60 ± 0.2^{b}	7.20 ± 0.1^{c}

Overall, a higher frequency of reciprocation and processing temperature resulted in a lower processing time. In addition to that, acidified thermal processing allowed the processing of products at much lower temperatures as compared to the conventional method. Therefore, one

would expect the best quality retention in the case of acidified thermal processing at 100 °C and 2 Hz of reciprocation frequency. At these processing conditions, the processing time for mushrooms was 7.4 min, and that of chickpeas was 7.2 min, giving an opportunity for superior quality retention compared to all cases considered in this study.

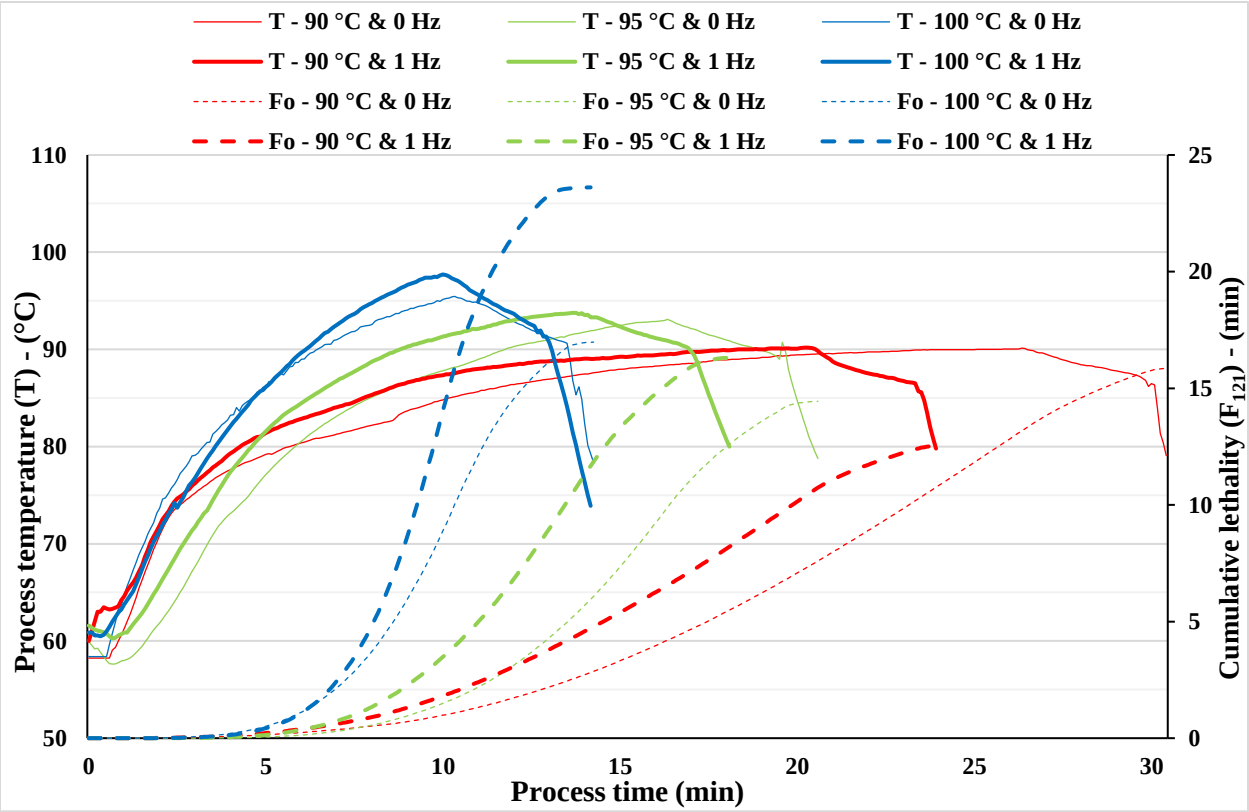

Figure 4.1. Process temperature and cumulative lethality evolution curve for mushrooms processed using acidified thermal processing at 0 Hz and 1 Hz.

