EFFECT OF RECIPROCATION AGITATION, END-OVER-END CONTINUOUS AND END-OVER-END OSCILLATORY AGITATION THERMAL PROCESSING ON PROCESS PARAMETERS AND QUALITY OF ATLANTIC SALMON AND RADISH

By

Kanishk Rawat

Department of Food Science and Agricultural Chemistry

Macdonald campus of McGill University

Montreal, Canada

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DEDICATED TO MY PARENTS

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ABSTRACT

Thermal processing is a critical method for ensuring the safety and extending the shelf life of low-acid foods. However, traditional static processing methods often result in prolonged heating times and reduced product quality due to uneven heat distribution. To address these challenges, advanced agitation thermal processing techniques have been developed to enhance heat transfer efficiency and improve product quality. This research focuses on evaluating the effects of reciprocation agitation thermal processing (RATP) and end-over-end (EOE) agitation in continuous and oscillatory mode on heat penetration rates and quality retention in model and real foods.

The first study examined the impact of RATP on the heat processing properties and the quality of Atlantic pink salmon chunks packed in glass jars. Thermal treatments were carried out at retort temperatures of 115, 120 and 125°C with reciprocation frequencies of 0, 1.0, and 1.5 Hz. The study evaluated the influence of RATP on heating rate index, heating lag factor and calculated processing time for a target lethality. Quality attributes of texture and color were also evaluated. Results demonstrated that increasing reciprocation frequency and retort temperature significantly enhanced heat transfer and reduced the process times. The optimal conditions for quality retention were found at 125°C and 1.0 Hz, where the salmon maintained the desirable texture and color. However, processing at higher frequencies (>1.5 Hz) led to excessive mechanical damage to particles, negatively affecting product integrity.

The second study explored the comparison between EOE continuous (EOE-C) and EOE intermittent oscillation (with a 10 s dwell time) (EOE-O) using Nylon spheres as food simulating heat transfer models in water, glycerin, and oil media. Experiments were carried out at rotational speeds of 10, 20, and 30 RPM and retort temperatures of 115, 120 and 125°C. Results revealed that EOE-C was more effective at lower speeds, but EOE-O was significantly superior with enhanced heat transfer all through the rotation speeds. This improvement was attributed to better mixing due to not only the oscillatory mode, but also due to the periodic reversal in oscillation direction after brief static dwell times. This study was further validated using radish as a typical food particle. Results were consistent with the Nylon particle study, and better texture and color properties were obtained at 125°C, 30 RPM EOE-O process.

Overall, both studies confirm that agitation thermal processing methods such as RATP, EOE-C and EOE-O can substantially improve heat transfer rates and product quality. These techniques offer promising advancements in thermal processing by reducing process times and preserving product quality attributes, making them suitable for industrial applications of particulate fluid food processing in cans or glass containers.

RÉSUMÉ

Le traitement thermique est une méthode essentielle pour garantir la sécurité et la durée de conservation prolongée des aliments peu acides. Cependant, les méthodes de traitement statiques traditionnelles entraînent souvent des temps de chauffage prolongés et une qualité de produit réduite en raison d'une répartition inégale de la chaleur. Pour relever ces défis, des techniques avancées de traitement thermique par agitation ont été développées pour améliorer l’efficacité du transfert de chaleur et la qualité des produits. Cette recherche se concentre sur l'évaluation des effets du traitement thermique par agitation réciproque (RATP) et de l'agitation End-over-End (EOE) en mode continu et oscillatoire sur les taux de pénétration de la chaleur et la rétention de la qualité dans les aliments modèles et réels.

La première étude a examiné l'impact de la RATP sur les propriétés de traitement thermique et la qualité des morceaux de saumon rose de l'Atlantique conditionnés dans des bocaux en verre. Les traitements thermiques ont été effectués à des températures de cornue de 115, 120 et 125°C avec des fréquences de mouvement alternatif de 0, 1,0 et 1,5 Hz. L'étude a évalué l'influence de la RATP sur l'indice de vitesse de chauffage, le facteur de décalage de chauffage et le temps de traitement calculé pour une létalité cible. Les attributs de qualité de texture et de couleur ont également été évalués. Les résultats ont démontré que l’augmentation de la fréquence de mouvement alternatif et de la température de la cornue améliorait considérablement le transfert de chaleur et réduisait les temps de traitement. Les conditions optimales pour la conservation de la qualité ont été trouvées à 125°C et 1,0 Hz, où le saumon a conservé la texture et la couleur souhaitées. Cependant, le traitement à des fréquences plus élevées (> 1,5 Hz) a entraîné des dommages mécaniques excessifs aux particules, affectant négativement l'intégrité du produit.

La deuxième étude a exploré la comparaison entre l'EOE continu (EOE-C) et l'oscillation intermittente de l'EOE (avec un temps de séjour de 10 s) (EOE-O) en utilisant des sphères de nylon comme aliments simulant des modèles de transfert de chaleur dans l'eau, la glycérine et l'huile. Les expériences ont été réalisées à des vitesses de rotation de 10, 20 et 30 tr/min et à des températures de cornue de 115, 120 et 125°C. Les résultats ont révélé que l'EOE-C était plus efficace à des vitesses inférieures, mais que l'EOE-O était nettement supérieur avec un transfert de chaleur amélioré tout au long des vitesses de rotation. Cette amélioration a été attribuée à un

meilleur mélange dû non seulement au mode oscillatoire, mais également à l'inversion périodique du sens d'oscillation après de brefs temps de séjour statique. Cette étude a ensuite été validée en utilisant le radis comme particule alimentaire typique. Les résultats étaient cohérents avec l'étude des particules de nylon, et de meilleures propriétés de texture et de couleur ont été obtenues à 125°C, 30 tr/min selon le procédé EOE-O.

Dans l'ensemble, les deux études confirment que les méthodes de traitement thermique par agitation telles que RATP, EOE-C et EOE-O peuvent améliorer considérablement les taux de transfert de chaleur et la qualité des produits. Ces techniques offrent des avancées prometteuses dans le traitement thermique en réduisant les temps de traitement et en préservant les attributs de qualité des produits, ce qui les rend adaptées aux applications industrielles de transformation alimentaire à base de particules fluides dans des canettes ou bocaux en verre.

CONTRIBUTION OF AUTHOR

Parts of this research have been presented as a poster in 2023 at the Northeast Agricultural and Biological Engineering Conference (NABEC), Guelph, Ontario, Canada; in 2024 at NABEC, Pennsylvania, USA. Some parts were also submitted as a manuscript to the Institute of Thermal Processing Specialists (IFTPS) Charles R. Stumbo Student Paper Competition, 2025. The manuscript was titled 'Comparison of EOE rotational vs EOE intermittent oscillation agitation thermal processing on the heat processing properties of Nylon spheres in water, glycerin and oil as medium' and was awarded 3rd place winner. Three authors have contributed to this research and their contributions are as follows:

Mr. Kanishk Rawat 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 results under the guidance of his supervisor. He drafted the thesis, posters 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 by editing the posters 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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Mr. Kanishk Rawat conducted experiments, gathered and analyzed data, and represented results under the guidance of his supervisor. He drafted the thesis, posters and manuscripts for scientific conferences and publications.

Dr. Hosahalli S. Ramaswamy supervised the experiments, reviewed the results, and final editing the thesis. He also edited the posters and manuscripts prepared for conferences and publications.

Dr Ali R. Taherian provided help with experimentation methods, reviewing results, and editing the thesis.

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NOMENCLATURE

a*	Redness or greenness
b*	Blueness or yellowness
ΔE	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 one of the most extensively used food preservation methods, ensuring microbial safety while maintaining the sensory and nutritional quality of food. The concept of thermal processing originated in 1810 when Nicolas Appert developed a technique involving the sealing of food in glass jars followed by heat treatment in boiling water. The success of this method was later explained by Louis Pasteur in the mid-19th century, when he demonstrated that heat inactivates microorganisms responsible for food spoilage. Over the years, thermal processing has undergone significant advancements, evolving into a controlled method that inactivates pathogens while minimizing adverse quality changes in food products (Awuah et al., 2007). Despite its effectiveness, thermal processing can degrade food quality, particularly in terms of texture, color, and nutrient retention (Taherian & Ramaswamy, 2009). However, with advancements in agitation techniques and process optimization, these effects can be minimized (Singh et al., 2018). This research aims to analyze the influence of reciprocation agitation thermal processing on heat penetration characteristics and product quality, as well as compare the effects of different agitation modes in varying mediums.

There are several methods of thermal processing, including pasteurization, commercial sterilization, cooking, and blanching. Pasteurization involves heating food below 100°C for a set duration to destroy harmful microorganisms while preserving quality. Since bacterial spores are not inactivated, low-acid pasteurized foods require refrigeration, whereas high-acid foods remain shelf-stable (Rodriguez-Amaya, 2019). In contrast, commercial sterilization process subjects food to temperatures above 110°C to inactivate both pathogens and spores, ensuring long-term shelf stability (Jimenez et al., 2024). Other heat treatments, such as cooking and blanching, serve different purposes, including texture modification and enzyme inactivation, and play a critical role in pre-processing steps (Singh & Ramaswamy, 2023). The focus of this study is on pasteurization and commercial sterilization, as they are the primary methods used to ensure microbial safety and product preservation.

One of the most concerning bacteria in thermal processing is *Clostridium botulinum*, whose spores require strict inactivation protocols to prevent foodborne illness (Esty & Meyer, 1922). While high-acid conditions ($pH \leq 4.6$) naturally inhibit spore germination, low-acid foods require more aggressive thermal treatments (Tola & Ramaswamy, 2018). Acidified thermal processing combines pH adjustment with mild heat treatment to achieve microbial safety while minimizing product degradation (Singh et al., 2016). This study explores the application of reciprocation agitation thermal processing and different end-over-end agitation modes in optimizing heat penetration while preserving food quality.

Thermal processing consists of several key steps, beginning with washing to remove contaminants such as dirt, pesticides, and fertilizers (Tola et al., 2014). Blanching follows, serving to inactivate enzymes, remove air from tissues, and prepare food for further heat treatment. The blanched food is then filled into containers and submerged in a canning liquid, which serves as a heat transfer medium (Mestdagh et al., 2008). The filled containers undergo air removal in an exhaust box before being sealed to prevent re-entry of oxygen.

Despite its benefits, thermal processing can negatively impact food quality, particularly in terms of texture, color, and nutrient retention. The breakdown of pectic substances leads to softening, proteins undergo denaturation, and pigments degrade, altering the sensory attributes of food (Singh et al., 2015). Nutrient losses, particularly in heat-sensitive vitamins such as vitamin C and thiamine, are common concerns (Bhat et al., 2021). To address these challenges, high-temperature short-time (HTST) processing has been developed, which applies an intense heat for a short duration, reducing quality losses while ensuring microbial safety (Ramaswamy & Marcotte, 2006). Ultra-high temperature (UHT) processing takes this further, achieving commercial sterility in a shorter time, though often at the expense of some quality parameters (Rodriguez-Amaya, 2019).

The application of agitation techniques during thermal processing has been shown to significantly improve heat penetration and product quality. Methods such as end-over-end rotation, fixed-axial rotation, bi-axial rotation, and reciprocation agitation enhance forced convection, reducing processing time and thermal gradients within the product (Rattan & Ramaswamy, 2014). Reciprocation agitation has demonstrated substantial improvements in heat transfer efficiency, making it a promising approach for optimizing thermal processing (Singh et al., 2018). Previous research has investigated the effects of end-over-end and axial agitation on vegetables, including potatoes, carrots, and green beans (Abbatemarco & Ramaswamy, 1994;

Dwivedi & Ramaswamy, 2010; You et al., 2016). However, there is limited research on reciprocation agitation, particularly for seafood applications.

End-over-end (EOE) rotational thermal processing is a widely used method for improving heat penetration in canned and packaged foods. It enhances convective heat transfer, reducing processing time and improving temperature uniformity, particularly in liquid-particulate systems (Dwivedi & Ramaswamy, 2010; Singh et al., 2015b). However, continuous EOE rotation can cause particle migration toward container walls due to centrifugal forces, leading to uneven heating and potential overprocessing in certain areas (Singh & Ramaswamy, 2015).

EOE intermittent oscillation has emerged as a potential alternative to mitigate these challenges. By incorporating periodic stops and reversals, this method increases internal fluid movement, enhances heat distribution, and prevents particle accumulation near container edges (McNaughton, 2018). While studies suggest that intermittent oscillation may improve heat transfer efficiency, there is limited comparative research evaluating its performance against conventional EOE rotation, particularly in different heat transfer media. This study aims to address this gap by systematically comparing the two agitation modes, with different viscosity media like water, glycerin, and oil, as well as with food matrices such as salmon, radish. Initial preliminary experiments were carried out with a food heat transfer simulating material like Nylon, providing insights into their impact on heat penetration efficiency and product quality.

The objectives of this research were to evaluate the:

1. Effect of reciprocation agitation thermal processing on heat penetration parameters and the quality of salmon chunks in glass jars
2. Compare end over end (EOE) Rotational with EOE intermittent oscillation agitation thermal processing with a) heat penetration characteristics of Nylon spheres in water, glycerin, and oil as covering media with different viscosities, and b) heating behavior and quality of radish packed in water

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CHAPTER 2

LITERATURE REVIEW

2.1 Thermal Processing

2.1.1 Overview of Thermal Processing

Thermal processing is one of the most widely used food preservation techniques, ensuring microbiological safety, extending shelf life, and maintaining nutritional and sensory attributes. It involves the application of heat to destroy or inactivate spoilage and pathogenic microorganisms, enzymatic activity, and other biological reactions that may cause food deterioration (Jimenez et al., 2024). The technique has evolved from traditional boiling and canning to advanced retort processing, high-temperature short-time (HTST) methods, and agitation-assisted processing to optimize heat penetration and quality retention (Singh et al., 2015).

The foundation of thermal processing was laid by Nicolas Appert in 1810 when he developed a method for preserving food in sealed glass jars through heat application (Featherstone, 2015). This led to the development of commercial canning and subsequent innovations in heat processing methodologies. Today, thermal processing plays a crucial role in ensuring food security and safety on an industrial scale, with applications ranging from conventional sterilization to pasteurization and emerging mild-heat treatments.

Thermal processing operates on the fundamental principle of heat transfer through conduction, convection, or radiation. The rate of heat penetration into food depends on factors such as food composition, container material, agitation, and processing temperature (Singh & Ramaswamy, 2015). The critical goal is to achieve a balance between microbial lethality and quality preservation.

2.1.1.1 Applications Across Food Categories

Thermal processing is widely used across multiple food categories, with specific temperature-time combinations tailored to ensure microbial safety while preserving product quality. These applications span from fruits and vegetables to dairy, meat, cereals, and beverages, each requiring precise control over heating conditions to balance safety and sensory attributes.

a. Fruits and Vegetables

Thermal processing is extensively applied to fruits and vegetables to improve shelf life while retaining color, texture, and nutritional value. Processes such as blanching, pasteurization, and sterilization help minimize microbial contamination while maintaining quality. Acidified thermal processing (ATP) has gained attention for low-acid vegetables like mushrooms, carrots, and potatoes, as it allows processing under pasteurization conditions rather than full sterilization, which helps retain nutrients and sensory attributes (Singh et al., 2023). Retort processing is commonly used for canned vegetables such as green beans, tomatoes, and peas, ensuring commercial sterility while preserving their physical and chemical properties (Singh et al., 2015). Additionally, blanching techniques, including infrared and water blanching, have been explored for optimizing processing efficiency and final product quality, particularly in applications like French fries, where processing conditions significantly influence texture and oil absorption (Pan et al., 2014).

a. Dairy Products

Thermal processing is essential for ensuring the microbial safety and stability of dairy products, particularly through pasteurization and sterilization methods. High-Temperature Short-Time (HTST) pasteurization, performed at 72°C for 15 seconds, remains the industry standard for milk, significantly reducing microbial load while preserving nutritional and sensory quality (Awuah et al., 2007). Ultra-High Temperature (UHT) processing, which involves heating milk at 135–150°C for 2–5 seconds, allows for extended shelf life without the need for refrigeration, making it a preferred choice for commercial dairy products (Awuah et al., 2007). Thermal treatments also play a significant role in cheese ripening and yogurt production, where controlled heating affects enzymatic activity and texture formation. Understanding the impact of heat treatment on dairy matrices is crucial for ensuring product consistency and quality over time (Holland et al., 2016).

b. Meat, Poultry, and Seafood

Thermal processing of meat and poultry is critical for pathogen reduction, particularly in eliminating Listeria monocytogenes, Salmonella, and Clostridium perfringens, which pose food safety risks. Heat treatments such as retort and sous-vide processing allow for extended shelf life while preserving the natural texture and moisture of ready-to-eat meat and poultry products (Hassan et al., 2013). Seafood, such as shrimp and salmon, benefits from agitation-assisted thermal processing, which enhances heat transfer and prevents overprocessing, resulting in better retention of moisture and texture (Ramaswamy et al., 2015). Canned seafood, including tuna, sardines, and mackerel, undergoes high-pressure retort sterilization to ensure microbial safety while preserving omega-3 fatty acids and essential nutrients (Dixon et al., 2020).

c. Cereal and Legume-Based Products

Legumes such as chickpeas, lentils, and soybeans undergo thermal processing to enhance digestibility by reducing anti-nutritional factors, such as trypsin inhibitors and phytic acid, which interfere with protein absorption (Xu et al., 2008). Cereal grains like rice, wheat, and corn frequently undergo extrusion cooking, a high-temperature process that improves shelf stability and modifies starch properties, enhancing textural attributes (Mohamed et al., 2007). Breakfast cereals and instant noodles often utilize dry heat processing techniques to achieve low microbial loads while maintaining crispness and desirable mouthfeel (Meng and Ramaswamy, 2007).

d. Beverages

Thermal processing plays a crucial role in the production of beverages, ensuring microbiological safety while maintaining the stability of flavors and nutrients. Pasteurization and sterilization methods are widely used in fruit juices, beer, and wine to prevent spoilage while preserving their sensory properties (Chutintrasri and Noomhorm, 2007). Aseptic processing is commonly applied to soft drinks and plant-based milks, allowing them to be packaged in sterile environments without refrigeration, thereby extending shelf life while reducing contamination risks (Mohamed, 2006). Additionally, studies on the thermal processing of acidified foods highlight the importance of optimizing time-temperature conditions to maintain desirable characteristics in beverages while ensuring microbial stability (Weemaes et al., 1999).

2.1.2 History of Thermal Processing

2.1.2.1 Early Development and Discovery

The origins of thermal processing date back to 1810, when Nicolas Appert developed a method for food preservation by sealing food in glass jars and applying heat, a process later known as Appertization (Featherstone, 2015). His innovation was motivated by the need to supply the

French military with shelf-stable food. Shortly thereafter, Peter Durand introduced the tin can, enhancing the durability of heat-processed food containers (Dwivedi & Ramaswamy, 2010).

In 1864, Louis Pasteur demonstrated that heat could inactivate spoilage microorganisms, leading to the development of pasteurization, primarily for dairy products (Awuah et al., 2007). These discoveries formed the foundation for modern thermal processing, with subsequent research refining heat application to balance microbial lethality and food quality (Singh et al., 2015).

2.1.2.2 Scientific Advancements in Thermal Processing

By the early 20th century, food scientists recognized the need for standardizing heat treatments. Bigelow and Esty (1920) classified bacterial spores based on their thermal resistance and introduced the concept of D-values (time required to reduce microbial populations by 90% at a given temperature) (Awuah et al., 2007). This development allowed for the design of safe and efficient thermal processing schedules.

In 1923, Ball and Olson introduced the General Method for calculating sterilization requirements, laying the groundwork for modern retort processing calculations (Singh & Ramaswamy, 2015). This model was later refined in the 1950s by Stumbo, who introduced the F-value concept, quantifying the lethality of a thermal process relative to a reference temperature (Awuah et al., 2007).

2.1.2.3 Evolution of Industrial Retort Processing

During the 1950s–1970s, industrial food processing underwent rapid advancements. Hydrostatic retorts and continuous rotary retorts were introduced to improve heat penetration and energy efficiency (Jimenez et al., 2024). The introduction of agitation thermal processing allowed for more uniform heating in canned foods, reducing process times and improving product quality (Singh et al., 2018).

The 1980s–2000s saw significant research into high-temperature short-time (HTST) processing and ultra-high temperature (UHT) sterilization, especially for dairy and liquid products (Awuah et al., 2007). These technologies minimized nutrient degradation while ensuring microbial safety, revolutionizing milk, juice, and soup processing (Rodriguez-Amaya, 2019).

2.1.2.4 Recent Innovations and Emerging Trends

In recent decades, thermal processing has been further optimized through computational modeling and automation. Computational Fluid Dynamics (CFD) has improved the understanding of heat transfer in different food matrices, allowing for more precise process design (Dixon et al., 2020).

Advancements in reciprocating agitation processing have further reduced heating time and improved quality in particulate foods such as shrimp, salmon, and legumes (Singh et al., 2015). Additionally, research into alternative thermal treatments, including ohmic heating, microwave-assisted processing, and infrared heating, continues to push the boundaries of efficiency and quality retention (Chung et al., 2018).

2.1.3 Steps Involved in Thermal Processing

2.1.3.1 Washing and Preparation

The first step in thermal processing is washing, which removes dirt, pesticide residues, and microbial contaminants from raw food products. Washing prevents cross-contamination and enhances the efficiency of subsequent processing steps (Chung et al., 2018). Different washing techniques are employed depending on the type of food product.

Common Washing Techniques:

- Water Spray Washing: Used for fruits, vegetables, and grains to remove soil particles, dust, and surface contaminants.
- Ozonated Water Treatment: Helps reduce microbial load and extend shelf life by breaking down bacterial cell membranes.
- Ultrasound-Assisted Washing: Uses high-frequency sound waves to dislodge contaminants, particularly effective for leafy greens and delicate fruits.
- Chlorinated Water Rinse: Effective for killing pathogenic bacteria but requires careful control to prevent chemical residues (Mozzoni et al., 2009).

For certain foods such as legumes and grains, soaking before thermal processing is crucial for rehydration and uniform heat penetration. Legumes like chickpeas and lentils expand when hydrated, allowing for more efficient cooking and sterilization. Additionally, soaking removes anti-nutritional factors such as tannins and trypsin inhibitors, making the food easier to digest (Singh et al., 2015).

Industrial washing systems use mechanical scrubbers, flotation tanks, and spray washers to ensure thorough cleaning. For leafy vegetables, flotation tanks prevent physical damage, while root vegetables undergo abrasive brushing to remove soil residues. Proper washing reduces spoilage risk and ensures better heat penetration during processing (Jimenez et al., 2024).

2.1.3.2 Blanching

Blanching is a preliminary heat treatment (70–100°C) that serves multiple functions, including enzyme inactivation, microbial reduction, and texture improvement (Mestdagh et al., 2008). It is particularly important for frozen and canned vegetables as it prevents enzymatic browning and undesirable textural changes.

Types of Blanching:

- **Hot Water Blanching:**
  - Process: Food is submerged in boiling water for 30 seconds to 5 minutes.
  - Advantages: Effective for most vegetables, enhances color retention.
  - Disadvantages: Nutrient loss due to leaching of water-soluble vitamins (Taherian & Ramaswamy, 2009).
- **Steam Blanching:**
  - Process: Superheated steam is applied to food without submersion.
  - Advantages: Minimizes nutrient leaching, better texture retention.
  - Disadvantages: Requires longer blanching times compared to hot water (Dixon et al., 2020).
- **Microwave Blanching:**
  - Process: Uses electromagnetic waves for rapid heating.
  - Advantages: Energy-efficient, retain antioxidants, short processing time.
  - Disadvantages: Uneven heating if not properly controlled (Chung et al., 2018).
- **Ohmic Heating Blanching:**

- Process: Electrical currents pass through food, heating it internally.
- Advantages: Faster enzyme inactivation, uniform heating, reduced processing time.
- Disadvantages: Expensive equipment (Jimenez et al., 2024).

Importance of Blanching in Thermal Processing:

- Prevents color and texture loss in carrots, tomatoes, and green beans.
- Reduces microbial load, ensuring safer thermal processing.
- Improves heat penetration, especially for dense foods like potatoes (Singh et al., 2018).
- Enhance shelf life by stabilizing food structure before sterilization.

Prevents off-flavors by deactivating enzymes such as lipoxygenase, which causes rancidity. Blanching is a key pre-processing step, particularly in canning, freezing, and dehydration, ensuring that processed food maintains better texture, flavor, and nutritional value (Jimenez et al., 2024).

2.1.3.3 Filling and Hot Fill Process

Once the raw material is blanched, it is filled into containers (cans, glass jars, retort pouches) along with a canning liquid. This liquid ensures heat transfer during processing and helps retain product moisture (Singh et al., 2015). The headspace in the container allows for expansion during heating, preventing structural damage (Dwivedi & Ramaswamy, 2010).

Types of Filling Methods:

- **Gravity Filling:** Used for free-flowing liquids like fruit juices and soups, ensuring consistent volume without additional force.
- **Vacuum Filling:** Common for viscous and semi-solid products, removing air pockets that could affect heat penetration.
- **Piston Filling:** Applied to thicker mixtures, such as pasta sauces and mashed vegetables, ensuring uniform weight distribution.

Hot Filling Process:

- Used primarily for acidic foods like fruit juices, tomato-based sauces, and jams.
- The product is filled at 85–95°C, creating a vacuum seal upon cooling.

- Prevents oxidation and microbial contamination (Awuah et al., 2007).
- Used in conjunction with pasteurization, ensuring product safety and extended shelf life.

For non-acidic foods, a more rigorous sterilization process is needed post-filling, ensuring complete microbial inactivation (Rodriguez-Amaya, 2019). The headspace is particularly important in retort processing as it prevents container deformation due to internal pressure changes during thermal treatment.

2.1.3.4 Sealing and Exhausting

Sealing is a critical step in thermal processing as it prevents contamination and ensures the food remains shelf-stable for long periods. Improper sealing can lead to post-process contamination, oxidation, or microbial spoilage (Singh et al., 2018).

Common Sealing Methods:

- Double-seam sealing (for cans): Creates an airtight and hermetic closure.
- Vacuum-sealing (for glass jars and retort pouches): Extends shelf life by removing oxygen from the headspace.
- Heat-sealing (for flexible packaging): Uses temperature-controlled bonding to create a secure seal (Jimenez et al., 2024).

Exhausting Process:

Before sealing, the exhausting process removes air from the container, preventing:

- Oxidation, which can degrade color and flavor.
- Internal pressure buildup, reducing the risk of container deformation.
- Spoilage microorganisms from surviving, as they require oxygen for growth (Breidt et al., 2014).

Exhausting is typically done using steam or vacuum systems. In some cases, a hot-fill-hold method is used to naturally push air out before final sealing.

2.1.3.5 Thermal Processing (Sterilization or Pasteurization)

The core of food preservation, thermal processing applies controlled heat to eliminate pathogens and extend shelf life. The choice between sterilization and pasteurization depends on food acidity, intended storage conditions, and microbial risk.

1. Sterilization (110–135°C, long duration):
    - Used for low-acid foods (e.g., vegetables, meats, dairy) that cannot rely on acidity for microbial inhibition.
    - Retort processing ensures complete microbial inactivation by reaching an F_0 value sufficient for Clostridium botulinum destruction (Singh et al., 2015).
    - Enhances shelf stability up to 3–5 years without refrigeration.
2. Pasteurization (<100°C, short duration):
    - Used for high-acid foods (e.g., fruit juices, fermented dairy).
    - Eliminates spoilage microorganisms while retaining quality (Breidt et al., 2014).
    - Typically provides a shelf life of several weeks to months, often requiring refrigeration.

Agitation Thermal Processing:

To enhance heat penetration and reduce processing times, food industries utilize:

- Reciprocating Agitation: Moves cans back and forth to increase convective heat transfer, beneficial for liquid-particulate foods (Singh et al., 2018).
- End-over-End Rotation: Provides even temperature distribution, reducing hotspots inside containers.
- Axial Agitation: Improves heat penetration for dense or layered products such as soups and stews (Jimenez et al., 2024).

Proper selection of agitation mode reduces nutrient loss and overprocessing, making sterilization more energy-efficient and effective.

2.1.3.6 Cooling

Once sterilization or pasteurization is complete, immediate cooling prevents overprocessing and preserves food texture, color, and nutritional value.

Cooling Methods:

- Water Immersion Cooling:
    - Common for canned goods (Dwivedi & Ramaswamy, 2010).
    - Provides rapid heat dissipation, preventing further microbial growth.

- Air Cooling:
    - Used for flexible pouches and vacuum-sealed products (Dixon et al., 2020).
    - Reduces thermal shock to packaging materials.
- Pressure Cooling:
    - Prevents container deformation, especially in glass jars and delicate packaging (Awuah et al., 2007).
    - Balances internal and external pressure to avoid stress fractures.

Optimizing cooling rates is crucial, as uneven cooling can cause container buckling, cracks, or internal condensation, which may impact product integrity and appearance (Jimenez et al., 2024).

2.1.3.7 Storage and Distribution

Once processed and cooled, the food must be stored under appropriate conditions to maintain shelf stability and product quality.

Storage Considerations by Product Type:

- Shelf-stable canned goods: Stored at ambient temperatures (Singh et al., 2015). Canned vegetables and meats require controlled humidity to prevent rusting of metal containers.
- Pasteurized beverages: Require refrigeration (Rodriguez-Amaya, 2019). Cold chain logistics are essential for maintaining freshness and microbial stability.
- Vacuum-sealed meats and retort pouches: Benefit from modified atmosphere packaging (MAP) to extend shelf life (Jimenez et al., 2024). Oxygen scavengers or nitrogen flushing are commonly used to prevent oxidation.

Quality Control and Labeling:

- Traceability systems ensure that batch recalls can be performed efficiently if necessary.
- Tamper-evident packaging helps maintain food security.
- Nutritional labeling and expiry dates provide consumer information on proper storage and consumption.

Storage temperature and handling conditions significantly impact product longevity. Regular microbial testing, sensory evaluation, and container integrity checks ensure food safety compliance throughout distribution.

2.1.4 Principles of Thermal Processing

Thermal processing is a critical method used to ensure the microbiological safety of food products while maintaining their sensory and nutritional qualities. The primary objective is to inactivate pathogenic and spoilage microorganisms through controlled heat treatments, which are designed based on factors such as microbial resistance, heat transfer efficiency, and product composition (Tucker et al., 2021).

2.1.4.1 Microbial Destruction and Thermal Resistance

- Thermal Resistance of Microorganisms: Microbial resistance to heat varies among species, with spore-forming bacteria like *Clostridium botulinum* being highly resistant. The required temperature and duration for inactivation depend on the specific microorganism, with sterilization processes typically set at 121.1°C for several minutes to ensure food safety (Tucker et al., 2021).
- Decimal Reduction Time (D-value): The D-value represents the time required at a specific temperature to achieve a 90% reduction in microbial population. This value differs among microorganisms and is influenced by factors such as pH, water activity, and food composition (Fellows et al., 2009).
- Thermal Death Time (TDT) and Z-value: The TDT defines the total time required to eliminate a microorganism at a given temperature. The Z-value quantifies the temperature increase needed to reduce the D-value by one log cycle, helping to determine how processing conditions can be adjusted to optimize microbial inactivation while preserving product quality (Ramaswamy et al., 1999).

2.1.4.2 Heat Transfer in Thermal Processing

- Conduction and Convection: Heat transfer in food occurs through conduction in solid foods and convection in liquids. Convection-enhanced heat transfer in liquid foods allows for more uniform heating, reducing processing times compared to conductive heat transfer in solid products (Singh et al., 2015a).
- Thermal Penetration and Agitation: Heat penetration is affected by the physical properties of food, including viscosity, density, and particle size. Agitation methods such as end-over-end rotation, reciprocating agitation, and biaxial rotation improve heat penetration

by reducing temperature gradients, ensuring uniform heating throughout the food matrix (Singh et al., 2016).

2.1.4.3 Time-Temperature Combinations and Process Optimization

- F-value and Process Lethality: The F-value represents the equivalent time required to achieve microbial inactivation at a reference temperature (usually 121.1°C). This metric allows for the comparison of different time-temperature combinations to optimize processing efficiency while minimizing quality loss (Tucker et al., 2021).
- High-Temperature Short-Time (HTST) Processing: HTST processing applies short bursts of high heat to inactivate pathogens while preserving sensory and nutritional qualities. This method is commonly used in dairy and liquid food industries to ensure microbial safety while retaining product freshness (Fellows et al., 2009).
- Balancing Overprocessing and Underprocessing: Excessive heat exposure can degrade food texture, color, and nutrient content, while inadequate processing may result in insufficient microbial inactivation. Optimizing time-temperature conditions ensures microbial lethality without compromising product integrity (Singh et al., 2015b).

2.1.4.4 Role of Acidity (pH) in Thermal Processing

- Low-Acid vs. High-Acid Foods: Foods with a pH > 4.6 require higher sterilization temperatures to inactivate heat-resistant spores, while high-acid foods (pH < 4.6) naturally inhibit microbial activity and require less intensive processing. Understanding pH-dependent microbial resistance helps design efficient thermal processes for different food categories (Bhattacharya et al., 1994).

2.1.4.5 Quality Control in Thermal Processing

- Microbial Testing: Verification of microbial inactivation through sterility tests ensures the effectiveness of thermal processing (Singh et al., 2016).
- Nutritional and Sensory Evaluation: Heat-sensitive vitamins, such as vitamin C and thiamine, degrade with excessive heat exposure. Monitoring nutrient retention and sensory attributes helps maintain product quality (Fanbin et al., 2007).

2.1.4.6 Ball Process Time Calculations

The Ball-Formula method is the most used and straightforward technique for thermal process calculations. Since its introduction by Ball in 1921, several variations of formula-based heat process analysis have been developed. This method offers multiple advantages: (1) it allows for calculating the required process time when the desired process lethality (F_o) is known; (2) it can be used to determine the lethality achieved by an existing process; (3) because it relies on heat penetration parameters (f_h and j_{ch}), it enables quick calculation of new processes for the same product in different container sizes through parameter conversions; and (4) it permits direct calculation of new processes when there are changes in the heating medium temperature (T_r) or the initial product temperature (T_i). Compared to General methods, formula methods are much quicker and particularly effective for analyzing the influence of various processing factors (Ramaswamy and Singh, 1997)

It is based on the following equation derived from the heat penetration curve (using the same symbols as detailed earlier):

$$B = f_h \log(j_{ch} I_h / g_c) \qquad \textbf{2.1}$$

where B is the process time, f_h is the heating rate index, j_{ch} is the lag factor, I_h is the initial temperature difference ($T_r - T_i$) and g_c is the temperature difference at the end of the cook ($T_r - T$) at $t = B$), T_r is the retort temperature, T_{pih} is the pseudo-initial product temperature, and T_i is the initial product temperature. The process time B is related to the Lethality F_o delivered through a graphical or table format to determine the process time for a given process lethality or to compute the delivered lethality for a given process time.

2.2 Retort Processing Operations

2.2.1 Retort Processing Overview

Retort processing is a widely used thermal preservation technique aimed at ensuring the microbiological safety and stability of food products. The method involves the application of heat to sealed food containers within a pressure vessel (retort), achieving commercial sterility by inactivating heat-resistant bacteria such as *Clostridium botulinum* (Jimenez et al., 2024). This technique extends shelf life while maintaining product integrity and quality (Featherstone, 2015).

2.2.2 Principles of Retort Processing

The sterilization procedure typically involves three key phases: (1) come-up time (CUT), (2) holding or cook phase, and (3) cooling phase. During CUT, the retort reaches a target temperature (115-121°C) and pressure (15-20 psi) using a high-flow heating medium. The holding phase ensures that the food product reaches the desired lethality (Fo value), while cooling is necessary to prevent overprocessing and structural damage to the packaging (Mosna & Vignali, 2015).

2.2.3 Equipment and Technological Developments

Traditional static retorts have evolved into more advanced systems incorporating agitation, steam-water spray, and high-speed rotational processing to improve heat transfer efficiency (Dwivedi & Ramaswamy, 2010). Hydrostatic retorts and continuous retorting methods are preferred for large-scale production due to their energy efficiency and reduced processing time (Hassan & Ramaswamy, 2013).

2.2.4 Types of Retort Processing

2.2.4.1 Batch Retort Processing

Batch retort processing is commonly used for smaller-scale operations and specialty food products. The primary advantage is the ability to accommodate different container sizes and processing conditions within the same system (Featherstone, 2015). However, batch processing has higher energy consumption and requires greater labor input compared to continuous systems (Jimenez et al., 2024).

2.2.4.2 Continuous Retort Processing

Continuous retorting, including hydrostatic and rotary retorts, enables high-throughput processing with minimized downtime (Jimenez et al., 2024). Hydrostatic retorts use steam pressure controlled by the water column height to achieve sterilization, while rotary retorts apply continuous motion to enhance convective heat transfer within liquid-particulate mixtures (Singh & Ramaswamy, 2015).

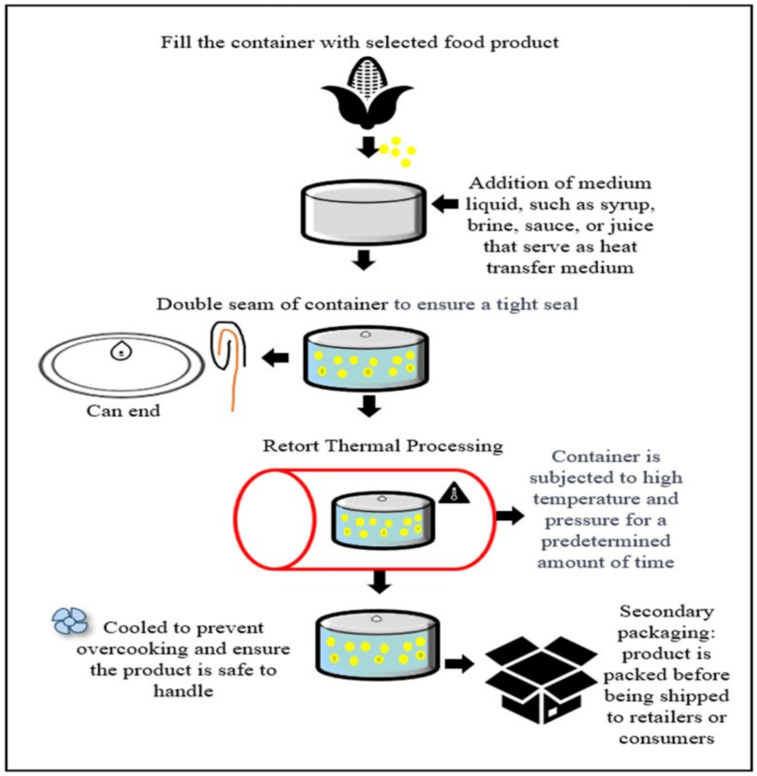


Figure 2.1: Standard commercial retort canning process (Jimenez et al., 2024)

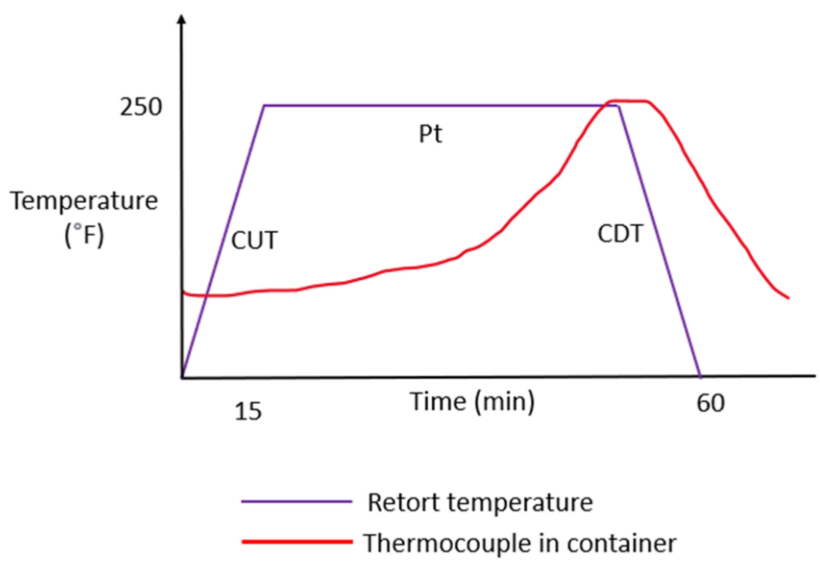


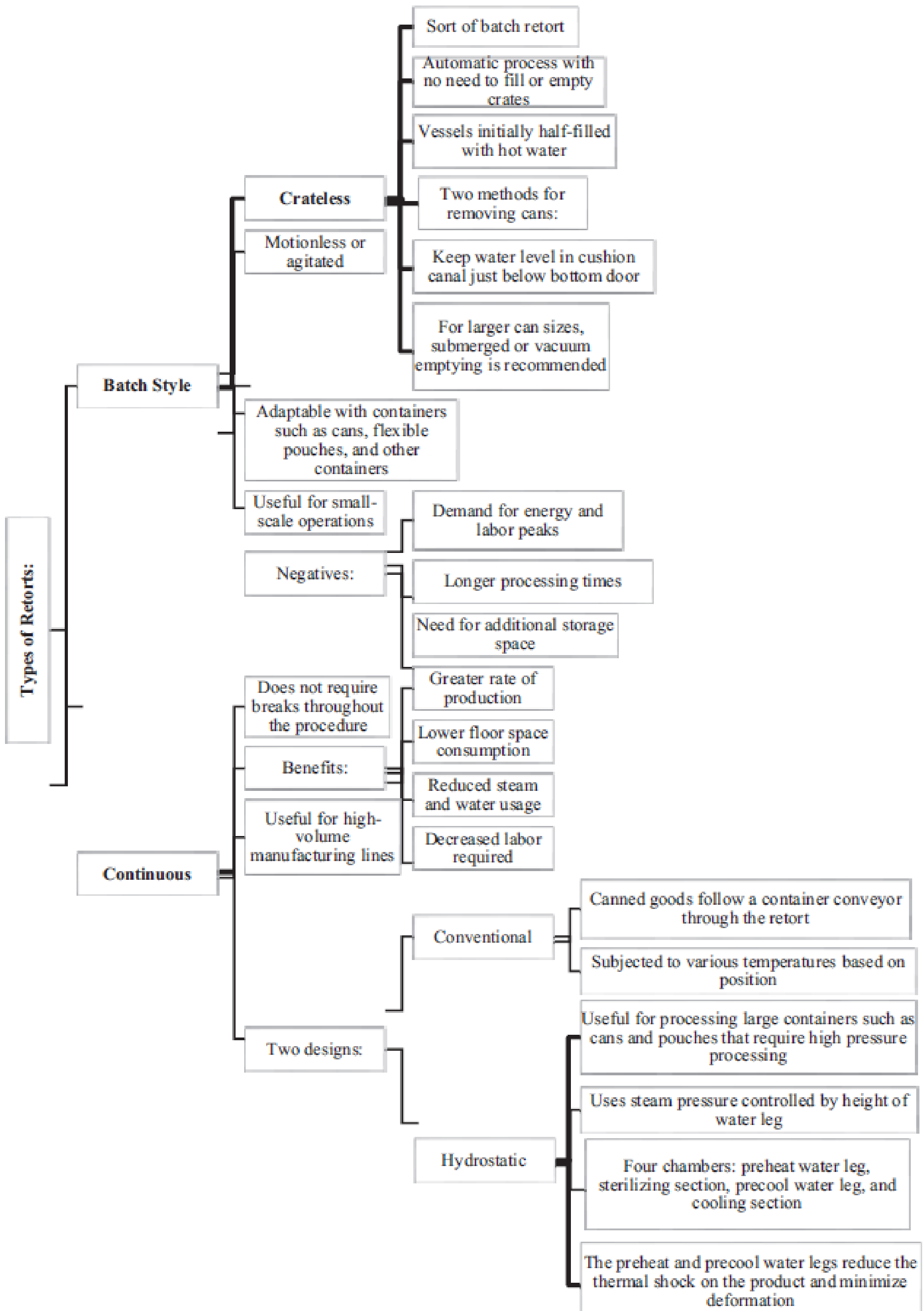
Figure 2.2: Basic temperature curve for retort thermal processing and profiles. CDT, come-downtime; CUT, come-uptime (Jimenez et al., 2024).

2.2.5 Methods of Heating in Retort Processing

Retort thermal processing is a widely used technique for preserving food by applying heat to sealed containers, ensuring both food safety and extended shelf life. Different heating methods optimize heat transfer, energy efficiency, and packaging integrity, depending on the food type and container material. The most used heating methods include saturated steam, water immersion, water spray, steam-air, and steam-water spray systems. Each of these methods has specific advantages and challenges that impact microbial inactivation, heat penetration, and overall processing efficiency.

2.2.5.1 Saturated Steam Heating

Saturated steam heating is one of the most traditional methods of thermal processing, used extensively for metal cans and glass jars. In this process, steam is directly injected into a sealed retort chamber, displacing air to create a uniform thermal environment (Jimenez et al., 2024). Steam has high latent heat capacity, allowing rapid heat penetration into food products, ensuring effective microbial inactivation and achieving commercial sterility (Holland, 2008).



Flowchart 2.1: Types of retorts (Berk 2018; Holland 2008; Jimenez et al., 2024).

To ensure uniform heating, complete air removal is essential, as any residual air can create cold spots that reduce lethality (Fellows, 2009). This is achieved through venting, where air is expelled before the heating phase begins. The process typically operates at temperatures above

121°C, a standard for processing low-acid foods (Singh et al., 2017). While saturated steam systems are highly effective for rigid containers, they lack independent pressure control, making them unsuitable for flexible packaging such as retort pouches (Bhattacharya et al., 1994).

A major drawback of saturated steam systems is their high steam consumption, as steam is continuously released during venting, leading to energy inefficiencies (Ramaswamy & Marcotte, 2006). Despite this, saturated steam heating remains the preferred method for processing canned vegetables, meats, and seafood due to its reliability, high lethality, and well-established industrial use (Ramaswamy et al., 1999).

2.2.5.2 Water Immersion Heating

Water immersion heating is commonly used for processing liquid-based foods and flexible packaging formats, such as retort pouches and semi-rigid plastic trays. This system ensures consistent heat transfer by completely submerging food containers in preheated water, eliminating temperature gradients that can cause uneven microbial lethality (Jimenez et al., 2024). The uniform heat distribution makes water immersion an ideal choice for delicate foods that require precise thermal processing (Holland, 2008).

A key advantage of water immersion heating is its ability to control pressure independently, which prevents the deformation of flexible packaging under high-temperature conditions (Singh et al., 2017). Additionally, this method reduces oxidative reactions in products with high-fat content, such as seafood and sauces, preserving their sensory and nutritional quality (Bhattacharya et al., 1994).

However, water immersion retorts require high water consumption, making water management a critical challenge (Fellows, 2009). Regular filtration and water treatment are necessary to prevent microbial contamination and extend the lifespan of processing water (Ramaswamy & Marcotte, 2006). While immersion systems typically have longer come-up times than direct steam heating, they offer superior protection for fragile packaging and heat-sensitive foods (Ramaswamy et al., 1999).

2.2.5.3 Water Spray (Cascade) Heating

Water spray or cascade heating is a more energy-efficient alternative to full water immersion. In this system, superheated water is pumped and sprayed over food containers through high-velocity nozzles, providing faster heat penetration while consuming less water (Jimenez et al., 2024). The high turbulence created by the cascading water improves heat transfer, leading to shorter processing times (Holland, 2008).

One of the main advantages of water spray heating is its shorter come-up time (CUT), allowing for faster processing while maintaining microbial lethality (Singh et al., 2017). Another major benefit is independent pressure control, which protects flexible packaging from deformation, making it highly suitable for plastic trays and retort pouches (Bhattacharya et al., 1994).

However, a key challenge in water spray retorts is the risk of nozzle clogging due to scale buildup from processing water. Regular maintenance is required to ensure proper water distribution and heat penetration (Ramaswamy & Marcotte, 2006). Despite these challenges, water spray systems are widely used in the production of ready-to-eat meals and vacuum-packed food products, where precise temperature control and packaging integrity are critical (Ramaswamy et al., 1999).

2.2.5.4 Steam-Air Heating

Steam-air retort systems use a combination of direct steam injection and forced air circulation to achieve uniform heat transfer. Unlike saturated steam systems, air is not vented out of the retort, allowing for independent control of temperature and pressure (Jimenez et al., 2024).

A high-velocity fan actively circulates the steam-air mixture, preventing temperature stratification and ensuring even heating across all containers (Holland, 2008). This method is particularly beneficial for flexible and semi-rigid packaging, which requires careful pressure regulation to avoid distortion (Singh et al., 2017). Another advantage of steam-air systems is their lower steam consumption, which significantly improves energy efficiency compared to pure steam heating (Ramaswamy & Marcotte, 2006).

However, steam-air systems require advanced control mechanisms, increasing capital costs and maintenance complexity (Bhattacharya et al., 1994). Additionally, if air circulation is not properly controlled, cold spots may form, resulting in incomplete heat penetration (Ramaswamy et al., 1999). Despite these drawbacks, steam-air heating remains a widely adopted method for processing retortable plastic trays and stand-up pouches, where precise pressure control is critical (Fellows, 2009).

2.2.5.5 Steam-Water Spray Heating

Steam-water spray heating is a hybrid thermal processing method that combines direct steam injection with a fine mist of superheated water. This system ensures rapid and uniform heat transfer, making it highly suitable for temperature-sensitive foods such as seafood, dairy, and premium ready meals (Jimenez et al., 2024).

A key advantage of steam-water spray heating is its ability to minimize thermal degradation, as the fine mist prevents surface overheating, reducing nutrient loss and texture damage (Holland, 2008). Additionally, pressure can be controlled independently, preventing packaging deformation and oxidative discoloration (Singh et al., 2017).

Despite its advantages, steam-water spray retorts require precise automation and control systems, increasing installation and operational costs (Ramaswamy & Marcotte, 2006). However, for high-value food products, this method offers significant advantages in preserving sensory attributes and nutritional quality, making it a preferred choice in premium food processing (Ramaswamy et al., 1999).

2.2.6 Types of Agitation Thermal Processing

Agitation thermal processing enhances heat penetration, reduces processing times, and improves food quality. Unlike static processing, which relies primarily on conduction and slow convective currents, agitation introduces controlled motion to the food container, increasing heat transfer efficiency and ensuring uniform temperature distribution. This is particularly critical for liquid-particulate food systems where inconsistencies in heating can compromise microbial lethality and product stability (Singh et al., 2018).

The four primary types of agitation thermal processing—end-over-end rotation, axial rotation, bi-axial rotation, and reciprocating agitation—each have unique mechanisms and advantages. This section provides an expanded discussion of these methods, incorporating recent research findings.

2.2.6.1 End-Over-End Rotation Processing

End-over-end (EOE) rotation involves rotating the food container along its horizontal axis, ensuring continuous mixing of the contents. This motion enhances convective heat transfer and minimizes temperature gradients within the container, leading to more uniform heating. EOE rotation has been extensively studied for its ability to reduce processing times while maintaining microbial lethality (Sablani & Ramaswamy, 1996).

Research has demonstrated that increasing the rotation speed in EOE processing significantly enhances heat transfer coefficients. However, excessive speeds can lead to product degradation, particularly in fragile food matrices. For example, high rotational speeds can cause mechanical stress on soft food particulates, leading to undesirable texture breakdown (Mohamed, 2007). Thus, optimizing rotation speed is essential to balance heat penetration efficiency with product integrity.

One of the key applications of EOE rotation is in canned vegetable processing, where it has been shown to improve heat penetration rates by up to 35% compared to static processing. The increased forced convection within the container ensures that even the coldest regions achieve the required thermal treatment, reducing the overall processing time (Hassan & Ramaswamy, 2013). Moreover, this method is effective in reducing overprocessing near container walls, thereby improving overall product quality.

2.2.6.2 Axial Rotation Processing

Axial rotation, also known as fixed axial rotation, differs from EOE in that the containers rotate along their longitudinal axis rather than being flipped end-over-end. This motion is particularly advantageous for low-viscosity liquids, where internal movement ensures rapid and uniform heat distribution (Singh et al., 2018).