4.5.2 Texture profile analysis

4.5.2.1 Hardness

4.5.2.1.1 Mushroom

Mushrooms that were processed using the acidified method had a hardness value that was twice as that of the ones processed using the conventional method. This is clearly indicated in Figure

4.2. This implies that conventional thermal processing softened the mushroom to a greater extent than the acidified method. A higher hardness value is desirable as it means that the processed product has retained more texture, rather than being cooked and softened. Acidified thermal processing of mushrooms retained a hardness value much closer to the blanched mushrooms. The conventional method reduced the hardness by 62.8%, whereas it reduced only by 23.4% for acidified thermal processing. Also, the hardness increased with temperature. This increment is due to the lower processing times associated with higher processing temperatures. However, the increments were insignificant in some cases.

For acidified thermal processing of mushrooms, the hardness increased by 4.3% from 0 Hz to 1 Hz, and suddenly reduced by 16.4% when the frequency was increased to 2 Hz. This is because 2 Hz of reciprocation frequency forced mushrooms to lose their hardness by colliding into each other. This loss of hardness due to collision dominated over the influence of a lower processing time and resulted in a softer product. Similar results were reported by You (2015). Therefore, the best value of hardness (4600 g Force) was obtained for acidified thermal processing at 1 Hz of reciprocation at 100 °C.

4.5.2.1.2 Chickpea

On average, acidified thermal processing of chickpeas resulted in a product with hardness of 4197 g force, which was almost 10 times more than the ones processed by the conventional method. This massive difference between the two processes indicates that chickpeas are sensitive to processing temperatures near 120 °C and completely lose its texture. The conventional method produced chickpeas that were almost mashed and most of the chickpeas split up halfway as shown in Figure 4.3 (a). They were also over-hydrated, swollen and mostly broken. Whereas the chickpeas that were processed using the acidified method had an intact texture, as seen in Figure 4.3 (b). Blanched chickpeas had a hardness value of 6262 g Force. The conventional method reduced the hardness by 93% from that of blanched chickpeas, and it reduced only by 23.4% for acidified thermal processing. The acidic condition resulted in some clouding of the covering liquid, but when drained and placed on a plate, they showed perfect formation with intact pieces and very uniform appearance.

The hardness increased by 6.2% from 0 to 1 Hz for acidified thermal processing, and reduced by 8.7% from 1 Hz to 2 Hz. Thus, the higher collision rate at 2 Hz degraded the hardness for chickpeas too. Once again, the best value of hardness (4483 g force) was obtained during acidified thermal processing at 100 °C and 1 Hz of reciprocation.

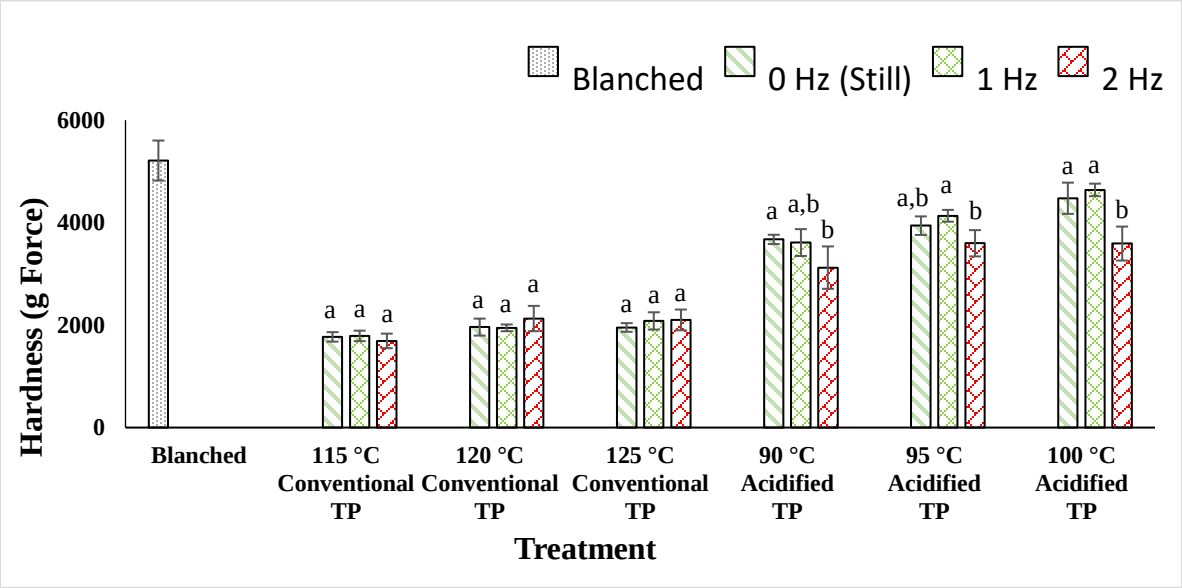

Figure 4.2. Hardness of mushrooms for different treatments at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

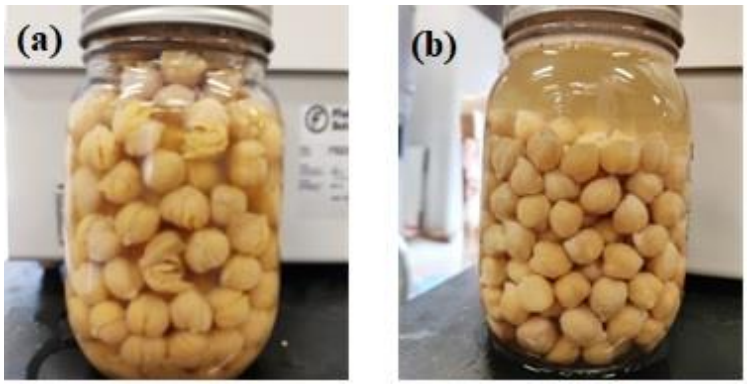

Figure 4.3. (a) Chickpeas processed using conventional thermal processing at 120 °C and 0 Hz. (b) Chickpeas processed using acidified thermal processing at 100 °C and 1 Hz.

4.5.2.2 Springiness

4.5.2.2.1 Mushroom

Table 4.2 shows the springiness of mushrooms for different processing conditions. The springiness of mushrooms processed using the acidified method was 7.8% more than the ones produced by the conventional method. During acidified thermal processing, the springiness increased by 11.9% when the frequency of reciprocation was stepped up to 1 Hz from still processing. The highest springiness of 58.6% on average was obtained for 1 Hz of agitation for the acidified method, dropping down to 47.7% at 2 Hz. This drop in springiness is a result of the higher collision rate for 2 Hz of reciprocation frequency, forcing the mushrooms to lose some of its elasticity. Usually, a consumer would prefer a product that has a higher springiness value as that add texture to the product. Therefore, the best result of springiness was obtained at 1 Hz of reciprocation and 95 °C as the processing temperature for acidified thermal processing.

4.5.2.2.2 Chickpea

As reported in Table 4.2, acidified thermal processing of chickpeas resulted in a springiness value that was 89.3% more than the ones processed using the conventional method. The

springiness was 55.3% lower than blanched chickpeas for the conventional method, and the same was only 15.3% for acidified thermal processing. Thus, the acidified method retains much more springiness. The best value (56.5% on average) of springiness for processed chickpeas was obtained at 1 Hz of reciprocation frequency for acidified thermal processing.

Table 4.2. Springiness of mushrooms and chickpeas for various processing conditions. Mean ± standard deviation with letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Sample	Treatment	Process temperature (°C)	0 Hz (%)	1 Hz (%)	2 Hz (%)
Mushroom	Conventional thermal processing	115	51 ± 2^{a}	52 ± 1^{a}	48 ± 2^{a}
		120	53 ± 2^{a}	49 ± 1^{b}	48 ± 2^{b}
		125	$47 \pm 1^{a,b}$	48 ± 0^{a}	$45 \pm 2^{a,b}$
	Acidified thermal processing	90	54 ± 1^{a}	60 ± 5^{a}	46 ± 2^{b}
		95	53 ± 1^{a}	61 ± 3^{b}	48 ± 1^{c}
		100	50 ± 4^{a}	55 ± 5^{a}	48 ± 2^{a}
Chickpea	Conventional thermal processing	115	25 ± 3^{a}	28 ± 4^{a}	28 ± 3^{a}
		120	31 ± 4^{a}	32 ± 4^{a}	30 ± 4^{a}
		125	42 ± 5^{a}	25 ± 4^{b}	23 ± 2^{b}
	Acidified thermal processing	90	53 ± 3^{a}	55 ± 3^{a}	56 ± 3^{a}
		95	59 ± 5^{a}	59 ± 4^{a}	54 ± 5^{a}
		100	54 ± 2^{a}	56 ± 6^{a}	55 ± 3^{a}