The effectiveness of axial rotation depends on several factors, including rotation speed, particle density, and headspace volume. Studies have shown that axial rotation significantly enhances microbial lethality compared to static retort processing by eliminating cold spots. However, in highly viscous foods, the lack of vigorous movement can result in slower heat penetration compared to EOE rotation (Hassan & Ramaswamy, 2013).

One challenge with axial rotation is its tendency to create centrifugal force that pushes particulates toward the container walls, potentially leading to uneven heating. Recent studies have explored modifications such as oscillatory axial rotation, where intermittent speed adjustments counteract particle settling and improve convective heat transfer (Mohamed, 2007).

This approach has been particularly useful in processing dairy-based soups and sauces, where achieving uniform consistency is crucial.

2.2.6.3 Bi-Axial Rotation Processing

Bi-axial rotation involves simultaneous movement along both horizontal and vertical axes, creating a highly turbulent environment that maximizes convective heat transfer. This method has gained prominence in the processing of liquid-particulate systems, where ensuring even heat distribution is critical (Hassan & Ramaswamy, 2013).

One of the primary advantages of bi-axial rotation is its ability to accelerate heat penetration while minimizing mechanical stress on particulates. Unlike EOE or axial rotation, which may cause excessive shearing in delicate foods, bi-axial motion provides a gentler yet highly effective mixing effect. Studies have reported up to a 40% reduction in processing times compared to static methods, making this an attractive option for commercial sterilization (Singh et al., 2018).

The complexity of bi-axial rotation necessitates precise control over movement patterns to optimize heat transfer. Computational fluid dynamics (CFD) modeling has been instrumental in refining processing parameters, allowing researchers to identify ideal rotation speeds and container orientations for different food products (Mohamed, 2007). As automation in food processing continues to evolve, bi-axial rotation is expected to see further refinement, making it a key player in the future of thermal processing.

2.2.6.4 Reciprocating Agitation Thermal Processing (RATP)

Reciprocating agitation is a unique method that employs linear back-and-forth motion rather than continuous rotation. This technique has gained traction in processing high-viscosity foods and liquid-particulate systems, where conventional rotational agitation may not provide optimal mixing (Rampurwala et al., 2023).

RATP has been shown to significantly enhance heat penetration by generating forced convection within the container. Unlike traditional rotation-based methods, which rely on gravitational forces to induce mixing, reciprocating agitation creates oscillatory fluid motion that improves thermal uniformity. Studies have reported up to an 87% increase in heat transfer efficiency with reciprocating agitation compared to static retort processing (Singh et al., 2018).

One of the key benefits of RATP is its ability to reduce processing times while maintaining product integrity. Unlike high-speed rotational methods that may cause mechanical stress on particulates, reciprocating motion provides controlled agitation, preventing excessive shearing (Hassan & Ramaswamy, 2013). This makes RATP particularly suitable for products such as canned legumes and dairy-based formulations, where preserving texture and consistency is crucial.

Recent advancements in reciprocating agitation have focused on optimizing motion frequency and amplitude to maximize heat transfer without compromising food quality. Studies have explored various oscillation patterns, including sinusoidal and pulsed motion, to identify the most efficient parameters for different food matrices (Mohamed, 2007). The integration of CFD models has further refined these optimizations, enabling precise control over processing conditions.

2.3 Factors Affecting the Rate of Heat Penetration in a Container

The rate of heat penetration during thermal processing is influenced by several interdependent factors, including container size and shape, product composition, and the type of heat transfer medium. The interaction between these factors determines the efficiency of thermal processing and ensures food safety and quality retention. An in-depth understanding of these factors is crucial for optimizing food sterilization and pasteurization processes.

2.3.1 Container Shape and Size

The geometry of the container significantly impacts heat distribution within the food product. Large or irregularly shaped containers often experience thermal gradients, leading to uneven heating, with the core requiring a longer time to reach the target temperature compared to the outer layers (Hassan et al., 2013). Retort pouches and thin-profile containers facilitate rapid heat transfer due to their reduced thickness, improving uniformity in heating (Sablani & Ramaswamy, 1997). The effect of container orientation has also been noted, where end-over-end rotation reduces thermal gradients, improving the rate of heat penetration (Mohamed, 2007). Studies have also shown that metallic containers have higher thermal conductivity compared to plastic or glass, significantly influencing the heating rate (Weng et al., 1992).

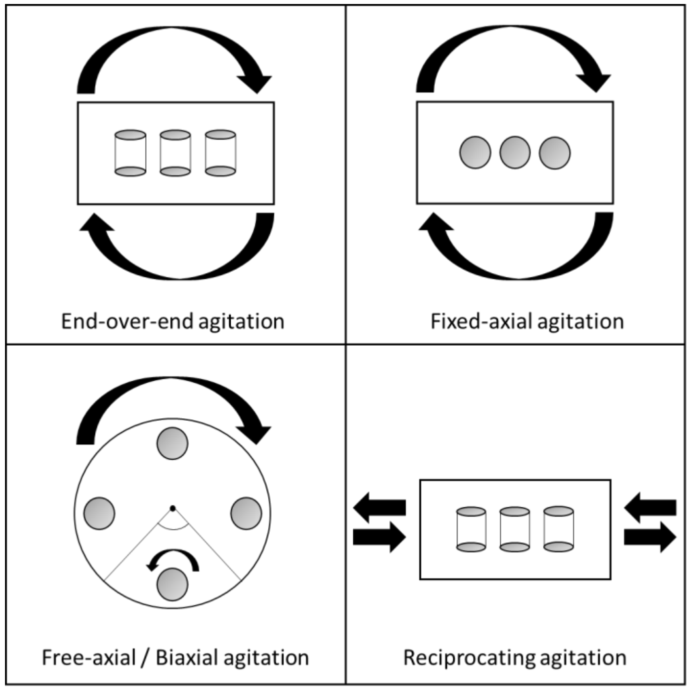


Figure 2.3. Agitation methods for thermal processing.

2.3.2 Product Viscosity and Composition

Viscosity is a key determinant of heat penetration, as higher viscosity foods hinder convective currents within the container, leading to slower heat transfer rates (Bekele Tola & Ramaswamy, 2014). Liquid-particulate foods introduce additional complexity, as solid particles act as heat sink, reducing the rate of heating in the surrounding liquid (Meng & Ramaswamy, 2007). Foods with high water content generally allow for better heat penetration due to the superior thermal conductivity of water compared to other food components (Borowski et al., 2015). The choice of acidulant in acidified foods has also been shown to influence thermal processing kinetics, with different acidifying agents affecting bacterial spore inactivation rates (Breidt et al., 2014). Fat content also plays a crucial role, as it has been found to insulate heat transfer, slowing the rate of thermal diffusion (Xu et al., 2008).

2.3.3 Headspace in Containers

The volume of headspace within a container affects heat penetration by altering the heat transfer dynamics. Excessive headspace leads to the presence of trapped air, which acts as an insulator and slows down heat transfer, increasing the risk of underprocessing (Cleland & Gesterkamp, 1983). Properly controlled headspace is critical to ensuring uniform heating and avoiding cold spots that could compromise food safety (McGlynn, 2010). Studies indicate that excessive headspace can also lead to oxidation reactions, which may degrade food quality during storage (Borowski et al., 2015).

2.3.4 Shape, Size, and Density of the Food Particle

Particulate foods exhibit differential heating rates depending on their size, shape, and density. Larger food particles require more time to heat at the core due to their lower surface-area-to-volume ratio, which can create temperature gradients within the product (Weng et al., 1992). Irregularly shaped particles introduce inconsistencies in heating patterns, with edges heating faster than the denser core regions (Borowski et al., 2015). The density of food particles also plays a role, as denser foods take longer to heat due to their lower thermal diffusivity (Mohamed, 2007). Research suggests that optimizing particle size distribution can enhance uniformity in heat penetration, ensuring more effective microbial inactivation (Tola & Ramaswamy, 2014).

2.3.5 Concentration of Particulates in the Container

A high concentration of solid food particles in a liquid suspension reduces the available space for liquid movement, thereby inhibiting convective heat transfer and slowing down the overall heat penetration rate (Bekele Tola & Ramaswamy, 2014). The effectiveness of heat transfer in particulate-laden foods depends on optimizing the liquid-to-particle ratio to maintain consistent temperature distribution within the container (Sablani & Ramaswamy, 1997). Research has also shown that increased solid concentrations may necessitate longer processing times or elevated temperatures to compensate for heat transfer limitations (Xu et al., 2008).

2.3.6 Viscosity of the Canning Liquid

The viscosity of the liquid medium used in canning directly influences heat penetration rates. Low-viscosity liquids such as water allow for more efficient convective heat transfer, whereas high-viscosity liquids impede heat movement, requiring extended processing times or increased agitation to compensate (Meng & Ramaswamy, 2007). Studies have demonstrated that fluid-to-particle heat transfer coefficients decrease with increasing viscosity, necessitating tailored processing conditions for different food matrices (Weng et al., 1992). Moreover, fluid viscosity changes during heating, and its dynamic behavior must be accounted for in process optimization (Xu et al., 2008).

2.3.7 Method and Rate of Agitation

Agitation during thermal processing enhances heat penetration by inducing forced convection, which improves heat distribution within the container. Rotational agitation, including end-over-end and axial rotation, has been shown to reduce processing times by breaking up thermal gradients and increasing convective currents within the food system (Hassan et al., 2013). Reciprocal agitation provides similar benefits by disrupting boundary layers around solid particles, enhancing heat transfer efficiency (Sablani & Ramaswamy, 1997). The selection of agitation intensity is crucial, as excessive agitation can lead to mechanical damage in delicate food products, whereas insufficient agitation may cause non-uniform heating (Mohamed, 2007). New developments in mechanical agitation methods, including intermittent rotation and oscillatory motion, have shown promise in optimizing heat transfer efficiency (Bekele Tola & Ramaswamy, 2014).

2.3.8 Effect of Cooling Phase on Lethality

Post-heating cooling can impact the final lethality of thermal processing. Irregular cooling patterns, influenced by factors such as retort pressure during cooling and can headspace, have been shown to cause variations in final lethality values (Cleland & Gesterkamp, 1983). Properly controlled cooling conditions ensure that microbial lethality is maintained throughout the process and prevents the risk of pathogen survival due to residual temperature variations (Breidt et al., 2014). The role of cooling rate in quality retention has also been studied, with faster cooling often preserving texture and color in thermally processed products (Xu et al., 2008).

2.4 Quality Loss During Thermal Processing

Thermal processing is widely used to ensure microbial safety and extend the shelf life of food products; however, it can lead to significant quality degradation, especially in heat-sensitive foods such as vegetables, seafood, and meats (Jimenez et al., 2024). The major quality deteriorations observed include texture degradation, color loss, and nutritional degradation, which impact the sensory and nutritional attributes of food (Yu et al., 2023). These changes depend on multiple factors, including the time-temperature profile, composition of the food matrix, processing method, and packaging type (Bhat et al., 2021).

Excessive heat exposure during retort processing and canning results in the denaturation of proteins, oxidation of pigments, and loss of heat-sensitive nutrients, reducing the overall product quality (Ovissipour et al., 2017). Studies have shown that reciprocating agitation thermal processing (RA-TP) and high-temperature short-time (HTST) processing can minimize these losses by improving heat penetration and reducing overall thermal exposure (Kubo et al., 2023). Additionally, microwave-assisted thermal sterilization (MATS) and acidified thermal processing have been explored for their potential to retain better sensory and nutritional quality (Rampurwala et al., 2024).

2.4.1 Texture Loss

Texture degradation is a significant challenge in thermally processed foods, particularly in muscle-based foods and cell-wall-rich vegetables. The primary cause of texture loss is protein denaturation and the breakdown of structural polysaccharides such as pectin and hemicellulose (Bhat et al., 2021).

In seafood, high temperatures lead to denaturation of myofibrillar proteins (myosin and actin), causing moisture loss, shrinkage, and increased firmness (Ovissipour et al., 2017). Research on Atlantic salmon indicates that myosin denatures at 45–50°C, while actin degradation begins at temperatures above 70°C, significantly altering texture (Bhat et al., 2021). In shrimp, prolonged heating results in higher shear force values, making the texture tougher. However, reciprocating agitation processing (RA-TP) has been shown to improve heat transfer, reducing processing time and minimizing texture degradation (Dixon et al., 2020).

In vegetables, textural degradation occurs due to cell wall breakdown caused by heat-induced solubilization of pectin and hemicellulose (Singh & Ramaswamy, 2023). Studies on radish and green beans have confirmed that prolonged exposure to heat leads to excessive softening and loss of firmness (Singh et al., 2016). High-viscosity food matrices slow heat penetration, leading to localized overprocessing (Singh et al., 2015). Techniques such as RA-TP and acidified thermal processing have been developed to preserve structural integrity while ensuring effective microbial inactivation (Rampurwala et al., 2024).

2.4.2 Color Loss

Color degradation during thermal processing is mainly attributed to pigment oxidation, enzymatic reactions, and Maillard browning (Bhattacharya et al., 1994).

In vegetables, heat exposure leads to the conversion of chlorophyll to pheophytin, turning green vegetables dull brown (Singh & Ramaswamy, 2023). Similarly, in seafood, carotenoids responsible for pink-orange pigmentation in salmon and shrimp undergo oxidation and isomerization, leading to faded coloration (Bhattacharya et al., 1994).

Studies on Pacific chum salmon show that processing temperatures exceeding 100°C result in significant color loss, particularly in retort-processed seafood (Bhattacharya et al., 1994). In shrimp, higher agitation speeds during thermal processing cause surface sloughing, further affecting the uniformity of color (Dixon et al., 2020). The Maillard reaction, which occurs in high-protein and carbohydrate-rich foods, contributes to additional browning (Głuchowski et al., 2019). Research suggests that shorter processing times and lower temperatures, such as those used in HTST and MATS, help maintain pigment stability better than conventional methods (Kubo et al., 2023).

2.4.3 Nutritional Loss

Nutritional degradation during thermal processing is particularly concerning heat-sensitive vitamins, antioxidants, and essential fatty acids (Bhat et al., 2021). Water-soluble vitamins such as vitamin C and B vitamins degrade rapidly under heat, with studies showing that conventional retort processing can lead to losses exceeding 50% (Singh & Ramaswamy, 2023).

In seafood, oxidation of polyunsaturated fatty acids (PUFAs), such as omega-3s (EPA and DHA), significantly reduces their bioavailability and nutritional value (Bhat et al., 2021). Research on Atlantic salmon and shrimp has demonstrated that higher processing temperatures accelerate lipid oxidation, further deteriorating nutritional quality (Ovissipour et al., 2017). Comparisons between retort pouches and traditional metal cans show that retort pouches allow faster heat penetration, reducing thermal exposure and better preserving nutrients (Owusu-Apenten & Vieira, 2023).

Additionally, techniques such as acidified thermal processing have been explored for their ability to reduce vitamin degradation while ensuring microbial safety (Rampurwala et al., 2024). By modifying pH conditions before heat treatment, acidified processing can help retain sensitive vitamins and nutrients, making it a promising method for future applications (Singh & Ramaswamy, 2023).

2.5 Origin and importance of the selected foods: Salmon and Radish

2.5.1 Salmon

Salmon, a member of the family Salmonidae, is a highly valued species found in the North Atlantic and Pacific Oceans. Among the most commercially and ecologically significant species are Atlantic salmon (*Salmo salar*) and five species of Pacific salmon: Chinook (*Oncorhynchus tshawytscha*), Coho (*O. kisutch*), Chum (*O. keta*), Pink (*O. gorbuscha*), and Sockeye (*O. nerka*). As anadromous fish, they migrate between freshwater and marine environments, playing a vital role in nutrient cycling and ecosystem balance (Noakes, 2014). The economic importance of salmon has expanded beyond wild fisheries, with aquaculture now dominating global salmon production, particularly in Norway, Chile, Canada, and Scotland, where controlled farming practices have made it possible to meet increasing consumer demand while alleviating pressure on wild populations (FAO, 2020).

Nutritionally, salmon is recognized for its high-quality protein, rich omega-3 fatty acid content, and essential vitamins and minerals. A 100g serving of Atlantic salmon provides approximately 20-25g of protein, making it an excellent source of complete protein, supplying all nine essential amino acids required for muscle development, immune support, and metabolic functions (Ovissipour et al., 2017). Beyond protein, salmon is one of the richest sources of long-chain omega-3 fatty acids, particularly EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid), which contribute to cardiovascular health, cognitive function, and inflammation reduction (Bhat et al., 2021). Research has demonstrated that regular consumption of EPA and DHA significantly lowers the risk of heart disease and enhances neurological function, underscoring salmon's role as a functional food for overall health (Harris et al., 2009). Additionally, salmon is abundant in vitamin D, B vitamins (B12, B6, and niacin), selenium, and phosphorus, supporting bone health, immune function, and antioxidant defense mechanisms (Kris-Etherton et al., 2002).

While salmon provides substantial health benefits, thermal processing can significantly alter its nutritional composition, affecting protein structure, lipid oxidation, and sensory properties. Heat-induced protein denaturation impacts digestibility, with moderate temperatures (55–65°C) improving enzymatic hydrolysis, while higher temperatures (≥85°C) cause protein aggregation, reducing digestibility and making the texture firmer and drier (Ovissipour et al., 2017). Similarly, lipid oxidation during thermal processing affects omega-3 bioavailability, with prolonged exposure to high temperatures degrading EPA and DHA. Studies indicate that steaming and sous-vide methods best preserve omega-3 integrity, while roasting and frying accelerate lipid degradation due to exposure to high heat and oxygen (Głuchowski et al., 2019). The texture of salmon is also impacted by thermal processing, as muscle fiber contraction at higher temperatures results in excessive moisture loss, leading to a tougher, less palatable texture. In contrast, low-temperature, long-time methods such as sous-vide (63°C for 80 minutes) retain higher moisture and result in a more tender texture (Bhat et al., 2021).

Another critical change observed during thermal processing is color degradation, attributed to the breakdown of astaxanthin, the carotenoid responsible for salmon's characteristic pink-orange hue. Higher temperatures, particularly those above 85°C, accelerate astaxanthin oxidation, leading to a noticeable browning effect, while lower temperature processing better preserves color stability (Ovissipour et al., 2017). Given these nutritional and sensory challenges associated with prolonged heat exposure, the implementation of high-temperature short-time (HTST) processing has emerged as an effective method to optimize nutritional retention while ensuring microbial safety. HTST processing reduces exposure time, minimizing protein degradation, lipid oxidation, and color loss, making it an ideal method for commercial salmon processing (Głuchowski et al., 2019).

2.5.2 Radish

Radish (*Raphanus sativus*) is a root vegetable belonging to the *Brassicaceae* family, widely cultivated and consumed worldwide. Originating from Southeast Asia, radish has been domesticated into various species and cultivars, including Daikon (*Raphanus sativus var. longipinnatus*) and red globe radish (*Raphanus sativus L.*). These varieties differ in size, shape, and flavor profiles, making them suitable for diverse culinary applications. Traditionally, radish has been consumed raw in salads, pickled, or incorporated into cooked dishes, particularly in Asian cuisines.

Beyond its culinary significance, radishes are recognized for its rich nutritional composition. It contains essential bioactive compounds such as phenols, flavonoids, and isothiocyanates, which contribute to its antioxidant, anti-inflammatory, and anticancer properties. Radish is an excellent source of vitamin C, fiber, and various minerals, making it a valuable component of a healthy diet. The presence of sulforaphane, a bioactive compound found in radish, has been associated with the inhibition of cancer cell proliferation, further emphasizing its health benefits. The preservation and enhancement of these nutritional attributes are crucial when processing radish for extended shelf life and convenience (Yang et al., 2023).

Thermal processing plays a pivotal role in ensuring food safety and extending the shelf life of vegetables, including radish. Conventional methods, such as retort processing, involve subjecting food products to high temperatures to inactivate microbial populations and enzymes responsible for spoilage (Yu et al.,2023). However, these processes can lead to significant quality deterioration, including texture softening, color changes, and nutrient degradation. Thermal processing can negatively impact the color of vegetables due to pigment degradation, as well as reduce the retention of antioxidants (You et al., 2016).

To address these challenges, high-temperature short-time (HTST) processing has emerged as an effective alternative. HTST processing minimizes the exposure time to high temperatures, thereby reducing nutrient loss while maintaining microbial safety (Singh et al., 2023). Studies have shown that optimized thermal treatments, such as reciprocating agitation thermal processing (RA-TP), can improve heat transfer efficiency, reduce process time, and enhance quality retention in canned radish (You et al., 2016). Additionally, acidification techniques have been explored to modify the pH of vegetables, thereby allowing for milder thermal processing conditions while ensuring microbial stability (Singh et al., 2023).

The application of advanced thermal processing techniques, such as ohmic heating and modified retort processing, offers potential advantages for improving the quality of packed radish. Ohmic heating, which utilizes electrical conductivity to generate heat uniformly within the food matrix, has been reported to provide rapid and uniform heating while preserving nutritional integrity (Duguay et al.,2016). In contrast, traditional retort processing methods require prolonged heating durations, which may compromise textural properties and bioactive compound retention (Yu et al., 2023). Therefore, understanding the impact of different thermal processing techniques on radish is essential for optimizing its quality in processed forms.

This study aims to explore the effects of various agitation thermal processing methods on radish quality, with a particular focus on end-over-end rotation and intermittent oscillation processing to improve its nutritional and sensory attributes. By leveraging advanced thermal processing techniques, the goal is to enhance the retention of bioactive compounds while ensuring microbial safety and product stability.

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PREFACE TO CHAPTER 3

Chapter 3 of this thesis dwells into the effect of reciprocation agitation thermal processing (RATP) on the heat penetration parameters and quality attributes of Atlantic salmon chunks packed in glass jars. The study systematically investigates the influence of reciprocation frequency and retort temperature on heating efficiency, processing time, and product integrity. Key parameters such as heating rate index, heating lag factor, and overall process lethality are analyzed to determine the optimal thermal processing conditions for salmon. Additionally, the study evaluates the impact of RATP on key quality attributes, including texture and color retention. Findings from this chapter contribute to the broader understanding of how reciprocation agitation improves heat distribution in liquid-particulate food systems, ensuring both microbial safety and superior product quality.

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

Rawat, K., Taherian, A.R., and Ramaswamy, H.S., 2023. Effect of reciprocal agitation on thermal processing of salmon. Northeast Agricultural and Biological Engineering Conference, Ontario, Canada.

CHAPTER 3

EFFECT OF RECIPROCATION AGITATION THERMAL PROCESSING ON HEAT PENETRATION PARAMETERS AND THE QUALITY OF SALMON CHUNKS IN GLASS JARS

3.1 Abstract

The objective of this study was to find the effect of reciprocation agitation thermal processing on the heat penetration parameters and quality of salmon chunks in glass jars and to find optimal conditions for thermal processing of salmon chunks to yield better quality. Atlantic pink salmon fillets were cut into circular shapes of 7 cm diameter and filled in into glass jars. Thermocouples were introduced into the jars through a packing gland attached to the lid and then into the center of a salmon piece initially positioned at the center of the jar. The glass jars were hot filled with 2% NaCl solution, and the lid closed. Thermocouples were also introduced into the retort for measuring the retort temperature. The thermocouple leads were then passed through the retort and connected to a data logger. Time temperature data were gathered throughout the process and were used to gather the temperature rise of salmon chunks with time. The glass jars were placed in the cage assembly inside the pilot-scale steam retort and were then processed under different conditions. Different temperature-frequency combinations were used as experiment conditions (115, 120 and 125°C; 0, 1 and 1.5Hz). Once the thermal processing was completed, jars were cooled by introducing water into the retort. Using the gathered heat penetration data, the heat penetration parameters (f_h and j_{ch}) were evaluated, and the required process times (Pt) were computed to deliver a designated process lethality (Fo value) of 5.0 min. Fresh salmon chunks filled jars were processed to the established times, cooled and the salmon chunks were taken for quality measurements- retention of texture and color properties were evaluated.

The results showed that the heat penetration parameters and the computed process times were influenced by the retort temperature and agitation frequency. Higher temperatures and agitation frequency resulted in more rapid heat transfer (lower f_h and j_{ch}) and lowered the required processing time. The quality was better retained at higher frequency or higher temperature processes. The maximum quality retained based on the texture change, color change and process

time was observed at 1 Hz frequency and 125°C temperature, with lower frequency and temperatures prolonging the process time and higher agitation frequency damaging the textural integrity.

3.2 Introduction

Thermal processing remains a fundamental technology in food preservation, ensuring microbial safety and extended shelf life by inactivating pathogenic microorganisms and spoilage enzymes (Kubo et al., 2023). Over the years, traditional thermal processing methods, including static retorts, conventional sterilization, and some agitation-based techniques—have evolved into advanced thermal systems designed to improve heat transfer while preserving product quality (Jimenez et al., 2024).

Beyond its preservative role, thermal processing significantly influences nutritional and sensory quality. High temperatures can degrade heat-sensitive vitamins such as ascorbic acid (Vitamin C) and thiamine (Vitamin B1) while also causing pigment degradation and structural changes in food (Awuah et al., 2007). However, research shows that certain compounds, such as lycopene in tomatoes, may become more bioavailable after processing due to cell wall breakdown, which enhances nutrient absorption (Pratap-Singh et al., 2016). In seafood processing, pasteurization and sterilization remain critical for preventing *Clostridium botulinum* contamination, particularly in low-acid, canned, or vacuum-packed products (Awuah et al., 2007; Tola et al., 2018; Ali et al., 2025).

To address the challenges of nutrient loss and excessive heating, modern thermal processing innovations focus on optimizing heat transfer efficiency and minimizing quality degradation. High-temperature short-time (HTST) processing has emerged as an effective method for reducing thermal exposure, thereby preserving bioactive compounds while ensuring microbial lethality (Awuah et al., 2007). Additionally, agitation-based thermal processing, including end-over-end, axial rotation, and reciprocating agitation, has gained widespread adoption for enhancing convective heat transfer and reducing processing time (Pratap-Singh et al., 2016; Pratap-Singh et al., 2018)

Reciprocating Agitation Thermal Processing (RATP) has gained recognition as an advanced thermal processing technique that significantly improves heat transfer efficiency while preserving product quality. Unlike static retorts, RATP applies a linear reciprocating motion, enhancing forced convection within the product, leading to shorter process times and better-quality retention. Studies have demonstrated that RATP can reduce process times up to 35%, significantly improving heat penetration and reducing thermal gradients (Singh et al., 2015). In the case of canned tomato puree, RATP at 2–3 Hz reduced process time by 63–81% compared to static processing while retaining higher levels of antioxidants, lycopene, and carotenoids (Pratap Singh et al., 2016).