4.5.2.3 Chewiness

4.5.2.3.1 Mushroom

Table 4.3 shows the chewiness of mushrooms processed at different conditions. The conventional method of thermal processing produced mushrooms with a chewiness higher that those processed using the acidified method. For 0 Hz and 1 Hz combined, the chewiness of

mushrooms processed conventionally was 19.9% more. This means that the conventional method resulted in a chewier product, which is undesirable. Therefore, acidified thermal processing gave better chewiness values and a rawer product.

4.5.2.3.2 Chickpea

The chewiness data of chickpeas processed using the conventional method is of little importance as the product was too mashed to gather any meaningful data. Such low values of chewiness (17.0 g force on average) show that the product lost its texture to such an extent that no relevant data could be obtained. This loss of texture is visible in Figure 4.3 (a), and Table 4.3 shows the chewiness of chickpeas processed at various conditions. Acidified thermal processing resulted in a product with an average chewiness of 319.8 g force, which is 35.1% lower than the chewiness of blanched chickpeas. As a lower chewiness value is preferable, the best results were obtained for acidified thermal processing at 100 °C and 2 Hz of reciprocation frequency.

Table 4.3. Chewiness of mushrooms and chickpeas for various processing conditions. Mean ± standard deviation with letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Sample	Treatment	Process temperature (°C)	0 Hz (g Force)	1 Hz (g Force)	2 Hz (g Force)
Mushrooms	Conventional thermal processing	115	452 ± 49^{a}	$371 \pm 55^{a,b}$	332 ± 22^{b}
		120	607 ± 50^{a}	685 ± 41^{a}	401 ± 54^{b}
		125	658 ± 72^{a}	695 ± 70^{a}	436 ± 43^{b}
	Acidified thermal processing	90	356 ± 33^{b}	490 ± 38^{a}	446 ± 32^{b}
		95	387 ± 20^{b}	552 ± 52^{a}	489 ± 35^{a}
		100	530 ± 36^{a}	578 ± 47^{a}	574 ± 55^{a}
Chickpeas	Conventional thermal processing	115	12 ± 2^{a}	13 ± 2^{a}	11 ± 1^{a}
		120	13 ± 1^{b}	21 ± 3^{a}	$16 \pm 2^{a,b}$
		125	40 ± 5^{a}	11 ± 1^{b}	14 ± 2^{b}
	Acidified thermal processing	90	362 ± 47^{a}	307 ± 42^{a}	309 ± 35^{a}
		95	314 ± 35^{a}	349 ± 23^{a}	339 ± 41^{a}
		100	302 ± 40^{a}	307 ± 34^{a}	290 ± 32^{a}

4.5.3 Color analysis

4.5.3.1 Lightness

4.5.3.1.1 Mushroom

The lightness of mushrooms processed using the acidified method was 40.65% higher than the ones processed by the conventional method. Figure 4.4 shows the lightness values of mushrooms. On average, the lightness of mushrooms produced by acidified thermal processing was 77.5. The highest value of lightness was 81.1 at 100 °C and 1 Hz of reciprocation frequency. This is 97.5% lightness retention from the blanched mushrooms. The lightness value increases as the reciprocation frequency increases from 0 Hz to 1 Hz, but drops dramatically for 2 Hz of

reciprocation. This is because the excessive collision rate at 2 Hz wounds the mushrooms, resulting in a darker color.

4.5.3.1.2 Chickpea

There was an insignificant change in the lightness value of chickpeas processed by the conventional and acidified method. This is because the lightness value of blanched chickpeas (51.6) is already so low that any further processing does not affect its lightness significantly. The lightness of chickpeas produced by the conventional method is 6% higher than the blanched chickpeas and the lightness of chickpeas produced by the acidified method is 4.9% higher than the blanched chickpeas. On average, the lightness of processed chickpeas (acidified and conventional) was 54.5 with a coefficient of variance of 2.2% only. Therefore, all treatments result in a product with similar lightness and for the same reason, no trend is observed to understand the influence of reciprocation frequency on the lightness of chickpeas.