Beyond improving process efficiency, RATP enhances product quality across different food matrices. Studies on green beans demonstrated that higher reciprocation frequencies preserved chlorophyll and antioxidant activity, though excessive agitation led to texture degradation (Singh et al., 2015). Similarly, mushroom processing using RATP resulted in higher heat transfer rates, shorter processing times, and better color retention, with an optimal frequency of 1 Hz balancing heat efficiency and textural integrity (Rampurwala et al., 2025).

For seafood applications, canned shrimp processed with RATP achieved superior quality compared to static retorting. The time to reach F_0 = 6 min was reduced by 42% at 180 shakes per min (SPM), significantly improving process efficiency. Moreover, shrimp processed with RATP at 90 SPM retained higher firmness (+62%) compared to static processing, while preserving visual integrity and yield at 73%. This indicates that RATP is highly effective in improving thermal processing efficiency while maintaining the structural and sensory qualities of high-value seafood.

The energy efficiency of RATP is another key advantage. Compared to static processing, reciprocal agitation significantly reduces energy consumption by shortening total thermal exposure, which in turn minimizes nutrient losses and maintains better sensory attributes (Singh et al., 2015). Additionally, in acidified low-acid foods, RATP improves heat transfer efficiency while reducing processing severity, enabling better quality retention than traditional sterilization (Rampurwala et al., 2025).

Salmon, with its high protein and omega-3 content, requires careful thermal treatment to avoid quality degradation. During processing, protein denaturation and collagen solubilization alter texture, resulting in toughness at certain stages, followed by tenderization as collagen breaks down (Kong et al., 2007; Haard, 1992). Similarly, color changes occur as carotenoid pigments degrade, reducing redness a^* and increasing lightness L^* (Bhattacharya et al., 1994; Van Loey et al., 1994). Optimized processing conditions, such as those achieved with RATP, mitigate these effects, preserving both texture and color while maintaining microbial safety (Dwivedi & Ramaswamy, 2010; Abbatemarco & Ramaswamy, 1994).

There has been extensive research on the effect of thermal processing on salmon quality, particularly in metal cans, which are the conventional choice for commercial sterilization. However, reciprocating agitation thermal processing (RATP) is a newer technique, and its application to seafood remains largely unexplored. Additionally, while most thermal processing studies focus on canned seafood, there is a growing interest in home canning, which often involves glass jars instead of metal containers. Glass jars offer a unique advantage by providing visibility into the product, allowing for real-time observation of color changes, texture retention, and heat penetration dynamics during processing.

This study aims to fill this research gap by evaluating thermally processed salmon chunks in glass jars, together with reciprocation agitation for efficient turbulence inside the container. The study if focused on texture retention, color stability, process time differences, heating rate index, and heating lag factor under different frequencies and temperatures. By incorporating glass jars instead of conventional cans, this research aligns with emerging trends in home food preservation and explores how container transparency, heat transfer, and agitation-based thermal processing interact to influence final product quality.

3.3 Materials and methods

3.3.1 Sample Preparation

Atlantic pink salmon fillets were purchased from a local supermarket. The upper dorsal side of the fish was selected for preparing the samples for this study. The skin was removed from the salmon. A cylindrical shaped cutting knife (like a cork borer) was used to cut the salmon into a cylindrical chuck of 7 cm diameter. Glass jars (volume: 250 ml, height: 7 cm) were used as containers for thermal processing of salmon. A flexible type-T thermocouple was inserted into the salmon chunk's center that was placed in the geometric center of a glass jar as it is the coldest spot in this fluid-in-particle phase (Pratap-Singh et al., 2015). In the configuration employed, the salmon chunks remained largely in place and only the covering liquid moved around to enhance the heat transfer under the RATP conditions.

To insert the thermocouple wire, a hole was made in the cap of jar, big enough to seal it with a packing gland and gaskets. The rigid thermocouple wire was also passed through the same hole. The jars were then filled with hot brine solution (2% NaCl) at 90°C, leaving 5-8% headspace (about 1/2 - 3/4 cm). Finally, the jars were sealed tightly by hand. The jars were placed vertically to the axis of reciprocation in the cage which was located inside the retort. The movement of jars within the cage was restricted, so that the only motion is through agitation. The thermocouple placed inside the salmon was used to measure the temperature increase with time at the coldest spot in salmon and another thermocouple lead was used to measure the retort temperature.

3.3.2 Retort Setup

A pilot-scale vertical static retort (Loveless Manufacturing Co., Tulsa, OK) was utilized for the study. It was modified into a reciprocating agitation retort by incorporating a reciprocating cage, a slider-crank assembly, and a permanent magnet motor (Pratap-Singh et al., 2015). The setup, as illustrated in Figure 3.1, was positioned at one-third of the retort's height from the top. This modification enabled the retort to hold jars within the cage and move them in a linear back-and-forth motion, referred to as reciprocating agitation.

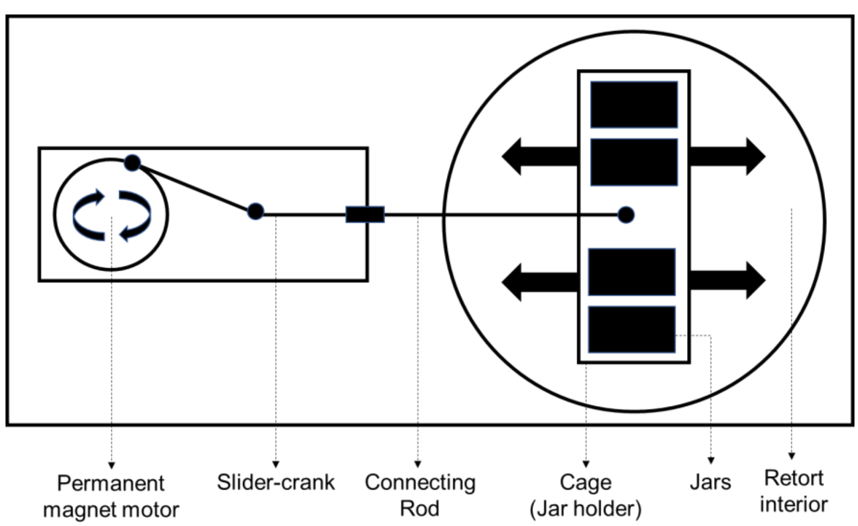

Figure 3.1. Reciprocating agitation retort assembly (Pratap-Singh et al., 2015).

The working mechanism involves converting the motor's rotational motion into linear reciprocating motion using a slider-crank system, with its end constrained through a narrowing. The amplitude of reciprocation was regulated by adjusting the crank's position, while the frequency was controlled by altering the input via the magnetic motor's voltage controller. Each rotation of the rotating shaft resulted in one complete reciprocating oscillation of the cage.

The temperature in the retort was controlled by the input pressure and pressure controller for steam and is determined by an analog pneumatic PID controller (Control & Readout Ltd., Worthing, Sussex, England). The temperature and pressure were set by the user, and the values were extracted from steam table. For 115°C – 169kPa, 120°C – 199kPa and 125°C – 232kPa were used as the set values of pressure. Steam entered the retort from the bottom. For cooling, cold water was introduced into the retort from the bottom, and after halfway through showered from the top.

3.3.3 Time and Temperature data gathering

Time–temperature data were gathered using the thermocouples (Type-T, diameter = 0.0762 mm, Omega Engineering Corp, Stamford, CT, USA). As mentioned earlier, one thermocouple was placed inside the sample located at the geometric center of the jar, while the other was positioned inside the retort to measure its temperature. The other ends of the thermocouples were connected to a data logger, configured to record temperatures every 5 seconds.

3.3.4 Thermal process determination

Salmon samples were thermally processed for each test condition involving combinations of temperatures, 115, 120, and 125 °C, and frequencies, 0,1 and 1.5 Hz. The number of runs were based on a full factorial test. The samples were processed two times for each combination. During the first run, the samples were processed until the temperature at the center of the sample reached the retort temperature (in this case 115, 120, and 125 °C respectively), and the rest of the data were interpolated to provide a time-temperature data for a particular combination, and this data were used to calculate the processing time for achieving a process lethality of 5 min. The lethality computed over every 5 s of processing was integrated to give the total lethality during the heating portion of the process using the following Equation:

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

where T_s represents the sample temperature. The point at which the target process lethality was achieved was taken as the processing time (Pt) for that temperature-frequency combination. The target process lethality used was Fo = F_{121} = 5 min as commonly used for the conventional thermal processing to result in commercial sterility.

Once the processing time was obtained, a similar process as highlighted above was used to create new samples and were processed to achieve the target process lethality. The thermally treated salmon jars were cooled partially in the retort and then cooled down to room temperature and moved to a refrigerator where they were stored until quality evolution. Duplicate runs were carried out for each treatment. The processed products were then subjected to assessment of different quality parameters.

Process time was also calculated based on Ball method. It is based on the following equation derived from the heat penetration curve (using the same symbols as detailed earlier):

$$B = f_h \log(j_{ch}\, I_h / g_c) \qquad \textbf{3.2}$$

B is the process time, f_h is the heating rate index, j_{ch} is the lag factor, I_h is the initial temperature difference ($T_r - T_i$) and g_c is the temperature difference at the end of the cook ($T_r - T$) at t = B), T_r is the retort temperature, T_{pih} is the pseudo-initial product temperature, and T_i is the initial product temperature.

3.3.5 Calculation of heat penetration parameters

A heating curve was generated by plotting the logarithm of the difference between the retort temperature and the sample temperature against time. The negative reciprocal of the slope of the straight-line portion of the heating curve represents the heating rate index, expressed mathematically as:

$$f_h = -1 / \text{slope} \qquad \textbf{3.3}$$

The heating lag factor was determined using the following formula:

$$j_{ch} = (T_R - T_{pih}) / (T_R - T_{ih}) \qquad \textbf{3.4}$$

Here, T_R denotes the retort temperature, T_{ih} is the initial temperature of the sample, and T_{pih} refers to the pseudo-initial temperature of the sample. The pseudo-initial temperature is obtained by extrapolating the straight-line portion of the heating curve, where the intersection of this extrapolation with the y-axis indicates the pseudo-initial temperature.

3.3.6 Quality Assessment

3.3.6.1 Texture Profile Analysis

A TA.XT Plus texture analyzer (Texture Technologies Corp, New York, USA) was utilized for texture analysis. The experiments were carried out using a custom-designed multi-wire probe developed in-house. This probe had a diameter of 70 mm and was fitted with 10 wires, each 0.25 mm thick and spaced 6 mm apart. The base consisted of a circular stainless-steel plate with a diameter of 60 mm. Samples measuring 20 x 20 x 15 mm were placed on the base and subjected to an 80% compression-cut of their height.

The force required for compression-cutting, and the work area were defined as firmness and toughness, respectively. These values for firmness and toughness were directly obtained using the Exponent software (Texture Technologies, New York, USA).

3.3.6.2 Color Analysis

Color analysis was conducted using a Minolta Tristimulus Colorimeter (Minolta Corp., Ramsey, NJ, USA). The parameters assessed included L^* for lightness, a^* for redness, C^* for chroma, and the hue angle, with measurements carried out through the Spectra Magic software (Minolta Corp., Ramsey, NJ, USA). Uniformly shaped samples were prepared and evaluated using the colorimeter to analyze the lightness, redness, chroma, and hue of raw salmon and thermally treated salmon chunks for different temperature-frequency combinations.

Each parameter was derived through a series of measurements taken 15 times per sample, with the average values calculated for analysis.

3.4 Statistical analysis

Statistical analysis was conducted using a single-factor ANOVA to assess the variance between groups, followed by a post hoc Kruskal-Wallis test for pairwise comparisons. The Kruskal-Wallis test, a non-parametric method, was chosen to ensure robust analysis without assuming normal distribution of the data. A significance level of $p < 0.05$ was used to determine statistically significant differences between groups.

3.5 Results and Discussions

3.5.1 Temperature and cumulative lethality evolution curve

Fig 3.2 illustrates the evolution of process temperature and cumulative lethality during the thermal processing of salmon at various temperatures and reciprocating frequencies. The graph shows that at a higher frequency of 1 Hz and 1.5 Hz, the temperature buildup and the target lethality F_{121} are achieved at a faster rate than at 0 Hz. It shows the significant impact of agitation on heat transfer efficiency. As the process temperature increases from 115°C to 125°C, the lethality is achieved much faster. It highlights the relationship between temperature and heat penetration.

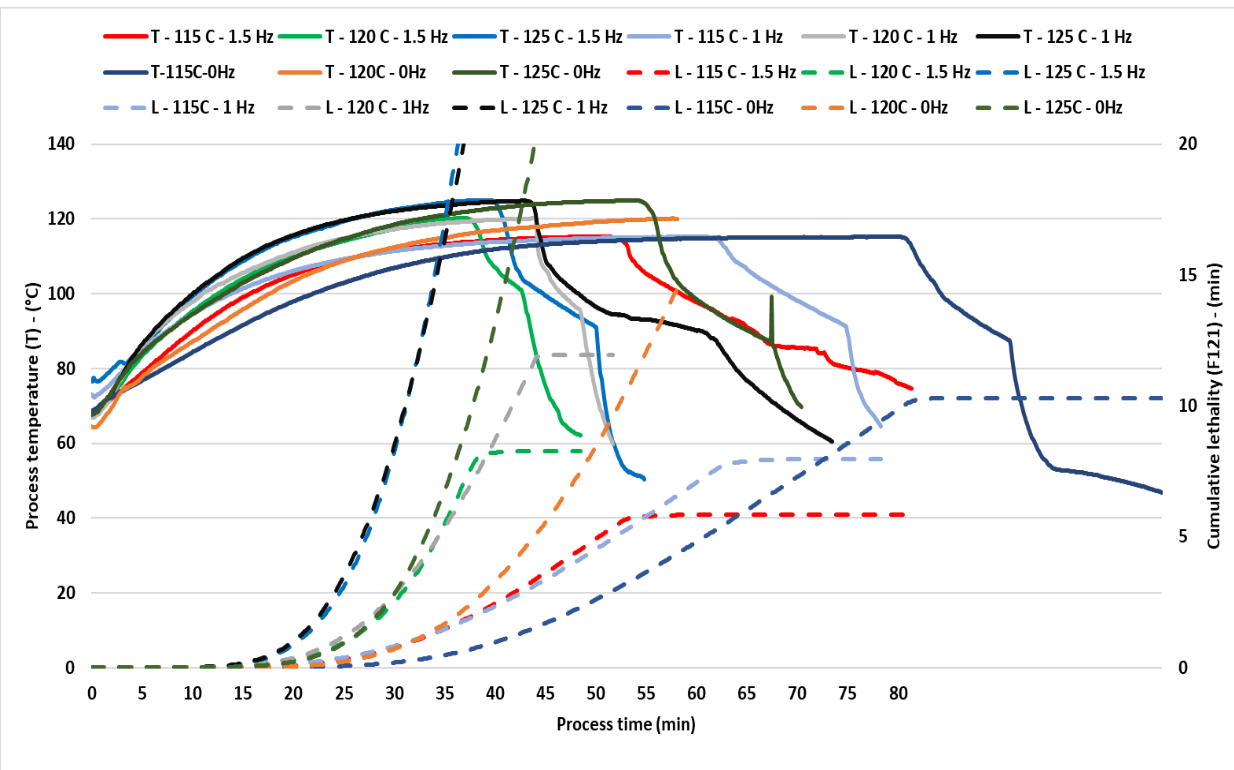

Figure 3.2. Process temperature and cumulative lethality evolution curve for salmon processed using conventional thermal processing at 0 Hz and 1.5 Hz.

3.5.2 Processing time

The processing time, defined as the time required to achieve cumulative lethality (F_{121}) of 5 minutes (Eq 3.1) was evaluated at temperatures of 115°C, 120°C, and 125°C with reciprocating frequencies of 0 Hz, 1 Hz, and 1.5 Hz. The data presented in Table 3.1 clearly shows the influence of processing temperature and reciprocating frequency on the processing time of salmon chunks. Various studies done on reciprocation agitation (You, 2015; Singh et al., 2015b; Singh et al.,2017; Ali et al.,2025) have observed a similar relationship between processing time and reciprocating agitation.

From Table 3.1, it can be observed that when agitation frequency is increased from 0 Hz to 1 Hz, the decrease in the process time ranged from 14.5% for 115°C, 21.4% for 120°C and 21.8% for 125°C . But on further increasing the agitation frequency, the process time only changes by an additional 3 to 5%. This clearly shows that increasing agitation speed (frequency) reduces the process time by a significant amount especially starting from the static mode (0 Hz), but increasing further may not yield the same degree of reduction in the process time. Hence there may be an optimum condition which provides a better turn over process overall from operation point of view. Another thing to be noted here is that at 125ºC, the process time slightly rises when frequency is increased from 1 to 1.5 Hz. This can be supported by the fact that a higher rate of agitation at the higher temperature could've led to a restriction in motion within the jars (possibly due to larger expansion of the particle volume), and that could've led to a lower heat rate transfer.

From Table 3.1 one can also see that when the temperature increases at any given frequency set, the process time decreases rapidly. This is mostly because when the process temperature is increased and it comes closer to 121ºC (reference temperature) faster, it contributes heavily towards the process lethality for that given time duration. The decrease in the process time was maximum when the temperature increased from 115ºC to 120ºC. This is because 115ºC takes the longest to achieve the process lethality. Interestingly, the process time at 125ºC was half the process time at 115ºC. So, high frequency and a high temperature had favorable results in terms of process time.

Table 3.1. Experimental and Ball process time for salmon chunks at different temperatures and frequencies. Mean ± standard deviation with lowercase letters of significance indicates significance ($p < 0.05$) between reciprocation frequencies, whereas uppercase letters of significance indicate significance ($p < 0.05$) between processing temperatures.

Process Time Type	Process Temperature (°C)	0 Hz (min)	1 Hz (min)	1.5 Hz (min)
Experimental	115	$61.0 \pm 0.5^{a,A}$	$52.1 \pm 0.2^{b,A}$	$50.4 \pm 0.3^{a,A}$
	120	$43.9 \pm 0.3^{a,B}$	$34.5 \pm 0.3^{b,B}$	$32.0 \pm 0.2^{c,B}$
	125	$33.3 \pm 0.3^{a,C}$	$26.0 \pm 0.4^{c,C}$	$27.0 \pm 0.3^{b,C}$
Ball	115	$61.5 \pm 0.5^{a,A}$	$51.6 \pm 0.2^{b,A}$	$51.2 \pm 0.3^{a,A}$
	120	$44.6 \pm 0.3^{a,B}$	$35.2 \pm 0.3^{b,B}$	$33.4 \pm 0.2^{c,B}$
	125	$33.1 \pm 0.3^{a,C}$	$27.2 \pm 0.4^{c,C}$	$27.0 \pm 0.3^{b,C}$

Ball Process Time vs. Experimental Process Time:

Ball process time was calculated for similar process and compared with experimental process time. Results show excellent correlation between the Ball process time and the experimental values with the difference between the two mostly less than 5%.

3.5.3 Heating rate index (f_h)

Heating rate index represents the time required for the temperature difference between the heating medium and the product to decrease by a factor of ten (one logarithmic cycle) on a temperature-time curve. In simple terms, it's the time it takes for the product to "catch up" to the heating medium's temperature to a significant degree. It quantifies the rate at which heat penetrates a food product.

Figure 3.3 shows values of f_h calculated for salmon at various process temperature-agitation frequency combinations. As observed from the graph, the values of f_h decreased with an increasing agitation frequency. Thus, the heat penetration rate increased with increasing agitation frequency. For salmon, the highest value of f_h was observed at 115ºC for static conditions (slowest heating condition) and the lowest value was observed at 125ºC for 1.5 Hz agitation frequency (fastest heating condition). The heating rate index decreased from 16-23%, for three temperatures, when the frequency was increased from 0 to 1 Hz and only decreased an average of 4% when the frequency was increased from 1 to 1.5 Hz. It was also observed that with an increase in processing temperature, the average reduction in processing time was 6% when increasing from 115ºC to 120ºC and 5% when increasing from 120ºC to 125ºC.

Several studies have shown that increasing agitation reduces the heating rate index f_h emphasizing the efficiency of agitation in enhancing heat transfer (Van Loey et al., 1994; Sablani and Ramaswamy, 1996; Dwivedi and Ramaswamy, 2010). In earlier work, Abbatemarco and Ramaswamy (1994) observed that increasing the rotational speed from 0 to 20 rpm in end-over-end thermal processing decreased f_h values consistently. Reciprocating agitation significantly reduces fh and process times by enhancing convective heat transfer through forced convection within the container. Increased agitation frequency and amplitude generally lead to improved heat transfer efficiency by promoting better mixing and reducing thermal resistance within food products.

Singh et al. (2015) observed that increasing the agitation frequency from static conditions to higher frequencies (2-4 Hz) drastically reduced fh values. For instance, the fh value for static mode (13.9 min) decreased to between 6.5 and 3.1 min with reciprocation agitation. Singh et al., (2016) observed similar results where f_h decreased when the frequency was increased from 0 Hz to 3 Hz for a similar viscosity liquid for green beans. Research by You (2015) confirmed that increasing the reciprocation frequency from 0 to 3 Hz lowered f_h values in foods such as potatoes and radishes. Ali et al. (2025) worked on thermal processing of white mushrooms in glass jars and observed that f_h decreased when frequency was increased from 0 Hz to 2 Hz. This further supports the trend of agitation reducing the heating rate index across different methods and food types.

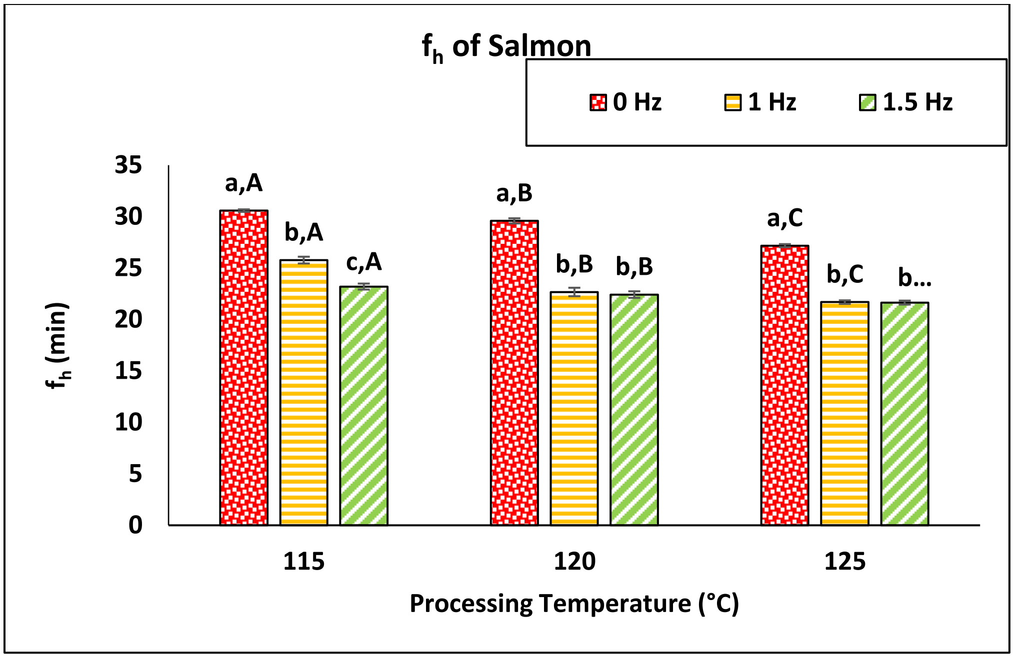

Figure 3.3. Heating rate index (f_h) of salmon vs process temperature at various reciprocating frequencies. Lowercase letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies, whereas uppercase letters of significance indicate significance ($p < 0.05$) between processing temperatures.

3.5.4 Heating lag factor (j_{ch})

The heat lag factor j_{ch} represents the thermal resistance or delay that the product experiences in reaching equilibrium with the surrounding heating medium during thermal processing. This factor is crucial as it reflects the product's ability to "lag" in temperature rise, impacting on the efficiency of heat penetration and, ultimately, the quality and safety of the final product. In the case of salmon, the data provided illustrates how j_{ch} values vary across different temperatures (115°C, 120°C, and 125°C) and frequencies (0 Hz, 1 Hz, and 1.5 Hz).

For salmon, the j_{ch} values decreased when the frequency increased from 0 to 1 Hz and when the temperature was increased from 115°C to 120°C. The data showed increased values of j_{ch} when the frequency was increased from 1 to 1.5 Hz and when the temperature was raised from 120°C to 125°C. So, nothing conclusive was obtained on the calculation of j_{ch} in the case of salmon.

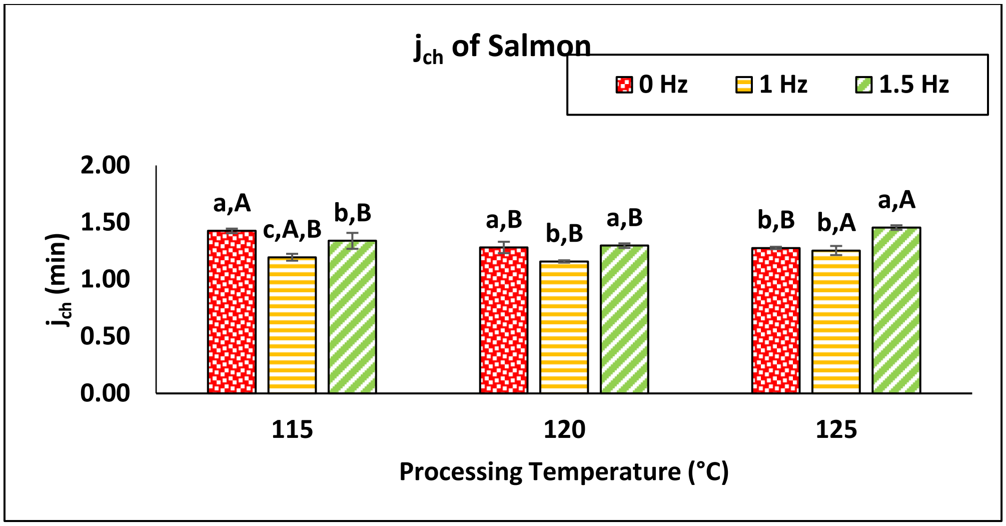

Figure 3.4. Heating lag factor (j_{ch}) of salmon vs process temperature at various reciprocating frequencies. Lowercase letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies, whereas uppercase letters of significance indicate significance ($p < 0.05$) between processing temperatures.

3.5.5 Texture Profile Analysis

3.5.5.1 Firmness

In the context of salmon, firmness (also referred to as hardness) is a key texture attribute that indicates the structural integrity of the muscle tissue during thermal processing. Firmness is quantified as the force required to deform the sample, with higher values signifying a firmer texture. During heating, changes in firmness primarily arise from protein denaturation and collagen solubilization, which alter the muscle structure, water retention, and ultimately, the textural properties perceived by consumers. This value is also reflected by the breakdown of particles due to high agitation speeds.

Raw salmon firmness averaged 50% higher than the firmness of treated salmon for various temperature-frequency combinations. The lowest firmness was observed for 115°C temperature and 0 Hz frequency combination (prolonged heating and overcooking of the product). As the frequency increased, the firmness of treated salmon increased. It is in alignment with the process time. The salmon processed with higher agitation were intact and held their structure firmly as compared to the ones processed with no agitation.

This pattern of change in firmness has been documented in various studies, where heating causes myofibrillar proteins to denature and collagen to shrink and solubilize, resulting in significant textural modifications (Kong et al., 2007). The thermal processing of salmon not only affects the overall hardness but also impacts moisture loss, which further contributes to the perception of firmness in the final product. Such textural transformations are critical for determining processing parameters that balance safety and quality in salmon products.

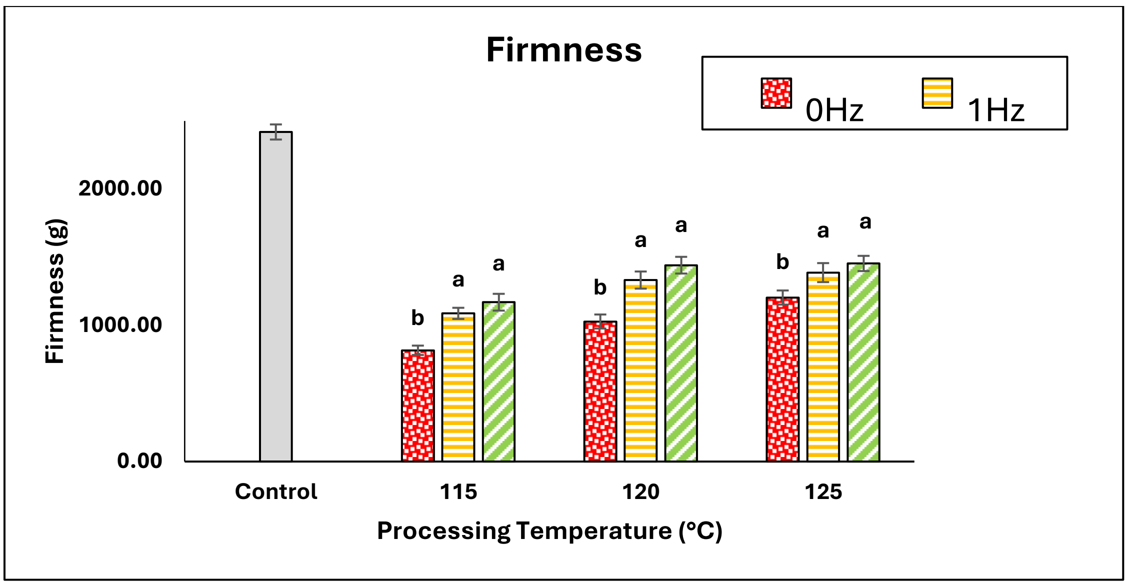

Figure 3.5. Firmness of salmon vs process temperature at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

3.5.5.2 Toughness

In texture measurement, toughness or chewiness refers to the resistance of a food product to deformation and the energy required to break it down during mastication (chewing). These attributes are particularly important in sensory evaluation, as they impact the overall mouthfeel and palatability of the food. The toughness/chewiness parameter is the total positive area under the curve in a Texture Profile Analysis (TPA) test. This measure effectively records the total 'work' involved in performing a TPA test. It therefore follows that a higher area value indicates a higher amount of energy involved in performing the test and subsequently is translated as a tougher/chewier sample to test or a product that is more difficult to bite.

As shown in Fig 3.6, the change in toughness shows the same trend as the change in firmness. Raw salmon toughness was measured to be 44% more when compared to the toughness of treated salmon chunks. With an increase in frequency and temperature respectively, the toughness of the treated salmon increased.

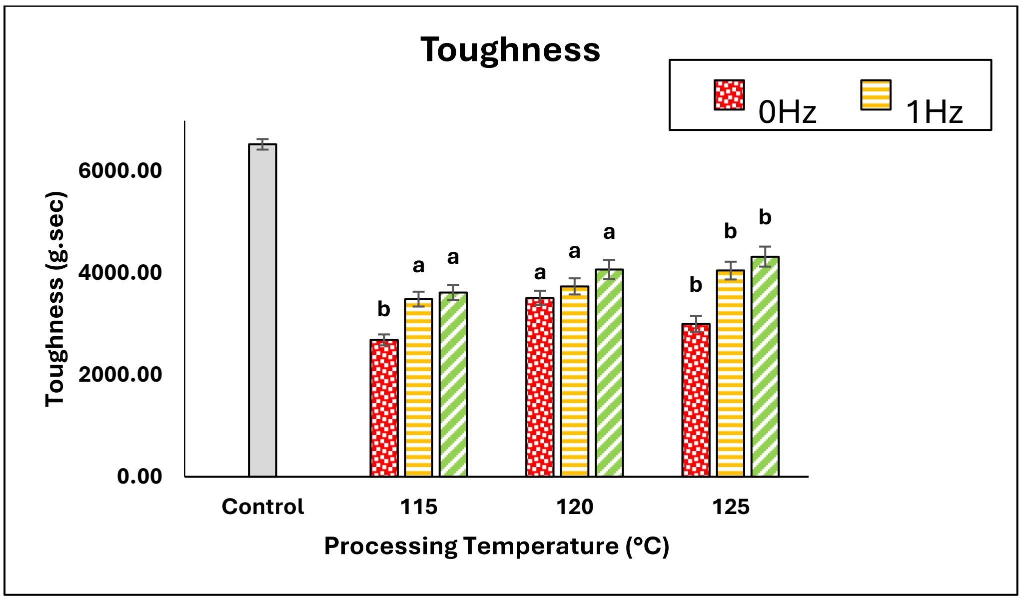

Figure 3.6. Toughness of salmon vs process temperature at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

3.5.6 Color Analysis

3.5.6.1 Lightness

The lightness of treated salmon increased by an average of 75% when compared to raw salmon. Thermal processing leads to an increase in lightness due to protein denaturation and water expulsion, which cause structural changes in the muscle fibers. These changes increase light reflectance, giving the meat a whitish or opaque appearance (Kong et al., 2007) (Bhattacharya et al., 1994). All the treatments showed an increase in lightness, but when compared with each other, there was no significant change in L* value. This is because at a higher temperature, the processing time, obtaining a similar lethality as the one at a lower temperature, is low. Thus, salmon is subjected to increased temperatures for short periods of time. In general, one can expect better color retention when processing under high temperature short time heating conditions, however, in combination with agitation, the process has yielded no significant differences.

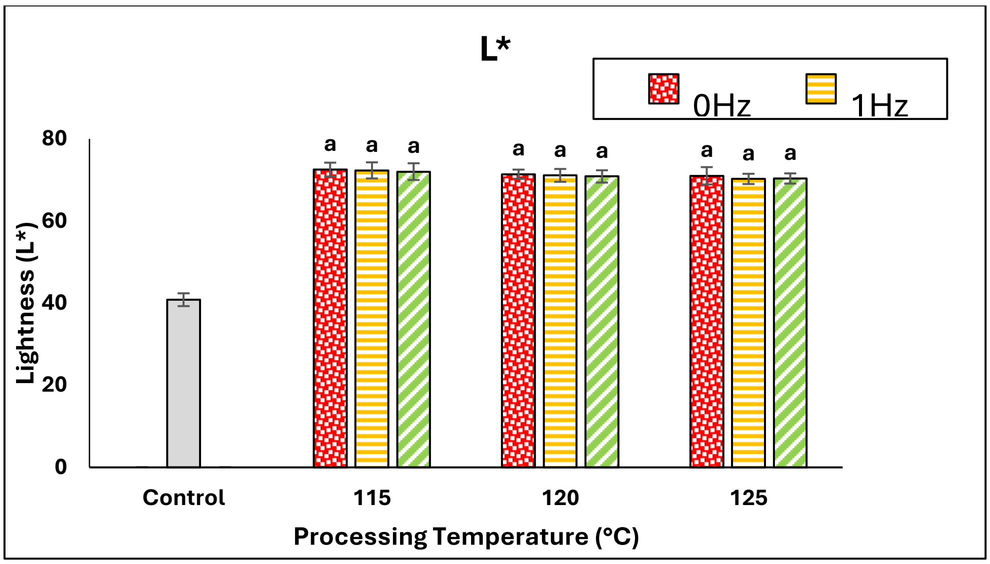

Figure 3.7. **Lightness (L^*) of salmon vs process temperature at various reciprocating frequencies.** Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

3.5.6.2 Redness

Fresh salmon color has redness in it. Thus, a higher value of redness is preferred when salmon is thermally processed. Figure 3.8 shows the change in redness value for salmon for various temperature frequency combinations. It clearly shows from the graph that a higher frequency or temperature gives a higher value of redness, which is favorable for treated salmon. The highest value of redness was observed for a temperature of 125°C and 1 Hz frequency, which coincided with the least thermal processing time. The redness of salmon diminishes as the carotenoid pigments, primarily astaxanthin, undergo thermal degradation and oxidation. This process reduces the vibrant red hue characteristic of raw salmon as observed in previous research (Kong et al., 2007) (Bhattacharya et al., 1994). As mentioned earlier, although the L values were not influenced, the color "a" value followed the conventional trend of HTST in terms of better preserving the red color.

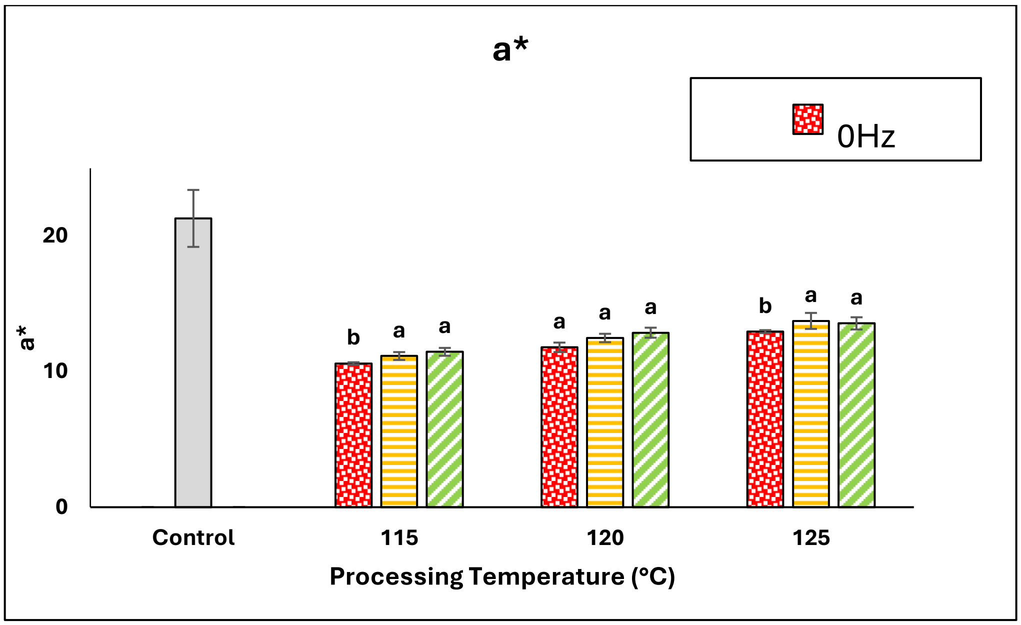

Figure 3.8. Redness (a*) of salmon vs process temperature at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

3.5.6.3 Hue

Hue refers to the dominant wavelength of color perceived and is expressed in degrees. It represents the type of color, such as red, yellow, green, or blue, and is measured in the a*b* color space. Red hues are closer to 0°, yellow around 90°, green at 180°, and blue at 270°. In the case of salmon, hue is used to assess the retention or degradation of its natural reddish-pink color during thermal processing. As shown in Figure 3.9, all the treated salmon lost part of their red color and moved towards the yellow wavelength. With an increasing frequency or temperature, the hue values decrease. The lower value of hue is more appealing to the consumers as it shows the resemblance to a fresh salmon.

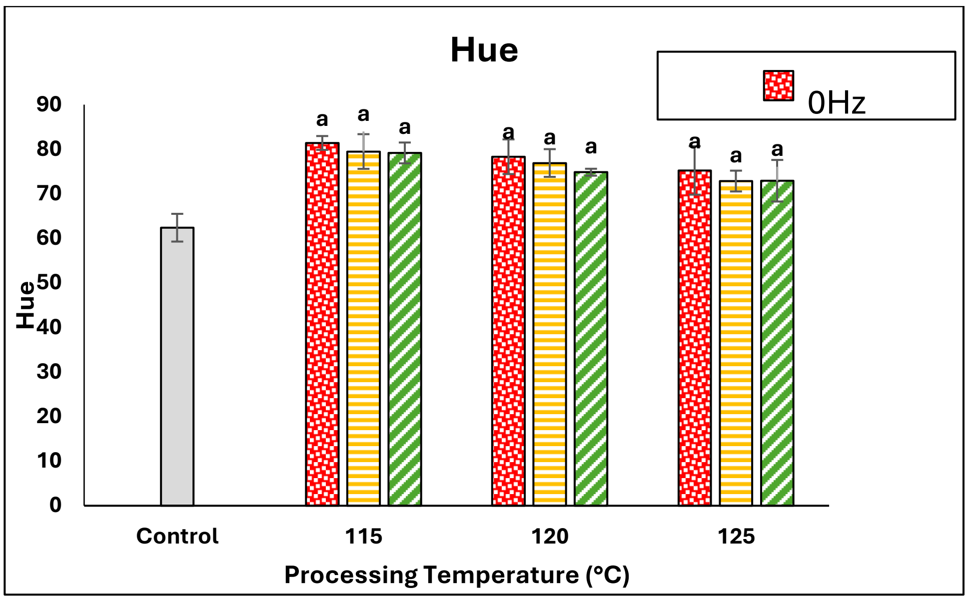

Figure 3.9. Hue of salmon vs process temperature at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

3.5.6.4 Chroma

Chroma represents the color intensity or saturation in color space. It describes how vivid or dull a color appears, indicating the strength or purity of the hue. Higher C^* values correspond to more saturated, vivid colors, while lower values indicate muted or grayish tones. In salmon, C^* is critical for visual appeal and consumer perception. The vivid orange-pink color of salmon, largely due to carotenoids like astaxanthin, is an indicator of quality and freshness. Changes in

C^* during thermal processing often indicate the degradation of carotenoids or alterations in the muscle structure that affect light reflectance. A decrease in C^* can suggest a loss of vibrant pigmentation, whereas stable or increased C^* could imply retained or enhanced visual quality.

From Figure 3.10 the raw salmon has a significantly higher value of C^*, indicating that thermal processing reduces color intensity. The value of C^* increased when processing temperature or frequency was increased, but the difference wasn't significant between them.

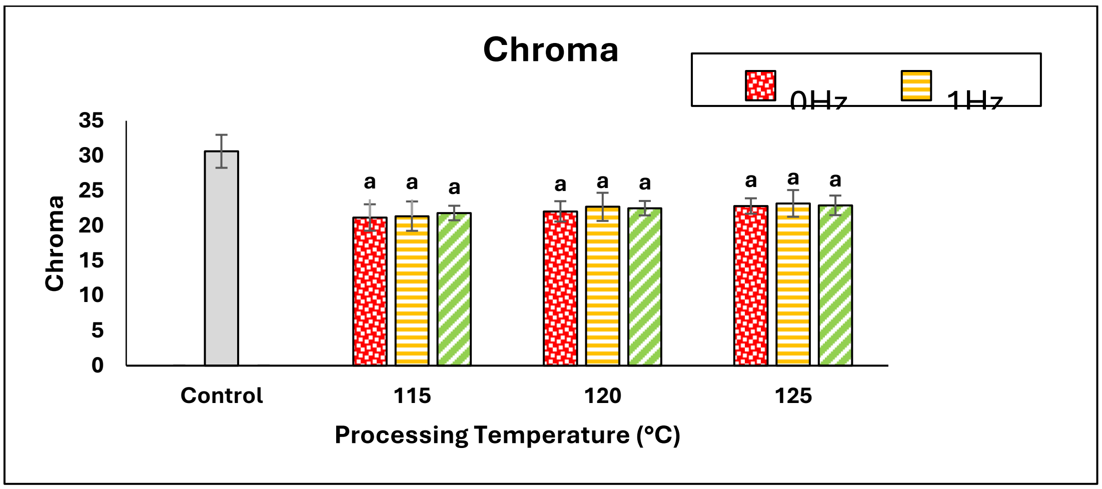

Figure 3.10. Chroma of salmon vs process temperature at various reciprocating frequencies. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

3.6 Conclusions

This study demonstrated the potential of reciprocation agitation thermal processing (RATP) to enhance the quality and efficiency of salmon thermal processing. Higher temperatures and agitation frequencies significantly reduced processing times and improved heat transfer, with 125°C and 1 Hz identified as the optimal conditions for maximizing efficiency while maintaining quality. Under these conditions, better retention of texture (firmness and toughness) and color (redness) was observed, indicating minimal quality degradation. While increasing the frequency beyond 1 Hz slightly improved heat transfer, it had diminishing returns and marginally impacted quality. Overall, RATP proved effective in achieving faster lethality while preserving the sensory and structural attributes of salmon, making it a promising method for industrial applications.

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PREFACE TO CHAPTER 4

In Chapter 3, the reciprocation agitation thermal processing (RATP) was explored in detail for processing of salmon in glass jars. Optimal conditions were identified for reducing the process time and improving quality retention of processed salmon. In this Chapter 4, two other forms of container agitation are explored in a different horizontal rotary retort. This chapter explores the comparative effectiveness of two end-over-end (EOE) agitation thermal processing methods: continuous rotation (EOE-C) and intermittent oscillatory rotation (EOE-O). The chapter assesses heat penetration characteristics using both model food systems (Nylon spheres in water, glycerin, and oil). Experiments were conducted across varying rotational speeds and retort temperatures to establish the impact of oscillatory dwell times on heat transfer efficiency. The study highlights the advantages of EOE-O in improving convective heat transfer, reducing processing times, and enhancing product quality. This chapter provides critical insights into optimizing agitation thermal processing techniques for particulate food systems, offering industrial applicability in the development of efficient and high-quality thermally processed foods.

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

Rawat, K., Taherian, A.R., and Ramaswamy, H.S., 2024. Comparing rotation vs oscillatory agitation for heat transfer analysis using Nylon spheres. Northeast Agricultural and Biological Engineering Conference, Pennsylvania, USA.

Part of this thesis has been submitted as a manuscript at the following scientific conference for the graduate student paper competition:

Rawat, K., Taherian, A.R., and Ramaswamy, H.S., 2025. Institute of Thermal Processing Specialists Charles R. Stumbo Student Paper Competition “Comparison of EOE rotational vs EOE intermittent oscillation agitation thermal processing on the heat processing properties of Nylon spheres in water, glycerin and oil as medium” Reno, USA. Judged and awarded the 3rd best paper.

CHAPTER 4

COMPARISON OF EOE ROTATIONAL VS EOE INTERMITTENT OSCILLATION AGITATION THERMAL PROCESSING ON THE HEAT PROCESSING PROPERTIES OF NYLON SPHERES IN WATER, GLYCERIN AND OIL AS MEDIA

4.1 Abstract

This study focuses on comparing two different types of rotational thermal processing: End-over-end Rotation vs End-over-end Intermittent Oscillation with a dwell time of 10 seconds. Nylon particulates were used to simulate food particles. A thermocouple was inserted into the geometrical center of a Nylon spehre which was then placed at the center of the can. Three Newtonian fluids; water, glycerin and oil, were used as different mediums for the cans. Different viscosity liquids were used to simulate various liquids used in food cans; from water to oil to thick gravy. The processing parameters used for this experiment were: Temperature – 115, 120 and125°C and Rotational speed – 10, 20 and 30 RPM. The cans filled and sealed with different mediums and Nylon spheres were placed inside the retort chamber in EOE position for thermal processing. After the thermal treatment, the time-temperature data was recorded. It was used to calculate heat processing properties (P_t, f_h, j_{ch}). The comparison between the processes was done by comparing these heat processing properties.

The results showed that at lower RPM (10 RPM), the EOE Rotation showed better results when compared to EOE Intermittent Oscillation. Overall, EOE Intermittent Oscillation showed the best results amongst all processes when processing was performed at a higher rotational speed of 30 RPM.

4.2 Introduction

Thermal processing has long been an essential method in food preservation, ensuring the microbial safety of canned products while maintaining an extended shelf life. Introduced in the 19th century, the canning process originally relied on static thermal treatments, where heat was applied uniformly to achieve sterilization. However, traditional methods often resulted in prolonged heating times, leading to over-processing, nutrient loss, and undesirable quality changes (Holdsworth & Simpson, 2007; Ramaswamy & Marcotte, 2006). Over time, innovations such as high-temperature short-time (HTST) processing were developed to address these limitations, offering faster heat penetration while minimizing damage to the sensory and nutritional attributes of canned foods (Sablani & Ramaswamy, 1996).

In the context of the canning industry, HTST processing has become a cornerstone of modern thermal technologies. By rapidly achieving target lethality, HTST processes reduce thermal exposure, preserving the texture, color, and nutritional content of products such as vegetables and seafood (Dwivedi & Ramaswamy, 2010; Singh et al., 2015b). Additionally, HTST technologies improve energy efficiency, making them highly suitable for large-scale production. These methods have been particularly effective in processing low-viscosity and homogeneous products; however, their application to heterogeneous systems, such as particulate-containing foods, remain challenging.

To overcome these challenges, agitation thermal processing has been widely adopted, incorporating controlled motion during heating to enhance convective heat transfer. Several agitation techniques have been explored, including end-over-end rotation, biaxial rotation, intermittent oscillation and reciprocating agitation. Agitation improves heat penetration by inducing fluid movement, reducing temperature gradients within the product (Walden & Emanuel, 2015). Studies have shown that agitation-based systems reduce process times by up to 50% compared to static methods while preserving product quality (Dwivedi & Ramaswamy, 2010; Singh et al., 2015a). Notably, reciprocating agitation has been particularly effective in processing particulate systems, achieving uniform heat transfer in viscous media like oil and glycerin (Pratap-Singh et al., 2015).

End-over-end (EOE) rotation, also referred to as axial mode pack rotation, is a widely employed thermal processing method that has gained prominence in recent years. This technique involves rotating containers within baskets or crates that allow limited rotation, making it a flexible batch processing approach suitable for various container types beyond the conventional cylindrical metal cans (Zhu et al., 2022; Jimenez et al., 2023). It is a core feature of commercial rotary retort systems such as Sterilmatic, Steristar, and Rotomat. However, despite its advantages, EOE rotation has its limitations. Researchers have observed that at higher rotational speeds, particles tend to migrate toward the container's edges. This accumulation disrupts the movement of the headspace bubble due to the equilibrium established between centrifugal and gravitational forces inside the container (Jimenez et al., 2023).

The success of the EOE method depends on maintaining adequate headspace within the container, as this is critical for enabling the circular motion that ensures uniform heat transfer. The process requires careful optimization of container design and rotation parameters to achieve effective thermal processing (Dwivedi & Ramaswamy, 2010). Despite these challenges, EOE rotation remains a highly effective technique for minimizing thermal gradients and improving heat transfer, particularly for low-to-medium viscosity foods (Ramaswamy & Marcotte, 2006; Jimenez et al., 2023).

Bi-axial rotation is a widely utilized method in continuous retort systems, offering improved heat transfer efficiency by addressing the limitations of end-over-end (EOE) rotation. In this process, metal can change their rotational direction twice during a single revolution of the cage, effectively mitigating the centrifugal effects seen in EOE systems and enhancing uniform heat penetration (Dwivedi & Ramaswamy, 2010; Singh et al., 2015a). Modern bi-axial systems further optimize this principle by integrating precise motion controls, making them ideal for viscous and particle-laden foods (Walden & Emanuel, 2015; Jimenez et al., 2023).

Even though bi-axial rotation continuous (FMC turbo cooker) thermal processing is widely used in the industry, its complex design increases the setup and operational costs. It increases the research for a newer technology which can be efficient as bi-axial rotation and can be produced at a lower cost. Intermittent oscillation or oscillation with a dwell time is a newer method of agitation thermal processing. Under this method, the cans are in end over end rotation for a fixed RPM and time. After a certain time, the rotation stops for a certain duration known as the dwell time, and the chamber starts moving in the opposite direction. This allows a proper mixing of the particles within the can and increases the heat transfer. According to a study conducted by McNaughton in 2018, the oscillating thermal processing reduces the processing time by 10-27% when compared to static processing under similar processing conditions. The study showed that oscillating with dwell time (10.5 RPM, 15° angle, 15-second dwell) produced the best results. It significantly improved heat penetration compared to both static and continuous oscillation methods.

There is a lack of research comparing oscillation with dwell time thermal processing with existing agitation thermal processing methods. So, this research focuses on comparing the EOE rotation to EOE intermittent oscillation.