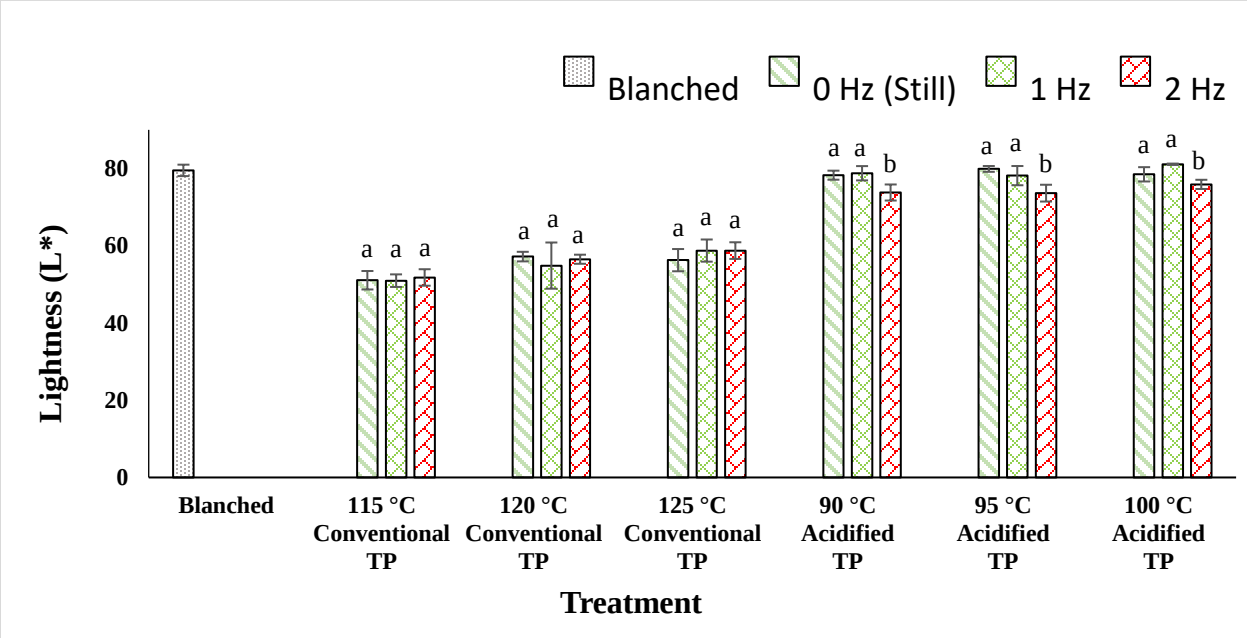

Figure 4.4. Lightness (L*) of mushrooms for different treatments at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

4.5.3.2 Redness

4.5.3.2.1 Mushroom

As mushrooms are white in color, any discoloration is clearly visible to the consumers. Thus, the redness of processed mushrooms is undesirable and the lowest redness value would be preferred. Figure 4.5 shows the redness value of mushrooms for different treatments. On average, the redness of mushrooms produced by acidified thermal processing is 1.38, which is 73.2% lower than the redness of mushrooms processed using the conventional method. Also, the redness of mushrooms produced by the acidified method is only 30.5% higher than the redness of blanched mushrooms, as compared to 388 % for the conventional method. Clearly, acidified thermal processing results in a redness value much lower than the conventional method. This difference in redness is evidently observed on comparing Figure 4.6 (a) and Figure 4.6 (b). The best value of redness was obtained at 95 °C and 1 Hz of reciprocation frequency for acidified thermal processing.

4.5.3.2.2 Chickpea

Similar to the results of lightness values of chickpeas, the change in redness values for different treatments was not considerable. On average, the redness of chickpeas processed by the conventional method was only 11.9% lower than the ones produced by the acidified method. However, the average redness of processed chickpeas was 44.4% lower than the redness of blanched chickpeas, which had a redness value of 10.8. This essentially means that the redness of chickpeas decreases when it undergoes thermal processing. The best redness value was observed at 120 °C at still processing for the conventional method. Regarding acidified thermal processing, the lowest value of redness of 5.3 was observed at 95 °C and 2 Hz of reciprocation frequency.