4.3 Materials and Methods

4.3.1 Sample Preparation

Metal cans of size 303×406 were used for this study (Home Canning Co., Montreal, QC). The cans were seamed by a manually operated canning machine (Home Canning Co., Montreal, QC). Nylon spheres of size 25 mm were used in the experiment to simulate the food particles (Small Parts Inc., Miami, FL). Three Newtonian liquids of different viscosities: Water, Glycerin and Oil, were used in the experiment to simulate various liquids in canned food. Table 4.1.1 shows the thermo-physical properties of different liquids at bulk mean temperature and were derived from different literatures. A hole was drilled in the Nylon sphere to reach the geometrical center of the sphere. A thermocouple wire was glued with an epoxy glue to the Nylon sphere. The rigid type-T thermocouples (wire diameter 0.0762 mm, Omega Engineering Corp., Stamford, CT, USA) measuring the particle temperature were introduced into the particle center through a fine hole drilled using a horizontal lathe and were fixed by a small amount of epoxy glue. Thermocouple leads from the retort were connected to a slip ring assembly at the end of the rotating shaft. The other end of these thermocouples was attached to a datalogger which was set to record the time-temperature data every 5 seconds.

Table 4.1 Thermo-physical properties of liquid materials at 20°C

Material	Density (kg/m^3)	Heat capacity (J/kg C)	Viscosity (Pa s)
Water	998	4,180	1E-03
Pure Glycerin	1,260	2,430	9.42E-01
Canola Oil	920	2,100	7.5E-02

4.3.2 Retort Setup

A single basket rotary retort (Stock Rotomat PR900, Hermann Stock Maschinenfabrik GmbH, Neumünster, Germany) was used in the study. Cans for EOE rotation were positioned inside the normal cage. The modified retort used the same control system for pressure, temperature, and cage rotation operation as in the regular retort and, hence, the performance was not affected. The can rotation principle was similar that to in a Steritort (FMC Corp., San Jose, CA).

For the intermittent oscillation with dwell/hold time, the cans were placed inside the cage in vertical direction and were fixed. Multiple rotational speeds were used in the experiment, the maximum being 30 RPM. The cage/chamber rotated in one direction at the set speed, stopped for 10 seconds before reversing to the other direction.

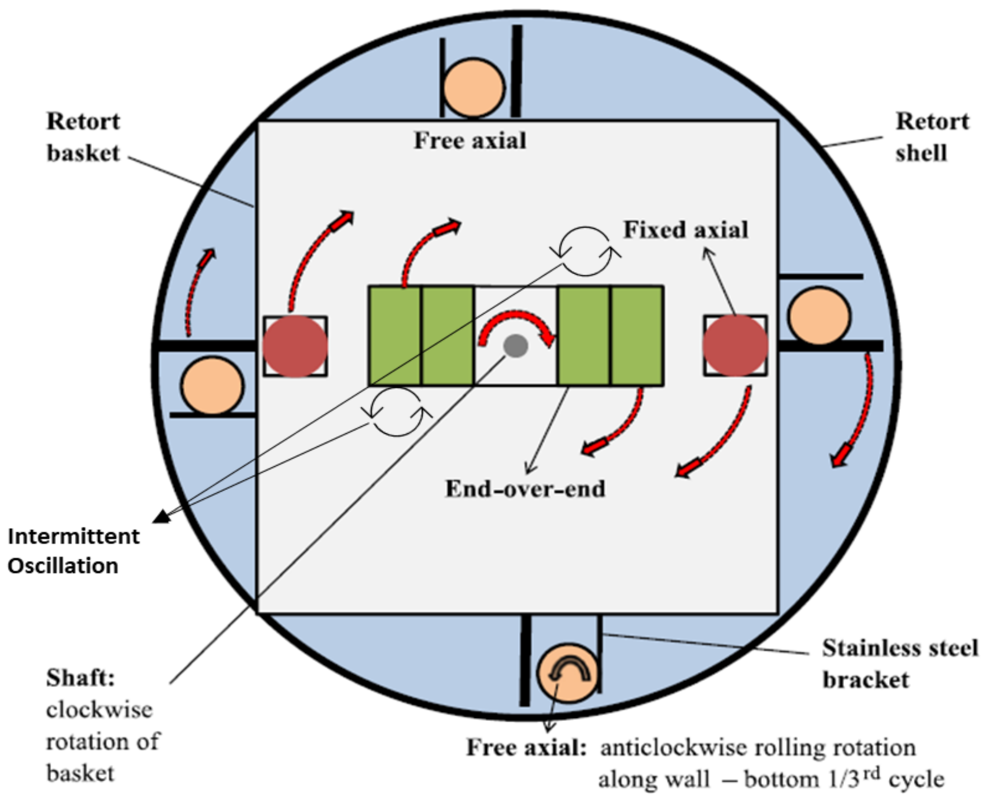

Figure 4.1: Schematic of retort rack showing different modes of rotation (Rattan & Ramaswamy, 2014)

4.3.3 Thermal processing conditions

The prepared were thermally processed for multiple combinations of temperatures, 115, 120, and 125 °C, and speed, 10, 20 and 30 RPM. The number of runs were based on a full factorial test. The samples were processed two times for each combination. Water, preheated in a storage vessel to approximately 10°C above the processing temperature, was transferred to the processing vessel. Throughout the sterilization cycle, the retort control system maintained the water temperature and system pressure at the pre-set levels. At the start of the cooling phase, the hot sterilizing water was pumped back to the storage vessel, where it was reheated to the required temperature for the next cycle. The cans were subsequently cooled by circulating cold water through the retort. The lethality for every 5 seconds of processing was calculated by using the following Equation:

$$Fo = \int L\,dt = \sum 10^{\frac{Ts-121.1}{10}} \frac{5}{60} \qquad \textbf{4.1}$$

where T_s represents the sample temperature. The next step was to determine the cumulative lethality. The point at which the target process lethality was achieved was documented as the processing time for that temperature-frequency combination. The target process lethality for the conventional thermal processing is F_{121} = 5 minutes.

Process time was also calculated based on Ball method. It is based on the following equation derived from the heat penetration curve (using the same symbols as detailed earlier):

$$B = f_h \log(j_{ch}\, I_h / g_c) \qquad \textbf{4.2}$$

B is the process time, f_h is the heating rate index, j_{ch} is the lag factor, I_h is the initial temperature difference ($T_r - T_i$) and g_c is the temperature difference at the end of the cook ($T_r - T$) at t = B), T_r is the retort temperature, T_{pih} is the pseudo-initial product temperature, and T_i is the initial product temperature.

4.3.4. Calculation of Heat Penetration Parameters

A heating curve was created by plotting the logarithm of the difference between the retort temperature and the sample temperature versus time. The negative reciprocal of the slope from the straight-line section of the heating curve represents the heating rate index, calculated as:

$$f_h = -1 / \text{slope} \quad \textbf{4.3}$$

The heating lag factor was determined using the following formula:

$$j_{ch} = (T_R - T_{pih}) / (T_R - T_{ih}) \quad \textbf{4.4}$$

Where T_R is the retort temperature, T_{ih} is the initial sample temperature, and T_{pih} is the pseudo-initial temperature of the sample. The pseudo-initial temperature is determined by extrapolating the straight-line portion of the heating curve, with the point where this extrapolation intersects the y-axis representing the pseudo-initial temperature.

4.4 Statistical Analysis

Statistical analysis was conducted using a single-factor ANOVA to assess the variance between groups, followed by a post hoc Kruskal-Wallis test for pairwise comparisons. The Kruskal-Wallis test, a non-parametric method, was chosen to ensure robust analysis without assuming normal distribution of the data. A significance level of $p < 0.05$ was used to determine statistically significant differences between groups.

4.5 Results and Discussions

4.5.1 Processing time

Processing time for different retort conditions was calculated to compare EOE Rotation and EOE Intermittent Oscillation. The point when the process lethality reached 5 minutes was considered as the process time for the individual condition. Figure 4.2 shows the process time obtained for EOE Rotation of Nylon spheres in water as the medium. As the RPM is increased from 10 to 20, the process time decreases by an average of 15% for all three temperatures. Similar studies on potatoes(Abbatemarco & Ramaswamy, 1994) have also reported a decrease in process time with increasing rotational speed. Interestingly, when RPM was increased from 20 to 30, the process time started to increase. It increased by an average of 27% for all three temperatures. Previous studies show that when the centrifugal and gravitational forces acting on the can are equal, no headspace movement occurs within the can (Clifcorn et al., 1950). This phenomenon can occur at higher rotational speeds and thus we observe an increase in process time. At high rotational speed, the particles inside the cans will be stuck to one side, giving them a lower chance of movement. This decreases the heat transfer, as there is less agitation because of the particles, and thus an increased process time is observed.

Figure 4.3 shows the process time obtained for EOE Intermittent Oscillation of Nylon spheres in water as the medium. As the RPM is increased from 10 to 20, the process time decreases by an average of 17% for all three temperatures. It continues to decrease with an increasing RPM. For an RPM increase from 20 to 30, the process time decreases by an average of 18%. The difference in the process time at higher RPM between EOE Rotation and EOE Intermittent Oscillation could be because of the change in direction of rotation constantly and a hold/dwell time which allows better mixing and thus a better heat transfer. According to a study conducted by McNaughton in 2018, the oscillating with a dwell time thermal processing reduced the process time when compared to static thermal processing.

Table 4.2 and 4.3 show the process time when the medium inside the cans was glycerin and oil and for EOE Rotation vs EOE Intermittent Oscillation respectively. The results are consistent with the results obtained for water as medium. The process time decreases from 10 to 20 RPM and increases when speed is increased from 20 to 30 RPM for EOE Rotation. In contrast to EOE Rotation, for EOE Intermittent Oscillation, the process time consistently decreases when the speed is increased from 10 to 20 to 30 RPM. Among the three mediums, the process time followed the trend: Water<Glycerin<Oil, across all combinations of temperature, speed and processing type.

Ball Process Time vs. Experimental Process Time:

Ball process time was calculated for similar process and compared with experimental process time. Results show excellent correlation between the Ball process time and the experimental values with the difference between the two mostly less than 5%.

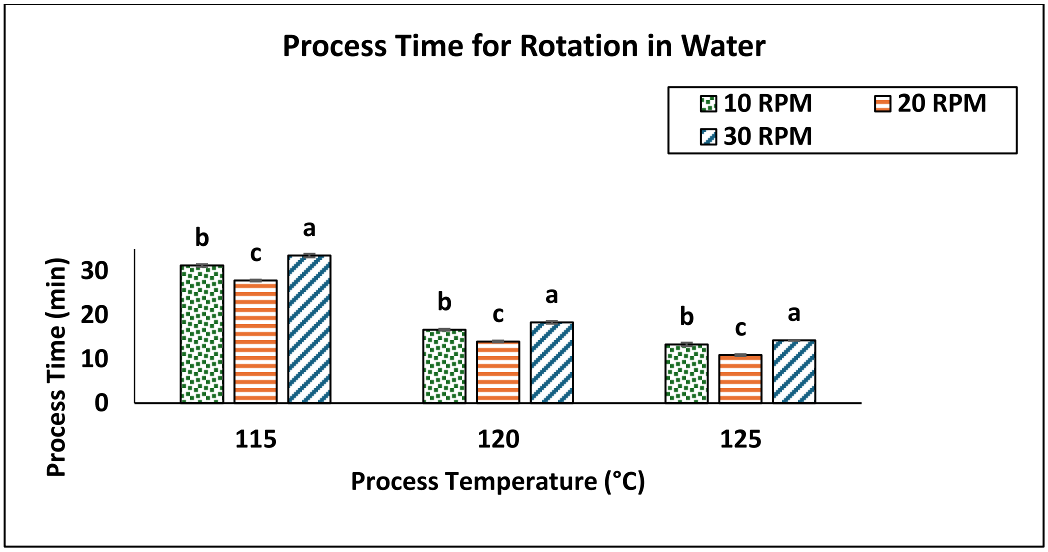

Figure 4.2 **Process time of Nylon spheres in rotational thermal processing with water as medium at different temperatures and RPM.** Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

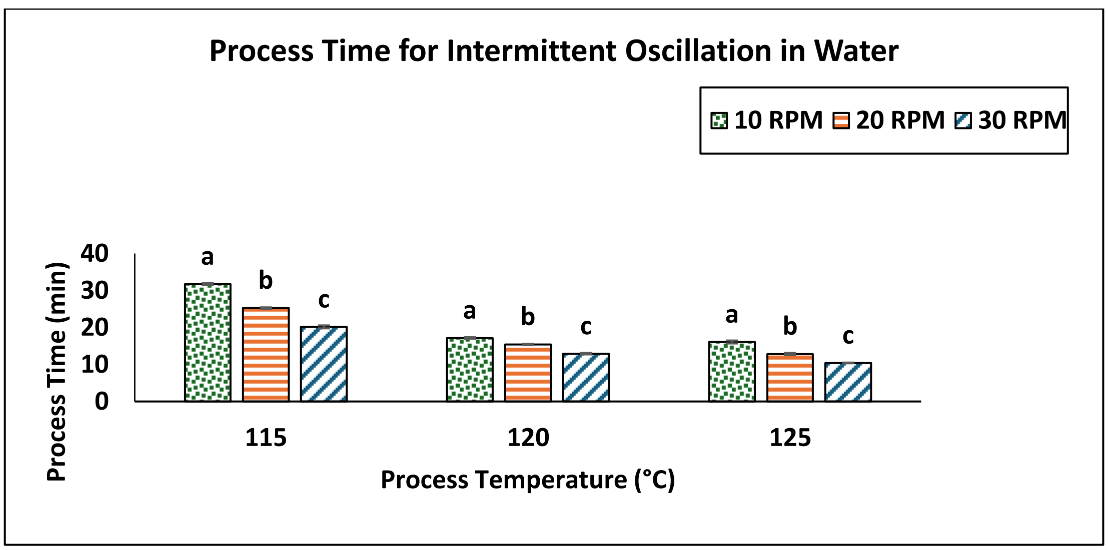

Figure 4.3 **Process time of Nylon spheres in intermittent oscillation thermal processing with water as medium at different temperatures and RPM.** Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Table 4.2 Process time of Nylon spheres in EOE Rotation and EOE Intermittent Oscillation thermal processing with glycerin as medium at different temperatures and RPM. Mean ± standard deviation with letters of significance indicates significance ($p < 0.05$) between different RPM.

Process Type	Process Temperature (ºC)	10 RPM	20 RPM	30 RPM
EOE Rotation	115	32.9±0.2[a]	28±0.4[a]	33.7±0.3[a]
	120	17±0.1[b]	16.3±0.2[b]	20.5±0.4[b]
	125	13.8±0.3[c]	11.1±0.4[c]	15.0±0.2[c]
EOE Intermittent Oscillation	115	32.9±0.2[a]	25.7±0.3[a]	22.9±0.4[a]
	120	18.4±0.1[b]	16.1±0.2[b]	15.2±0.2[b]
	125	16.6±0.1[c]	13.3±0.5[c]	10.6±0.3[c]

Table 4.3 Process time of Nylon spheres in EOE Rotation and EOE Intermittent Oscillation thermal processing with oil as medium at different temperatures and RPM. Mean ± standard deviation with letters of significance indicates significance ($p < 0.05$) between different RPM.

Process Type	Process Temperature (ºC)	Rotation Speed 10 RPM	Rotation Speed 20 RPM	Rotation Speed 30 RPM
EOE Rotation	115	32.8±0.5[a]	33.3±0.3[a]	34.9±0.1[a]
	120	21.1±0.3[b]	18.3±0.2[b]	22.1±0.2[b]
	125	16.8±0.1[c]	12.5±0.2[c]	19.3±0.4[c]
EOE Intermittent Oscillation	115	33.2±0.2[a]	31.2±0.4[a]	28.6±0.3[a]
	120	21.4±0.3[b]	20.0±0.5[b]	17±0.3[b]
	125	17.9±0.4[c]	16.2±0.1[c]	11.9±0.4[c]

Table 4.4 Ball process time of Nylon spheres in EOE Rotation and EOE Intermittent Oscillation thermal processing with water as medium at different temperatures and RPM. Mean ± standard deviation with letters of significance indicates significance ($p < 0.05$) between different RPM.

Process Type	Process Temperature (°C)	10 RPM	20 RPM	30 RPM
EOE Rotation	115	33.9±0.5[a]	28.1±0.5[a]	36.7±0.6[a]
	120	18.8±0.3[b]	16.0±0.3[b]	19.7±0.3[b]
	125	13.4±0.3[c]	11.1±0.4[c]	14.7±0.2[c]
EOE Intermittent Oscillation	115	35.1±0.2[a]	30.9±0.3[a]	26.7±0.1[a]
	120	19.5±0.3[b]	16.4±0.2[b]	15.3±0.2[b]
	125	14.8±0.1[c]	13.3±0.4[c]	10.6±0.3[c]

4.5.2 Heating rate index (f_h)

The heating rate index f_h is a critical parameter in thermal processing that represents the time it takes for the temperature difference between the heating medium (e.g., steam or hot water) and the product to reduce by 90%, or one logarithmic cycle, on a temperature-time curve. Essentially, it measures how effectively and quickly heat transfers into the core of the product, ensuring that the temperature approaches equilibrium with the heating medium.

From Figure 4.4 when RPM is increased from 10 to 20, the f_h value decreases to an average of 24% for all three temperatures. These findings align with various studies demonstrating that increased agitation reduces the heating rate index (f_h) (Van Loey et al., 1994; Sablani and Ramaswamy, 1996; Dwivedi and Ramaswamy, 2010; Singh et al., 2015b). Previous research also observed that raising the rotational speed from 0 to 20 rpm during end-over-end thermal processing led to a reduction in f_h values (Abbatemarco and Ramaswamy, 1994). Interestingly, when the RPM is increased from 20 to 30, the f_h values increased by an average of 48%. This is consistent with the change in process time with increasing RPM discussed above.

From Figure 4.5 when RPM is increased from 10 to 20, the f_h value decreases to an average of 29% for all three temperatures. In contrast to the EOE Rotation, when RPM is increased from 20 to 30 in EOE Intermittent Oscillation, the f_h value keeps on decreasing and gets lower by an average of 12%. This is consistent with the findings for the changing process time with RPM as discussed above.

Table 4.5 and 4.6 shows the change in Heating rate index f_h when the medium inside the cans was glycerin and oil and for EOE Rotation vs EOE Intermittent Oscillation respectively. The results are consistent with the results obtained for water as medium. The f_h decreases from 10 to 20 RPM and increases when speed is increased from 20 to 30 RPM for EOE Rotation. In contrast to EOE Rotation, for EOE Intermittent Oscillation, f_h consistently decreases when the speed is increased from 10 to 20 to 30 RPM. Amongst the three mediums, the heating rate index was highest in the order- Water<Glycerin<Oil, for all respective combinations of temperature, speed and type of process.

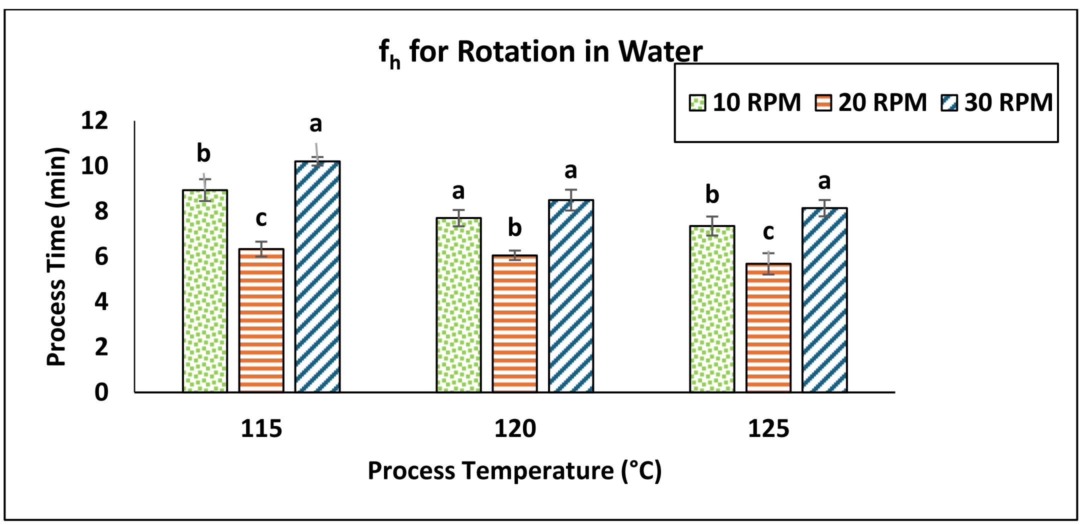

Figure 4.4 Heating rate index (f_h) of Nylon spheres in rotational thermal processing with water as medium at different temperatures and RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

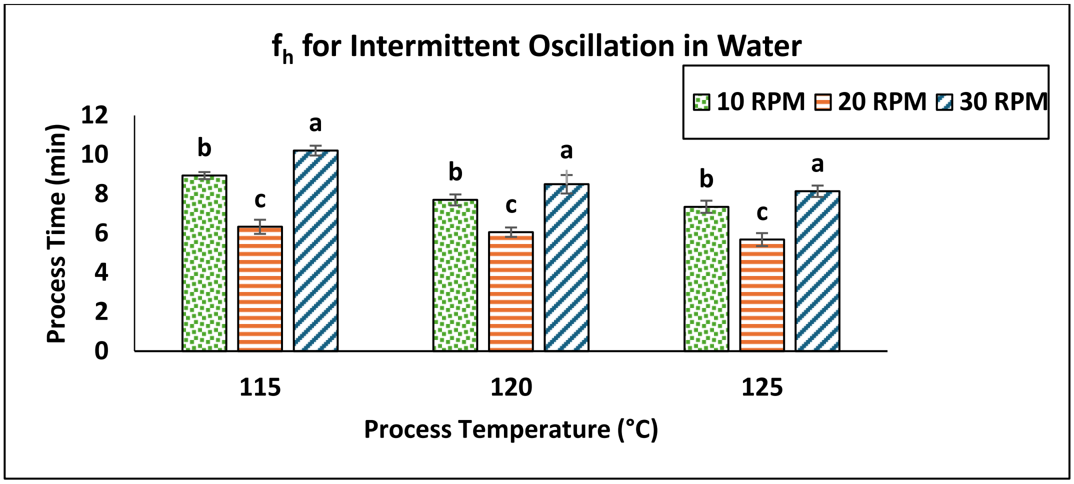

Figure 4.5 Heating rate index (f_h) of Nylon spheres in intermittent oscillation thermal processing with water as medium at different temperatures and RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Table 4.5 Heating rate index (f_h) of Nylon spheres in EOE Rotation and EOE Intermittent Oscillation thermal processing with glycerin as medium at different temperatures and RPM. Mean ± standard deviation with letters of significance indicates significance ($p < 0.05$) between different RPM.

Process Type	Process Temperature (°C)	Rotation Speed 10 RPM	Rotation Speed 20 RPM	Rotation Speed 30 RPM
EOE Rotation	115	9.23 ± 0.29^{a}	6.89 ± 0.25^{a}	10.59 ± 0.19^{a}
	120	7.67 ± 0.16^{b}	$6.48 \pm 0.28^{a,b}$	8.78 ± 0.34^{b}
	125	7.42 ± 0.11^{b}	5.95 ± 0.31^{b}	8.50 ± 0.23^{b}
EOE Intermittent Oscillation	115	10.36 ± 0.23^{a}	7.26 ± 0.21^{a}	6.50 ± 0.33^{a}
	120	8.89 ± 0.21^{b}	6.31 ± 0.28^{b}	6.15 ± 0.29^{a}
	125	8.60 ± 0.41^{b}	5.97 ± 0.35^{b}	5.24 ± 0.37^{b}

Table 4.6 Heating rate index (f_h) of Nylon spheres in EOE Rotation and EOE Intermittent Oscillation thermal processing with oil as medium at different temperatures and RPM. Mean ± standard deviation with letters of significance indicates significance ($p < 0.05$) between different RPM.

Process Type	Process Temperature (ºC)	Rotation Speed 10 RPM	Rotation Speed 20 RPM	Rotation Speed 30 RPM
EOE Rotation	115	10.35±0.17[a]	7.99±0.29[a]	11.75±0.42[a]
	120	9.23±0.31[b]	7.66±0.35[a,b]	9.62±0.38[b]
	125	9.04±0.28[b]	7.18±0.23[b]	9.41±0.22[b]
EOE Intermittent Oscillation	115	10.77±0.25[a]	9.12±0.25[a]	7.28±0.37[a]
	120	9.37±0.33[b]	8.38±0.22[b]	6.35±0.41[b]
	125	9.18±0.26[b]	7.93±0.19[c]	5.67±0.28[b]

4.5.3 Heating lag factor (j_{ch})

The heating lag factor j_{ch} quantifies the delay or thermal resistance that a food product experiences as it heats up and reaches thermal equilibrium with the surrounding heating medium. Essentially, it reflects the rate at which the product's temperature "lags" behind that of the heating medium during thermal processing. This lag is a key factor in assessing the efficiency of heat transfer, as a higher j_{ch} indicates greater resistance to heat penetration. The j_{ch} value is crucial for understanding how the product's thermal properties—such as density, moisture content, and thermal conductivity—affect the overall processing time and quality.

For EOE Rotation, the j_{ch} value decreases by an average of 6% for all three temperatures when RPM is increased from 10 to 20 and increases by an average of 12% when RPM is increased from 20 to 30, as shown in Figure 4.6. As per Figure 4.7, the j_{ch} value decreases by an average of 9% when RPM is increased from 10 to 20 for EOE Intermittent Oscillation. It decreases even further when RPM is increased from 20 to 30, by an average of 7%. These findings are consistent with the change in process time and heat rate index with changing RPM for different processes as discussed above.

Table 4.7 and 4.8 show the change in j_{ch} values when the medium inside the cans was glycerin and oil and for EOE Rotation vs EOE Intermittent Oscillation respectively. The results show consistency with the results obtained for water as medium. The j_{ch} decreases from 10 to 20 RPM and increases when speed is increased from 20 to 30 RPM for EOE Rotation. In contrast to EOE Rotation, for EOE Intermittent Oscillation, j_{ch} consistently decreases when the speed increases from 10-20-30 RPM. Amongst the three mediums, the heating lag factor was highest in the order- Water<Glycerin<Oil, for all respective combinations of temperature, speed and type of process.