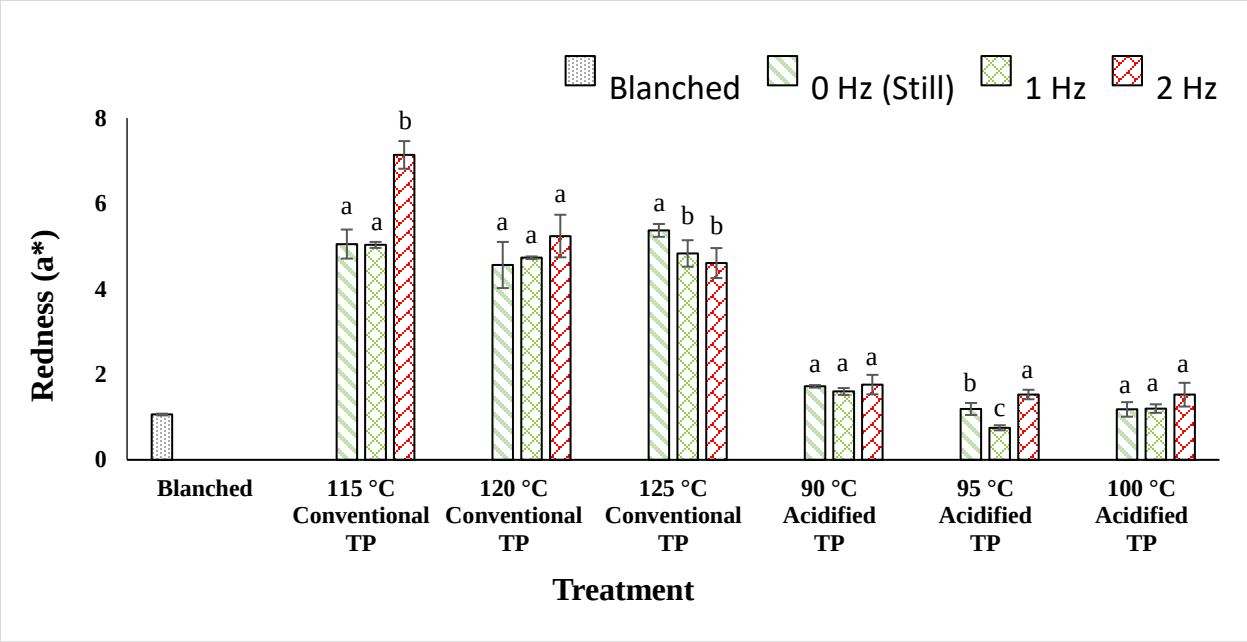

Figure 4.5. Redness (a*) of mushrooms for different treatments at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

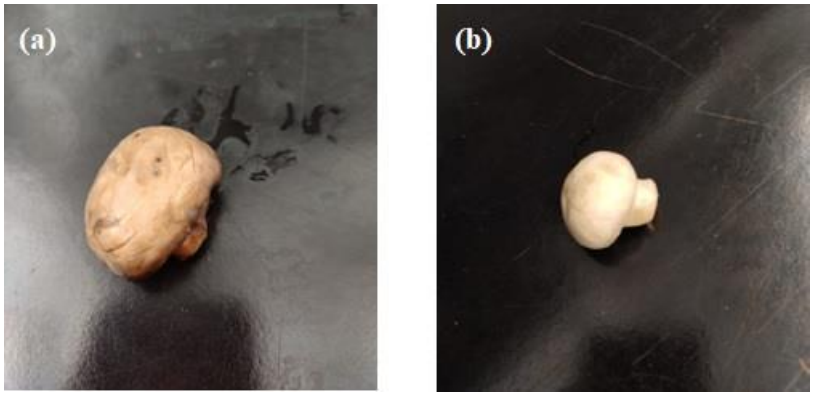

Figure 4.6. (a) Mushroom processed using conventional thermal processing at 120 °C and 1 Hz. (b) Mushroom processed using acidified thermal processing at 90 °C and 1 Hz.

4.5.4 Antioxidant activity

4.5.4.1 Mushroom

The antioxidant activity of mushrooms produced by the conventional method of thermal processing is higher than the blanched mushrooms, which had a DPPH Radical Scavenging Activity of 83%. The average antioxidant activity of mushrooms processed by the conventional method is 3.5% higher than blanched mushrooms. It was also noted that acidified thermal processing gave an antioxidant activity even higher than the mushrooms produced by the conventional method. This is because acidified thermal processing involves the usage of Citric acid to lower the pH of mushrooms, and this acid is an antioxidant itself. The antioxidant activity of mushrooms processed by acidified thermal processing is 8.4% higher than blanched mushrooms and 4.7% higher than the mushrooms produced by the conventional method. Therefore, the best results were obtained for acidified thermal processing, with an average DPPH radical scavenging activity of 90%. The results of each treatment have been recorded in Table 4.4.

4.5.4.1 Chickpea

The antioxidant activity of chickpeas for different treatments, as shown in Table 4.4, followed a similar trend to that of mushrooms. The DPPH radical scavenging activity of blanched chickpeas was 28.7%. The antioxidant activity increased by 18% from blanched chickpeas to the ones processed conventionally, and increases further for acidified thermal processing by 51.2%. Therefore, the best results were obtained for acidified thermal processing, with an average DPPH Radical Scavenging Activity of 53.7%.

Table 4.4. Antioxidant activity (DPPH Radical Scavenging Activity - %) of mushrooms and chickpeas for various processing conditions. Mean ± standard deviation with letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Sample	Treatment	Process temperature (°C)	0 Hz (RSA - %)	1 Hz (RSA - %)	2 Hz (RSA - %)
Mushrooms	Conventional	115	85.6 ± 0.5^{a}	86.0 ± 0.6^{a}	86.7 ± 06^{a}
	thermal	120	85.3 ± 0.1^{c}	86.0 ± 0.2^{b}	87.9 ± 0.1^{a}
	processing	125	85.2 ± 1.1^{a}	85.4 ± 0.4^{a}	85.0 ± 1.1^{a}
	Acidified	90	89.9 ± 0.7^{b}	91.5 ± 0.1^{a}	89.5 ± 0.4^{b}
	thermal	95	88.7 ± 1.6^{b}	90.0 ± 0.5^{a}	90.8 ± 0.3^{a}
	processing	100	90.0 ± 0.4	89.8 ± 1.2	89.6 ± 0.8
Chickpeas	Conventional	115	47.0 ± 4.9^{a}	28.6 ± 3.9^{b}	33.5 ± 2.6^{b}
	thermal	120	41.4 ± 6.4^{a}	43.7 ± 2.3^{a}	31.2 ± 3.8^{b}
	processing	125	34.8 ± 4.4^{a}	20.8 ± 3.7^{b}	24.3 ± 0.1^{b}
	Acidified	90	69.5 ± 4.4^{a}	50.2 ± 4.0^{c}	60.7 ± 2.2^{b}
	thermal	95	71.8 ± 3.5^{a}	39.5 ± 4.1^{c}	47.4 ± 4.0^{b}
	processing	100	55.2 ± 3.2^{a}	52.2 ± 2.8^{a}	36.5 ± 2.1^{b}

4.6 Conclusions

The retention of the product's texture and color clearly increases as the frequency of reciprocation increases. However, in most cases the retention drops down when the frequency of reciprocation is increased from 1 Hz to 2 Hz. This is primarily because 2 Hz of reciprocation frequency is extremely harsh due to the excessive rate of collision of food particles. Thus, 1 Hz of reciprocation frequency is the best choice for maximum quality retention of mushrooms and chickpeas. As the processing temperature increases, the processing time decreases and more quality is retained. So, 125 °C is the best processing temperature for the conventional method of thermal processing and 100 °C is the most preferred processing temperature for acidified thermal processing.