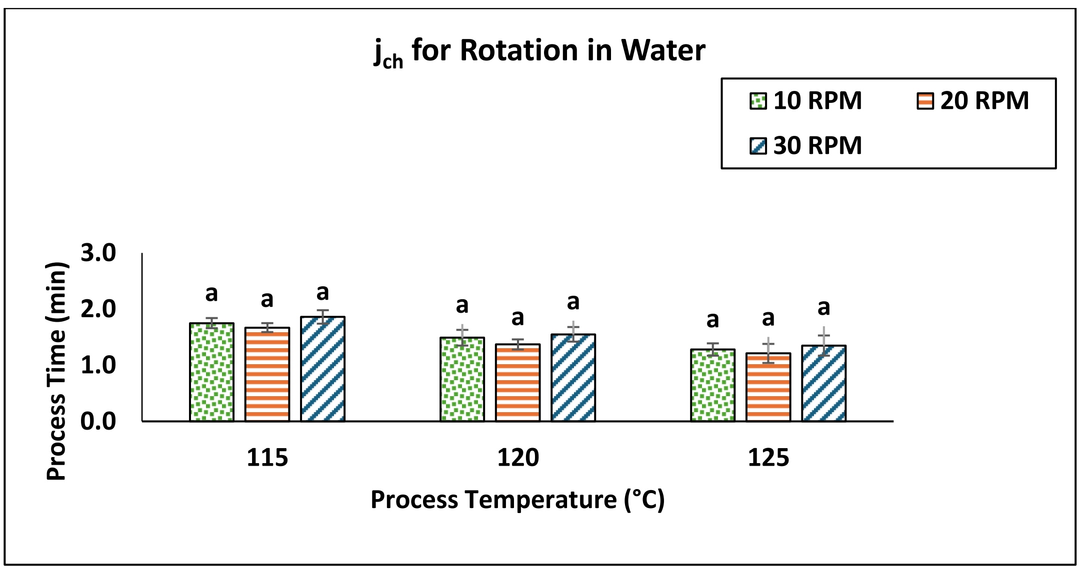

Figure 4.6 Heating lag factor (j_{ch}) of Nylon spheres in rotational thermal processing with water as medium at different temperatures and RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

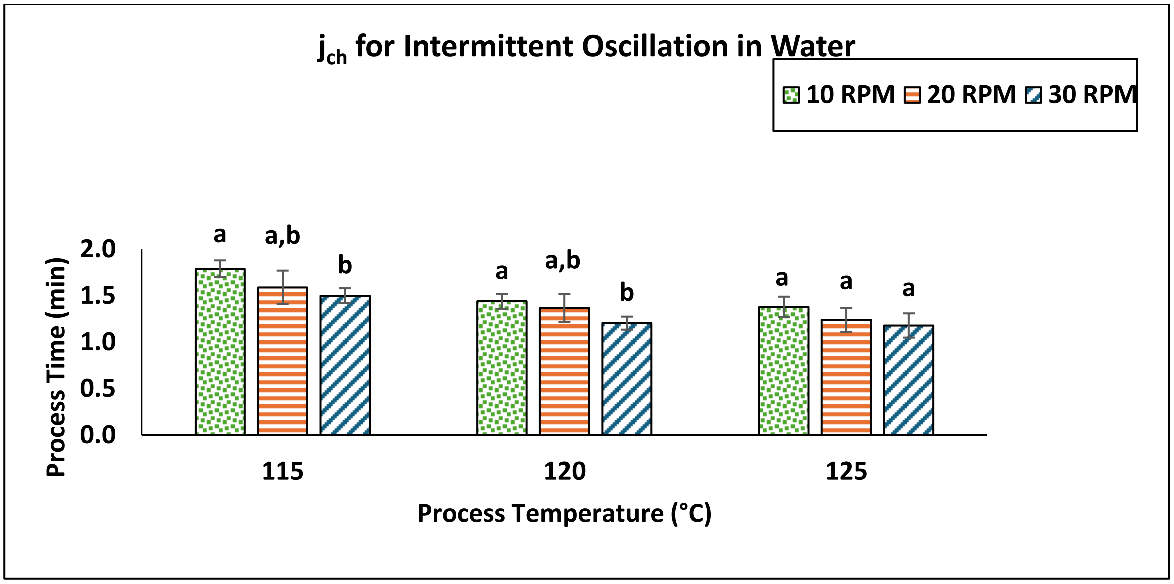

Figure 4.7 Heating lag factor (j_{ch}) of Nylon spheres in intermittent oscillation thermal processing with water as medium at different temperatures and RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Table 4.7 Heating lag factor (j_{ch}) of Nylon spheres in EOE Rotation and EOE Intermittent Oscillation thermal processing with glycerin as medium at different temperatures and RPM. Mean ± standard deviation with letters of significance indicates significance ($p < 0.05$) between different RPM.

Process Type	Process Temperature (ºC)	Rotation Speed 10 RPM	Rotation Speed 20 RPM	Rotation Speed 30 RPM
EOE Rotation	115	1.81±0.09[a]	1.77±0.09[a]	1.92±0.11[a]
	120	1.58±0.07[b]	1.46±0.06[b]	1.59±0.14[b]
	125	1.35±0.08[c]	1.21±0.12[c]	1.39±0.16[b]
EOE Intermittent Oscillation	115	1.81±0.17[a]	1.64±0.14[a]	1.60±0.07[a]
	120	1.64±0.14[a]	1.39±0.13[a,b]	1.28±0.19[b]
	125	1.39±0.08[b]	1.23±0.09[b]	1.14±0.11[b]

Table 4.8 Heating lag factor (j_{ch}) of Nylon spheres in EOE Rotation and EOE Intermittent Oscillation thermal processing with oil as medium at different temperatures and RPM. Mean ± standard deviation with letters of significance indicates significance ($p < 0.05$) between different RPM.

Process Type	Process Temperature (°C)	Rotation Speed 10 RPM	Rotation Speed 20 RPM	Rotation Speed 30 RPM
EOE Rotation	115	1.85±0.08^{a}	1.88±0.08^{a}	1.96±0.21^{a}
	120	1.66±0.16^{a,b}	1.58±0.11^{b}	1.69±0.14^{a,b}
	125	1.52±0.14^{b}	1.24±0.17^{c}	1.41±0.16^{b}
EOE Intermittent Oscillation	115	1.85±0.11^{a}	1.66±0.06^{a}	1.59±0.07^{a}
	120	1.53±0.16^{b}	1.49±0.08^{b}	1.37±0.13^{b}
	125	1.48±0.15^{b}	1.37±0.12^{b}	1.23±0.11^{b}

4.6 Conclusions

The comparison between end-over-end (EOE) rotation and EOE intermittent oscillation revealed key differences in heat transfer efficiency and processing time, depending on rotational speed.

At moderate speeds (10 to 20 RPM), EOE rotation significantly reduced process time due to enhanced convective heat transfer, as observed in prior studies on canned vegetables (Abbatemarco & Ramaswamy, 1994) and liquid-particulate systems (Dwivedi & Ramaswamy, 2010). This effect aligns with established thermal processing principles, where increased agitation enhances heat penetration by reducing thermal resistance and improving fluid movement (Singh & Ramaswamy, 2015).

However, at higher speeds (20 to 30 RPM), process time increased in EOE rotation. This is attributed to the equilibrium between centrifugal and gravitational forces, which restricts headspace movement and limits particle circulation within the container (Clifcorn et al., 1950).

When particles adhere to the can's surface, heat transfer efficiency declines, leading to longer processing times.

In contrast, EOE intermittent oscillation consistently improved heat transfer across all speeds. By periodically reversing direction with a controlled dwell time, this method prevents particle adhesion, enhances fluid mixing, and ensures more uniform heat distribution (MacNaughton, 2018). This resulted in continuous reductions in process time from 10 to 30 RPM, unlike traditional EOE rotation, where process time increased beyond 20 RPM. The effectiveness of intermittent oscillation aligns with prior studies demonstrating reduced thermal resistance and improved heating rate index in oscillatory systems (McNaughton, 2018).

Additionally, intermittent oscillation reduced the heating lag factor (jch) and heating rate index (fh) more effectively than EOE rotation. While EOE rotation showed optimal performance at intermediate speeds, intermittent oscillation provided superior heat penetration at all speeds, making it a promising alternative for improving energy efficiency and product quality in canned foods. Overall, EOE intermittent oscillation presents a more efficient method of agitation thermal processing, especially at higher speeds, where traditional EOE rotation becomes less effective.

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PREFACE TO CHAPTER 5

In Chapter 4, the two forms of end-over-end (EOE) agitation thermal processing methods—continuous rotation (EOE-C) and intermittent oscillatory rotation (EOE-O) were compared. To evaluate the system performance a heat transfer model food system (Nylon spheres in water, glycerin, and oil) was used, and superiority of EOE-O was demonstrated. In this chapter, a real food matrix (radish) is used to evaluate the heat influence of these two EOE agitation thermal processing systems on product quality . Experiments were conducted across varying rotational speeds and retort temperatures to establish the impact of oscillatory dwell times on heat transfer efficiency. The study highlights the advantages of EOE-O in improving convective heat transfer, reducing processing times, and enhancing product quality.

CHAPTER 5

COMPARISON OF EOE ROTATIONAL VS EOE INTERMITTENT OSCILLATION AGITATION THERMAL PROCESSING ON THE HEAT PROCESSING PROPERTIES OF RADISH IN WATER

5.1 Abstract

The purpose of this study is to compare two rotational thermal processing: End-over-end Rotation vs End-over-end Intermittent Oscillation with a dwell time of 10 seconds. Radish slices (10mm thick) were used in this study. A thermocouple was attached to the center of a radish slice which was placed at the center of the glass jar. The rest of the glass jar was filled with radish slices, leaving a small headspace to create vacuum. A 2% brine solution was used as the medium inside the can. For this experiment, the processing parameters were Temperature – 115, 120 and 125°C and Rotational speed – 10 and 30 RPM.

The glass jars were hot filled, sealed and placed inside the retort chamber in EOE position for thermal processing. During the processing, time temperature data were recorded using a datalogger, which is then used to calculate heat processing properties (P_t, f_h, j_{ch}). Differences between these properties were used to compare both processes.

The results showed that EOE Intermittent Oscillation shows the best results amongst all the processes when the thermal processing was done at 30RPM. At a lower RPM (10RPM), EOE Rotation had better heat processing properties when compared to EOE Intermittent Oscillation.

5.2 Introduction

Thermal processing remains a fundamental technique in food preservation, ensuring microbial safety and extending shelf life. Traditional static thermal processing, while effective for sterilization, often results in prolonged heating times, leading to degradation of food quality and nutritional value (Holdsworth & Simpson, 2007; Ramaswamy & Marcotte, 2006). To mitigate these issues, advanced agitation thermal processing methods, including high-temperature short-time (HTST) processing, have been developed to improve heat penetration and quality retention (Sablani & Ramaswamy, 1996).

End-over-end (EOE) rotational thermal processing is a widely adopted technique in the food industry, particularly for canned and packaged foods. This method enhances convective heat transfer by inducing controlled rotation of containers during heating. Studies have demonstrated that EOE rotation can significantly reduce processing time and improve heat distribution in particulate-liquid systems, making it a preferred method for achieving commercial sterility while preserving textural and sensory attributes (Dwivedi & Ramaswamy, 2010; Singh et al., 2015b). However, one challenge with continuous EOE rotation is the potential for particles within the container to migrate toward the edges due to centrifugal forces, reducing overall mixing efficiency and leading to uneven heat distribution (Singh & Ramaswamy, 2015).

To address these limitations, intermittent oscillation during end-over-end agitation has been proposed as an alternative technique to improve heat transfer efficiency. Unlike continuous rotation, intermittent oscillation incorporates periodic stops (dwell time) and reversals in rotation. This enhances internal fluid movement and minimizes particle aggregation at the container walls. Research has shown that this method can lead to improved heat penetration, reduced processing time, and better uniformity in thermal distribution (McNaughton, 2018).

Despite its potential advantages, there is a lack of comparative studies evaluating EOE intermittent oscillation against conventional EOE rotation, particularly for processing particulate foods in liquid media. Radish, a common vegetable with high water content, presents an ideal model for studying the impact of different agitation thermal processing techniques on heat penetration characteristics. The behavior of radish during thermal processing in water can provide insights into the effectiveness of intermittent oscillation in reducing thermal resistance and optimizing sterilization efficiency.

This study aims to compare the heat processing properties of radish in water under two distinct agitation thermal processing methods: (1) EOE rotational processing and (2) EOE intermittent oscillation processing. Key heat transfer parameters, including heating rate index (f_h), heating lag factor (j_{ch}), and process time, will be analyzed to determine the relative efficiency of each method. The results from this study will provide valuable insights into optimizing agitation thermal processing conditions for particulate-liquid food systems, contributing to advancements in food processing technology and quality retention.

By systematically analyzing the impact of rotational versus intermittent oscillation processing, this study seeks to bridge the knowledge gap in agitation thermal processing and offer recommendations for improved industrial applications in retort processing of vegetables and similar food products (Ramaswamy & Marcotte, 2006; Jimenez et al., 2023).

5.3 Materials and Methods

5.3.1 Sample Preparation

Glass jars of volume 500 ml were used for this study. 9 kg of radish was obtained from an orchard in Kirkland, Quebec. The radishes were thoroughly washed of any impurities, the outer skin was removed and sliced into 10 mm thick pieces using an electric slicer. Each slice was then punched with punch die to create cylindrical pieces measuring 10 mm in thickness and 18 mm in diameter. These cylindrical samples were placed in glass jars to prevent moisture loss before further experiments. The cut samples were blanched before processing. 200 grams of blanched samples were placed in the jars. The glass jars were hot filled with 2% brine (salt) solution to create vacuum inside the jars.

The rigid type-T thermocouples (wire diameter 0.0762 mm, Omega Engineering Corp., Stamford, CT, USA) measuring the temperature were attached to the center of the radish slice. Thermocouple leads from the retort were connected to a slip ring assembly at the end of the rotating shaft. The other end of these thermocouples was attached to a datalogger which was set to record the time-temperature data every 5 seconds. The glass jars were hot filled with 2% brine (salt) solution to create vacuum inside the jars.

5.3.2 Retort Setup

A single-basket rotary retort (Stock Rotomat PR900, Hermann Stock Maschinenfabrik GmbH, Neumünster, Germany) was employed for this study. Cans undergoing EOE rotation were arranged inside the standard cage. The modified retort maintained identical control settings for pressure, temperature, and cage rotation as the conventional system, ensuring consistent performance. The principle of can rotation closely resembled that of a Steritort (FMC Corp., San Jose, CA).

For the intermittent oscillation method incorporating dwell/hold time, cans were vertically positioned and secured within the cage. Various rotational speeds were tested, with a maximum of 30 RPM. The chamber rotated in a single direction at the designated speed, then paused for 10 seconds before reversing direction.

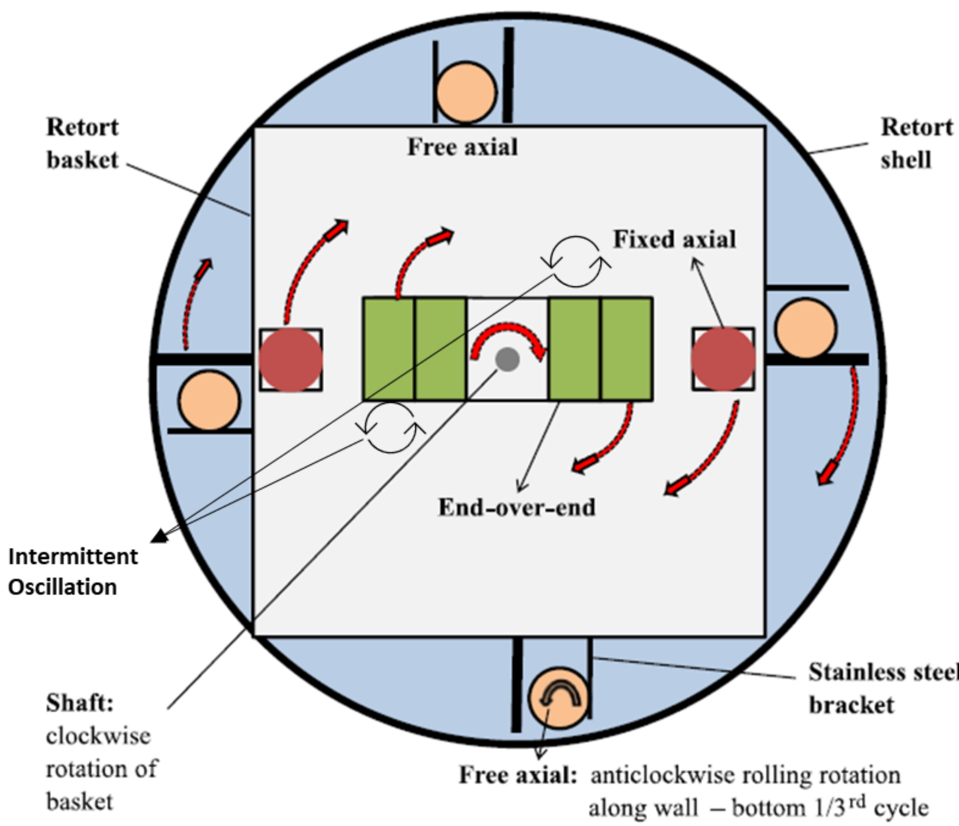

Figure 5.1: Schematic of retort rack showing different modes of rotation (Rattan & Ramaswamy, 2014)

5.3.3 Thermal processing conditions

The prepared samples underwent thermal processing at various temperature-speed combinations, specifically 115, 120, and 125°C, with rotational speeds of 10 and 30 RPM. A full factorial design was employed, and each combination was tested twice. Water, preheated to approximately 10°C above the target processing temperature, was transferred from a storage vessel into the processing vessel. During sterilization, the retort control system regulated both temperature and pressure to maintain consistent processing conditions.

During the cooling phase, the heated sterilizing water was recirculated back to the storage vessel, where it was reheated for subsequent cycles. The cans were then cooled using cold water circulating within the retort. The lethality of the process was calculated every 5 seconds using the following equation:

$$Fo = \int L\,dt = \sum 10^{\frac{Ts-121.1}{10}} \frac{5}{60} \qquad \textbf{5.1}$$

where Ts denotes the sample temperature. The cumulative lethality was then determined, with the processing time recorded at the point when the target lethality was achieved. For conventional thermal processing, the target process lethality is set at F_{121} = 5 minutes.

Process time was also calculated based on Ball method. It is based on the following equation derived from the heat penetration curve (using the same symbols as detailed earlier):

$$B = f_h \log(j_{ch}\, I_h / g_c) \qquad \textbf{5.2}$$

B is the process time, f_h is the heating rate index, j_{ch} is the lag factor, I_h is the initial temperature difference ($T_r - T_i$) and g_c is the temperature difference at the end of the cook ($T_r - T$) at t = B), T_r is the retort temperature, T_{pih} is the pseudo-initial product temperature, and T_i is the initial product temperature.

5.3.4. Calculation of Heat Penetration Parameters

A heating curve was created by plotting the logarithm of the difference between the retort temperature and the sample temperature versus time. The negative reciprocal of the slope from the straight-line section of the heating curve represents the heating rate index, calculated as:

$$f_h = -1 / \text{slope} \qquad \textbf{5.3}$$

The heating lag factor was determined using the following formula:

$$j_{ch} = (T_R - T_{pih}) / (T_R - T_{ih}) \quad \textbf{5.4}$$

Where T_R is the retort temperature, T_{ih} is the initial sample temperature, and T_{pih} is the pseudo-initial temperature of the sample. The pseudo-initial temperature is determined by extrapolating the straight-line portion of the heating curve, with the point where this extrapolation intersects the y-axis representing the pseudo-initial temperature.

5.4 Statistical Analysis

Statistical analysis was conducted using a single-factor ANOVA to assess the variance between groups, followed by a post hoc Kruskal-Wallis test for pairwise comparisons. The Kruskal-Wallis test, a non-parametric method, was chosen to ensure robust analysis without assuming normal distribution of the data. A significance level of $p < 0.05$ was used to determine statistically significant differences between groups.

5.5 Results and Discussions

5.5.1 Processing time

The processing time for different retort conditions was analyzed to compare EOE rotation and EOE intermittent oscillation when radish was used as the food matrix in water as the heating medium. The process time was determined at the point where the process lethality (F_0) reached 5 minutes, providing a basis for comparison across different conditions.

Figure 5.2 shows the process time obtained for EOE rotation of radish in water at different rotational speeds (10 RPM and 30 RPM) and processing temperatures (115°C, 120°C, and 125°C). As the RPM increased from 10 to 30, the process time initially showed a slight increase at all temperatures, contrary to the expected trend of reduced processing time with increased agitation. When the temperature was raised from 115°C to 120°C, the process time decreased by 42% for 10 RPM and 40% for 30 RPM. Similarly, when the temperature increased from 120°C to 125°C, the process time further decreased by 14% for 10 RPM and 13% for 30 RPM.

Interestingly, despite an increase in agitation speed from 10 RPM to 30 RPM, the process time increased slightly instead of decreasing. On average, processing time increased by 4% at 115°C, 7% at 120°C, and 8% at 125°C when shifting from 10 RPM to 30 RPM. This phenomenon can be explained by the interaction of centrifugal and gravitational forces, as described by Clifcorn et al. (1950), where excessive rotation pushes particles toward the container walls, leading to reduced internal agitation and, consequently, a longer heat penetration time.

This behavior contrasts with other studies that have observed an initial decrease in processing time with increased agitation up to an optimal speed, beyond which the process time increased (Abbatemarco & Ramaswamy, 1994). The increase in process time at higher RPM suggests that the convective heat transfer efficiency of radish in water may be limited at 30 RPM due to particle displacement toward the periphery of the container, reducing the extent of forced convection.

Figure 5.3 presents the process time obtained for EOE intermittent oscillation of radish in water at different rotational speeds (10 RPM and 30 RPM) and processing temperatures (115°C, 120°C, and 125°C). As the RPM increased from 10 to 30, the process time decreased consistently across all temperatures, suggesting improved convective heat transfer due to enhanced internal mixing and increased surface contact between radish and the surrounding medium. When the temperature increased from 115°C to 120°C, the process time decreased by 41% for 10 RPM and 41% for 30 RPM. Similarly, as the temperature increased from 120°C to 125°C, the process time further decreased by 19% for 10 RPM and 26% for 30 RPM.

Unlike EOE rotation, where higher RPM resulted in an increase in processing time due to particle accumulation at the container walls (Clifcorn et al., 1950), the EOE intermittent oscillation mode consistently reduced process time with increased RPM. When the speed was increased from 10 RPM to 30 RPM, the process time decreased by an average of 9% at 115°C, 10% at 120°C, and 17% at 125°C. These findings align with the study by McNaughton (2018), which demonstrated that oscillatory agitation with dwell times leads to improved heat transfer efficiency compared to continuous rotation.

The effectiveness of EOE intermittent oscillation in reducing process time compared to continuous rotation is likely due to frequent direction changes and dwell times that allow better fluid circulation and more uniform heat transfer within the container (Singh & Ramaswamy, 2015). Previous research has shown that intermittent oscillation can prevent particle sedimentation and reduce boundary layer resistance, further improving heat penetration rates (Abbatemarco & Ramaswamy, 1994; Singh et al., 2015).

In contrast to EOE rotation, where the process time increased at higher RPM, EOE intermittent oscillation consistently decreased processing time as RPM increased. This indicates that continuous oscillatory motion enhances convective mixing, reducing heat transfer limitations and improving overall processing efficiency. Similar trends have been observed in other studies evaluating oscillatory agitation in liquid-particulate thermal processing (Duguay et al., 2016).

The results confirm that EOE intermittent oscillation is a more efficient mode of agitation for thermally processing radish in water, as it eliminates the negative effects of centrifugal forces seen in continuous rotation. These findings suggest that oscillatory agitation techniques should be further explored for optimizing thermal processing of solid food matrices, particularly for reducing heat penetration times while maintaining quality.

Ball process time was also calculated and it was similar to experimental process time.

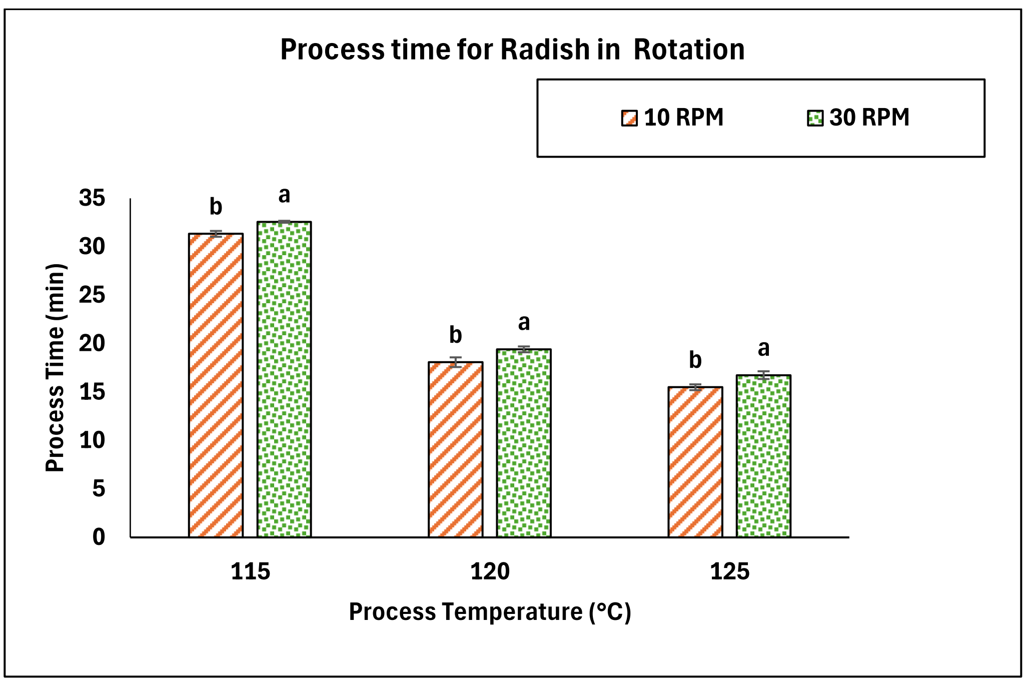

Figure 5.2 Process time of radish in rotational thermal processing with water as medium at different temperatures and RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

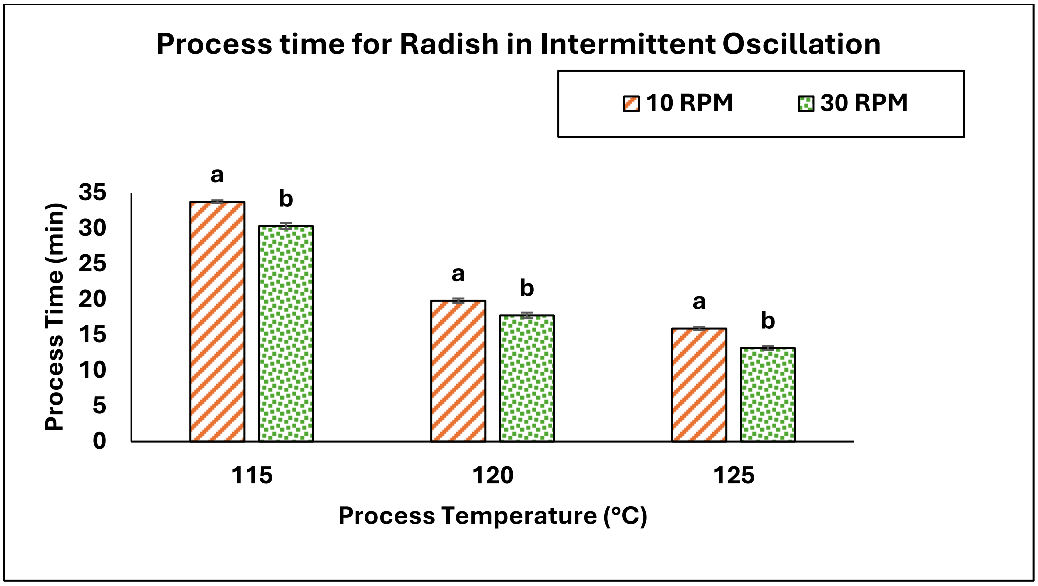

Figure 5.3 **Process time of radish in intermittent oscillation thermal processing with water as medium at different temperatures and RPM.** Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Table 5.1 **Ball process time for radish in EOE rotation and EOE intermittent oscillation at different temperatures and RPM.** Mean ± standard deviation with lowercase letters of significance indicates significance ($p < 0.05$) between reciprocation frequencies, whereas uppercase letters of significance indicate significance ($p < 0.05$) between processing temperatures.