Acidified thermal processing resulted in products that have a much higher retention in quality as compared to the conventional method. For every parameter tested in the analysis of texture and color, acidified thermal processing gave better results. The only exception was the redness of chickpeas, but the difference was not substantial. Also, the antioxidant activity was higher for acidified thermal processing due to the addition of Citric acid, which is an antioxidant. Therefore, acidified thermal processing gives superior quality over conventional thermal processing for mushrooms and chickpeas. Overall, acidified thermal processing of mushrooms and chickpeas at a processing temperature of 100 °C and reciprocation frequency of 1 Hz resulted in maximum retention in the product's quality.

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CHAPTER 5

GENERAL CONCLUSIONS

The heat penetration characteristics of mushrooms and chickpeas were greatly affected by a change in the frequency of reciprocating agitation. As the frequency of agitation increased, the heating rate index decreased, heating lag factor decreased, and the processing time to achieve the target lethality also decreased. Greater change was observed when the frequency increased from 0 Hz to 1 Hz, as compared to increasing the frequency from 1 Hz to 2 Hz. The rate of heat transfer was maximum at 2 Hz. As the temperature of the process increased, the rate of heat transfer increased drastically, and the processing time decreased as a result. The lowest processing times for mushrooms and chickpeas was observed at 125 °C and 2 Hz. Thus, maximum retention in product quality was expected to for the same processing condition. However, on examining the color, texture and antioxidant activity for conventional thermal processing of the mentioned commodities, it was found that maximum retention of product quality was at 125 °C and 1 Hz. This was because 2 Hz of reciprocating frequency forced the food particles to collide at a higher rate inside the jars, forcing them to lose their quality.

On comparing acidified thermal processing with the conventional method of thermal processing, it was observed that acidified thermal processing retained much more color and texture of processed mushrooms. Regarding chickpeas, the retention of texture was substantially more for acidified thermal processing. However, the effect on color was not considerable as blanched chickpeas were already too dark. Thus, further processing did not impact the color of chickpeas significantly. The antioxidant activity was fairly higher for acidified thermal processing of both commodities as the process of acidification involved the addition of citric acid, which is an antioxidant itself. The quality retention for acidified thermal processing was higher than the conventional method as it uses milder processing temperatures.

This is the first study that combines acidified thermal processing with reciprocating agitation thermal processing. Therefore, it is crucial to find the processing parameters at which maximum quality of the products is retained for this combination of thermal processes. Overall, the best quality of processed mushrooms and chickpeas were observed for acidified thermal processing at a temperature of 100 °C and a reciprocating agitation frequency of 1 Hz.

CHAPTER 6

FUTURE RECOMMENDATIONS

Although this study revealed the advantages of combining acidified low acid food thermal processing (ALAFTP) with reciprocating agitation thermal processing (RATP), there are many food commodities that may or may not follow the trend. For example, it is well-known that most of the green vegetables like green beans and spinach lose their color on acidification due to degradation of chlorophyll. In addition to that, low acid foods that have a weak textural integrity could lose most of its texture even at low reciprocating frequencies. Therefore, these treatments must be tested on multiple low acid foods to understand the individual and combined effect of ALAFTP and RATP on each type of food item.

One important parameter that must be tested to put ALAFTP in practice is the taste of the resulting product. As the low acid food is acidified, it is expected to have a sour taste. However, the amount of acid required is generally low, resulting in a product that is not unpleasantly sour. Food-grade acids like glucono-d-lactone are extremely mild in sourness, making it a preferable candidate for acidifying low acid food. Furthermore, salads and cooked vegetables are usually acidified using lemon juice. In such cases, acidified food products would largely be accepted by consumers as it eliminates the need of adding lemon juice or any other sour flavor.

Lastly, the process could always be optimized to obtain a specific amount of acid required for acidifying various low acid foods. The minimum amount of acid required to reduce the pH below 4.5 would be the most preferred. Similarly, the frequency of reciprocation required to increase the rate of heat transfer the most while keeping the texture intact would be best frequency. These numbers would vary in accordance to the sample that is being tested. Therefore, it is essential to test every low acid food for its appropriate parameters of processing.

Overall, the combination of ALAFTP and RATP must be studied on a wide variety of low acid foods to analyse the effectiveness of the process, optimize the process parameters for each of

them and study how it influences the resulting taste of the product. Certainly, it would have an advantage for non- green color foods.

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