Rotation	Ball Process Temperature (°C)	10 RPM	30 RPM
EOE rotation	115	33 ± 0.1^{b}	33.6 ± 0.3^{a}
	120	18.6 ± 0.2^{b}	20.1 ± 0.2^{a}
	125	15.8 ± 0.4^{b}	17.0 ± 0.5^{a}
EOE intermittent oscillation	115	34.4 ± 0.2^{a}	33 ± 0.3^{b}
	120	19.9 ± 0.3^{a}	18.2 ± 0.2^{b}
	125	16.2 ± 0.1^{a}	13.6 ± 0.2^{b}

5.5.2 Heating rate index (f_h)

The heating rate index (f_h) is a crucial parameter in thermal processing, reflecting the time required for the temperature difference between the heating medium and the product to decrease by 90%. It serves as an indicator of heat transfer efficiency and determines how effectively heat reaches the core of the product. For radish undergoing End-Over-End (EOE) rotation, the impact of rotational speed on f_h was evaluated across different processing temperatures and is shown in Figure 5.4.

When the RPM increased from 10 to 30, the f_h value at 115°C increased slightly by approximately 1.5%, rising from 8.82 to 8.95. At 120°C, however, an increase of 5.8% was observed, with *fh* rising from 7.58 to 8.02. A similar trend was noted at 125°C, where f_h increased from 7.11 to 7.67, representing a 7.9% increase. These results suggest that while an increase in rotational speed may be expected to enhance convective heat transfer, at higher speeds, the movement of radish within the container is altered due to centrifugal forces, leading to reduced internal mixing and, consequently, a decline in heat transfer efficiency.

Comparing f_h across different temperatures at a constant RPM reveals that increasing temperature generally reduces f_h, indicating improved heat transfer efficiency at higher temperatures. At 10 RPM, increasing the temperature from 115°C to 120°C led to a 14% reduction in f_h, while raising it further to 125°C resulted in an additional 6% decrease. This trend is expected, as higher temperatures create a greater thermal gradient, accelerating heat penetration and reducing heating time (Tola & Ramaswamy, 2014). However, at 30 RPM, a different trend was observed. While f_h initially increased by 5.8% from 115°C to 120°C, it then slightly decreased by 4% when the temperature was raised to 125°C. This suggests that at higher temperatures, even with increased RPM, the benefits of forced convection are limited due to the interaction between the radish pieces and the container.

For radish undergoing End-Over-End (EOE) intermittent oscillation, the effect of rotational speed on f_h was analyzed at different processing temperatures and is shown in Figure 5.5.

When increasing the RPM from 10 to 30, a noticeable decrease in f_h was observed across all temperatures, indicating improved heat transfer with higher agitation. At 115°C, the f_h value decreased from 9.17 to 8.81, reflecting a reduction of 3.9%. A more significant decrease was noted at 120°C, where f_h dropped by 16.5%, from 8.83 to 7.37. Similarly, at 125°C, the f_h value decreased by 20.8%, from 8.66 to 6.86. These findings suggest that intermittent oscillation enhances convective heat transfer within the container, promoting better mixing and reducing heat penetration time. This trend aligns with studies demonstrating that oscillatory motion improves heat distribution compared to continuous rotation by reducing particle settling and enhancing fluid circulation within the container (McNaughton, 2018).

When comparing f_h across different temperatures at the same RPM, an overall decline in f_h was observed with increasing temperature. At 10 RPM, increasing the processing temperature from 115°C to 120°C resulted in a 3.7% reduction in f_h, while increasing from 120°C to 125°C led to a smaller 1.9% decrease. A similar trend was seen at 30 RPM, where f_h decreased by 16.3% between 115°C and 120°C and then by an additional 6.9% between 120°C and 125°C. These reductions highlight the role of higher temperatures in accelerating heat penetration by increasing the thermal gradient between the heating medium and the product.

Overall, the results show that EOE intermittent oscillation offers significant advantages over continuous EOE rotation by reducing f_h values across all tested temperatures. The ability to maintain efficient heat transfer without the limitations of excessive centrifugal forces suggests that oscillatory agitation could be a more effective approach for optimizing thermal processing conditions in radish and similar food products.

5.5.3 Heating lag factor (j_{ch})

The heating lag factor (j_{ch}) quantifies the delay in heat penetration experienced by a food product during thermal processing. It reflects the thermal resistance of the product as it gradually approaches equilibrium with the surrounding heating medium. A higher j_{ch} value suggests greater resistance to heat transfer, influencing the overall efficiency of thermal processing. This parameter is particularly important in evaluating the thermal properties of food products, such as density, moisture content, and thermal conductivity, which directly impact heating uniformity and process time.

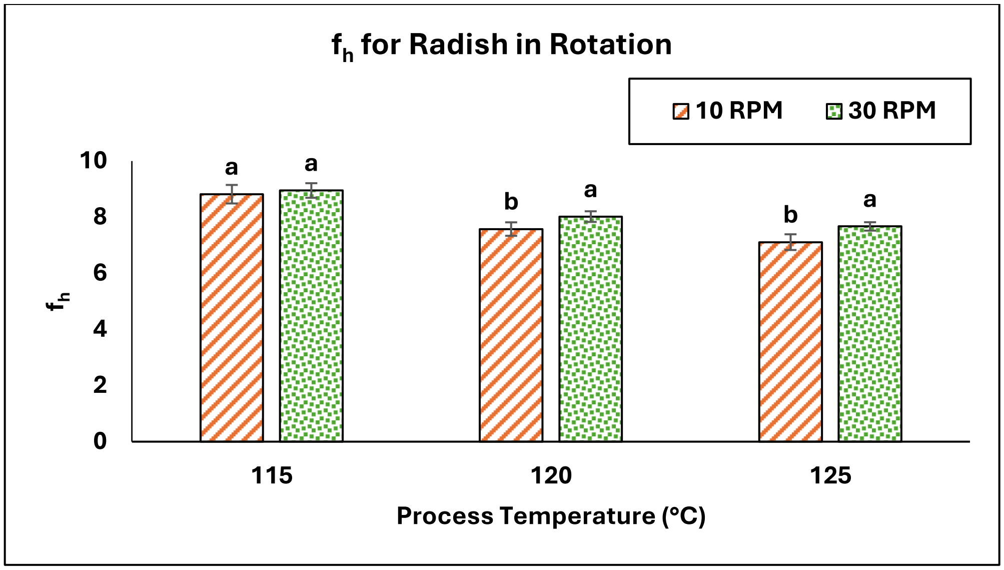

Figure 5.4 Heating rate index (f_h) of radish in rotational thermal processing with water as medium at different temperatures and RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

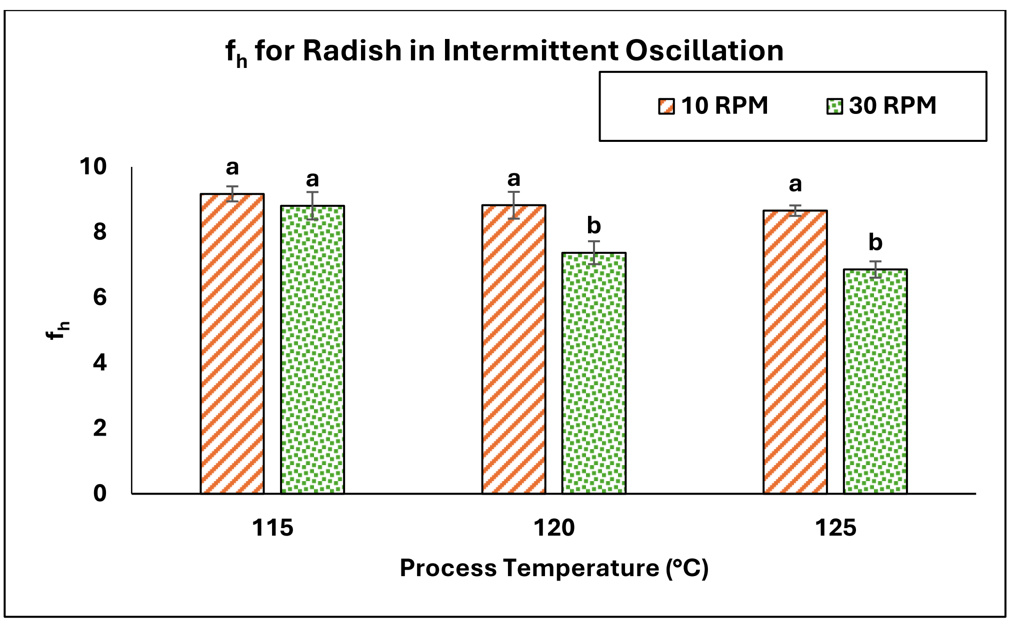

Figure 5.5 Heating rate index (f_h) of radish in intermittent oscillation thermal processing with water as medium at different temperatures and RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

For End-Over-End (EOE) rotation of radish in water, which is shown in Figure 5.6, the j_{ch} value exhibits a slight increase when RPM is raised from 10 to 30 across all processing temperatures. At 115°C, j_{ch} increases from 1.88 to 1.95, showing a 3.7% increase. Similarly, at 120°C, it rises from 1.48 to 1.52, indicating a 2.7% increase, while at 125°C, j_{ch} increases from 1.43 to 1.49, reflecting a 4.2% change. These results suggest that at higher RPMs, the heat transfer dynamics change, likely due to increased centrifugal forces that cause food particles to adhere to the container walls, reducing the overall convective movement within the system.

Comparing j_{ch} across different temperatures at the same RPM, a general decrease in j_{ch} is observed with increasing temperature. At 10 RPM, increasing the temperature from 115°C to 120°C leads to a 21.3% reduction in j_{ch}, while increasing from 120°C to 125°C results in a smaller 3.4% decrease. Similarly, at 30 RPM, the transition from 115°C to 120°C decreases j_{ch} by 22.1%, whereas the shift from 120°C to 125°C results in a 2% reduction. This pattern suggests that higher temperatures promote faster internal heat conduction within the radish matrix, reducing its resistance to thermal equilibrium.

The application of End-Over-End (EOE) intermittent oscillation is particularly relevant in optimizing j_{ch}, as its periodic directional changes and dwell times promote better internal mixing, enhancing heat transfer efficiency.

For EOE Intermittent Oscillation of radish in water, shown in Figure 5.7, an overall decrease in j_{ch} is observed as RPM increases from 10 to 30 across all processing temperatures. At 115°C, jch decreases from 1.91 to 1.82, reflecting a 4.7% reduction. Similarly, at 120°C, j_{ch} decreases from 1.57 to 1.41, showing a 10.2% reduction, while at 125°C, j_{ch} drops from 1.49 to 1.28, marking a 14.1% reduction. These results indicate that intermittent oscillation enhances convective mixing, preventing particle adhesion to container walls and promoting better thermal uniformity. The trend aligns with previous studies demonstrating that oscillatory motion disrupts stagnant thermal layers, improving heat penetration and reducing processing times (McNaughton, 2018).

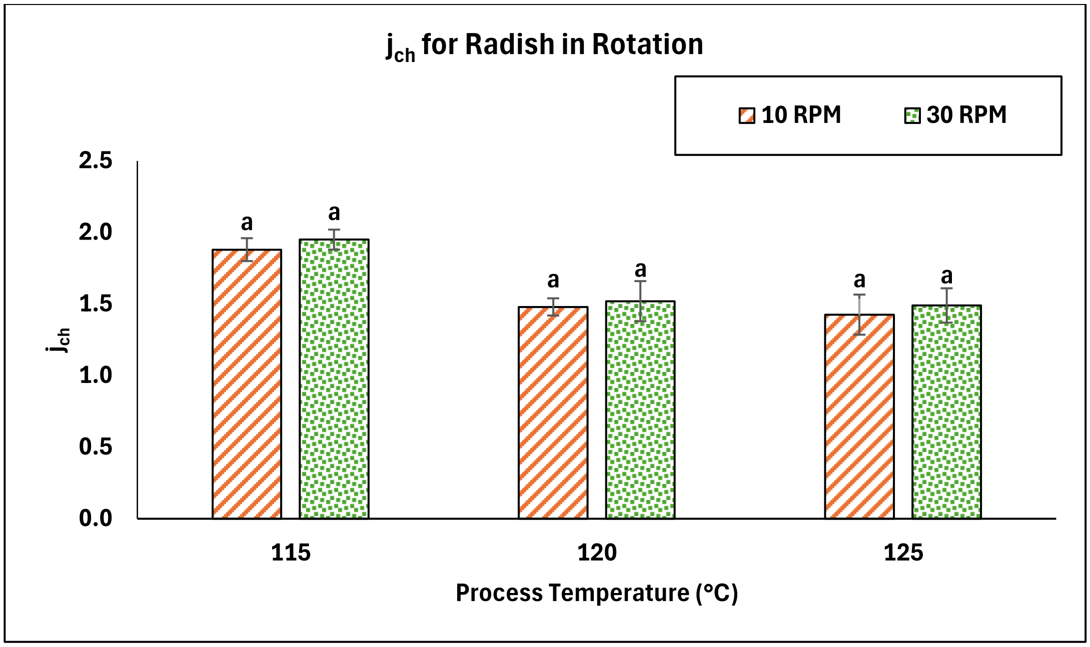

Figure 5.6 Heating lag factor (j_{ch}) of radish in rotational thermal processing with water as medium at different temperatures and RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

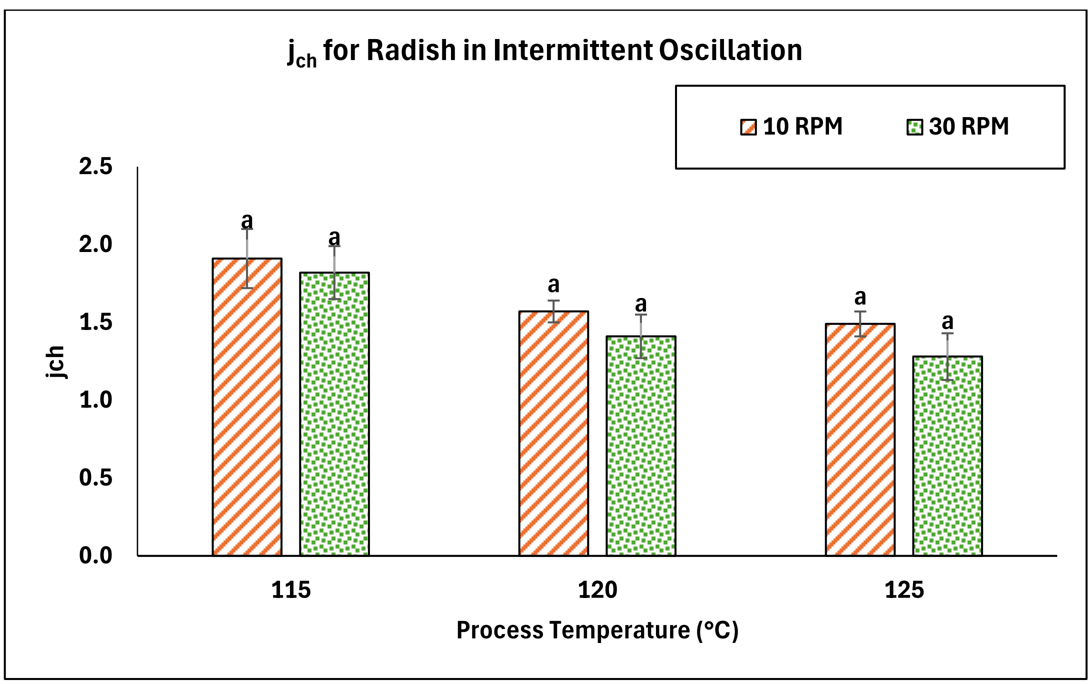

Figure 5.7 Heating lag factor (j_{ch}) of radish in intermittent oscillation thermal processing with water as medium at different temperatures and RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

Comparing j_{ch} across different temperatures at the same RPM, a consistent decrease is observed with increasing temperature. At 10 RPM, raising the temperature from 115°C to 120°C results in a 17.8% decrease in j_{ch}, while an increase from 120°C to 125°C leads to a 5.1% reduction. Similarly, at 30 RPM, increasing the temperature from 115°C to 120°C lowers j_{ch} by 22.5%, while further increasing to 125°C leads to a 9.2% reduction. These findings highlight the impact of higher temperatures in enhancing heat transfer by increasing the thermal gradient between the heating medium and the product, thus lowering thermal resistance.

5.5.4 Texture Profile Analysis

a. Hardness

The change in hardness of radish when thermally processed using EOE rotation is shown in Figure 5.8. The hardness of thermally processed radish significantly decreased compared to the control sample (4204.55 g), with variations depending on processing temperature and rotational speed. At 115°C, the hardness at 10 RPM was 950.74 g, while at 30 RPM, it dropped further to 847.23 g, indicating an 11% reduction due to increased agitation. At 120°C, the hardness values were 1043.94 g at 10 RPM and 931.34 g at 30 RPM, showing a 10.8% decrease with increasing speed. Similarly, at 125°C, hardness was 1376.77 g at 10 RPM, reducing to 1215.52 g at 30 RPM, representing an 11.7% reduction.

When comparing the effect of temperature, increasing from 115°C to 120°C resulted in a 9.8% increase in hardness at 10 RPM and a 9.9% increase at 30 RPM. A further temperature increases from 120°C to 125°C led to a 31.9% increase at 10 RPM and a 30.6% increase at 30 RPM.

The hardness values for radish processed under EOE intermittent oscillation demonstrate a clear trend of textural degradation with increased thermal exposure. As shown in Figure 5.9, compared to the control sample, which had a hardness of 4204.55 g, all processed samples exhibited a significant reduction in hardness. At 115°C, radish processed at 10 RPM had a hardness of 715.48 g, while at 30 RPM, the hardness was 1111.34 g, indicating an increase of 55.4% due to higher agitation. As the processing temperature increased to 120°C, the hardness values at 10 RPM and 30 RPM increased to 895.80 g and 1149.27 g, respectively, showing an improvement in firmness by 25.2% and 3.4% compared to 115°C. At the highest temperature of 125°C, radish retained the highest firmness, with hardness values of 911.47 g at 10 RPM and 1210.41 g at 30 RPM, marking an increase of 1.7% and 5.3%, respectively, from 120°C.

Yu et al., 2023 shows a significant reduction in hardness as processing time increases. This follows a trend where prolonged thermal exposure leads to softening, which is a key concern in maintaining the structural integrity of vegetables.

The primary reason behind this texture degradation is the breakdown of pectic substances, which are crucial for the structural integrity of radish cells. As heat is applied, pectin undergoes de-esterification and solubilization, leading to a loss of firmness. Additionally, the depolymerization of hemicellulose and cellulose weakens the cell walls, further contributing to softening.

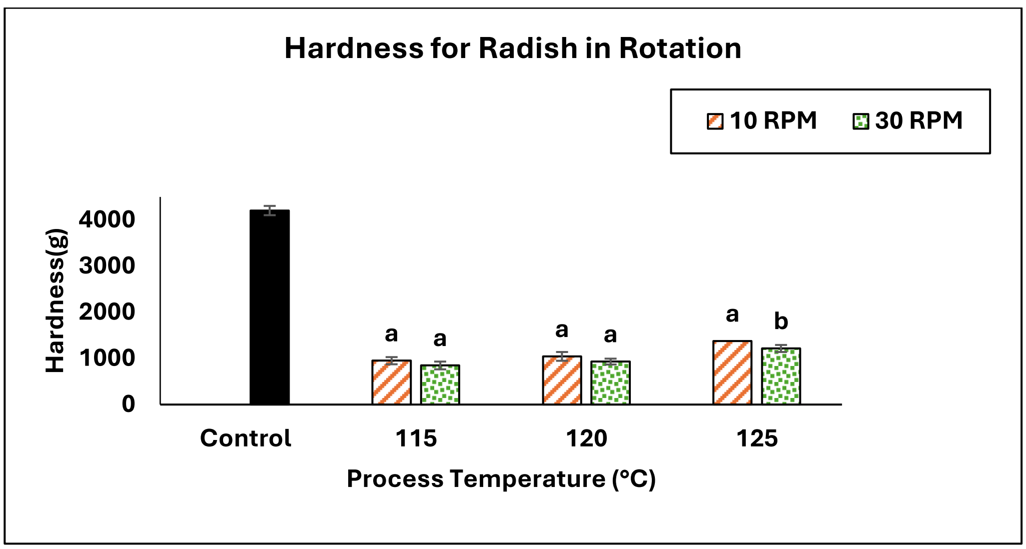

Figure 5.8 Hardness of radish in rotational thermal processing vs process temperature at various RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

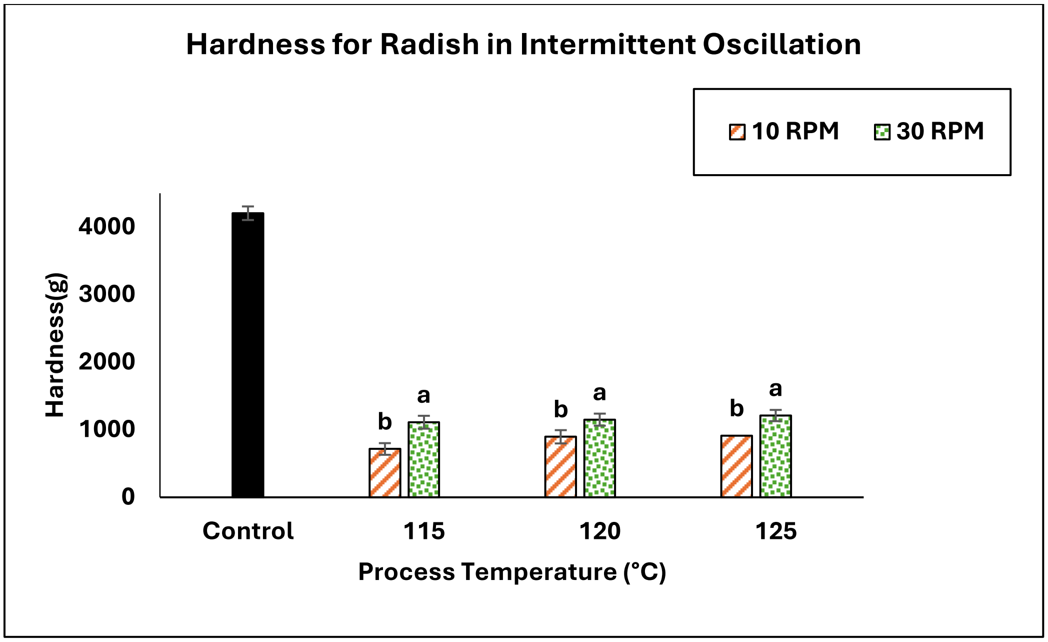

Figure 5.9 Hardness of radish in intermittent oscillation thermal processing vs process temperature at various RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

5.5.5 Color Analysis

a. Lightness

Lightness (L*) is an important indicator of color retention in thermally processed radish, reflecting pigment stability and moisture loss. In EOE Rotation, shown in Figure 5.10, L* values decreased significantly from the control (62.74) due to pigment degradation and cellular collapse. At 10 RPM, L* dropped by 47.8% at 115°C, increasing slightly with temperature by 11.8% at 120°C and 7.4% at 125°C. A similar trend was observed at 30 RPM, but lightness was consistently 3.8–5.6% lower than at 10 RPM, indicating that higher agitation accelerated pigment degradation and moisture loss.

For EOE intermittent oscillation, shown in Figure 5.11, L* values were higher across all conditions, suggesting better color retention. At 115°C, L* was 6.1% and 8.1% higher than rotation at 10 RPM and 30 RPM, respectively. At 120°C and 125°C, the differences widened to 7.2–22.9%, highlighting the advantage of oscillatory motion in reducing shear stress and limiting pigment breakdown (Yu et al., 2023). Higher RPMs in oscillation preserved lightness better, while rotation led to greater oxidative degradation and increased structural changes.

Overall, EOE intermittent oscillation outperformed EOE rotation in preserving lightness, particularly at 30 RPM, due to its alternating motion and dwell time that limited excessive pigment loss. Higher processing temperatures improved L* by reducing prolonged exposure to oxidation, reinforcing the benefits of high-temperature short-time processing combined with controlled agitation (Duguay et al., 2016).

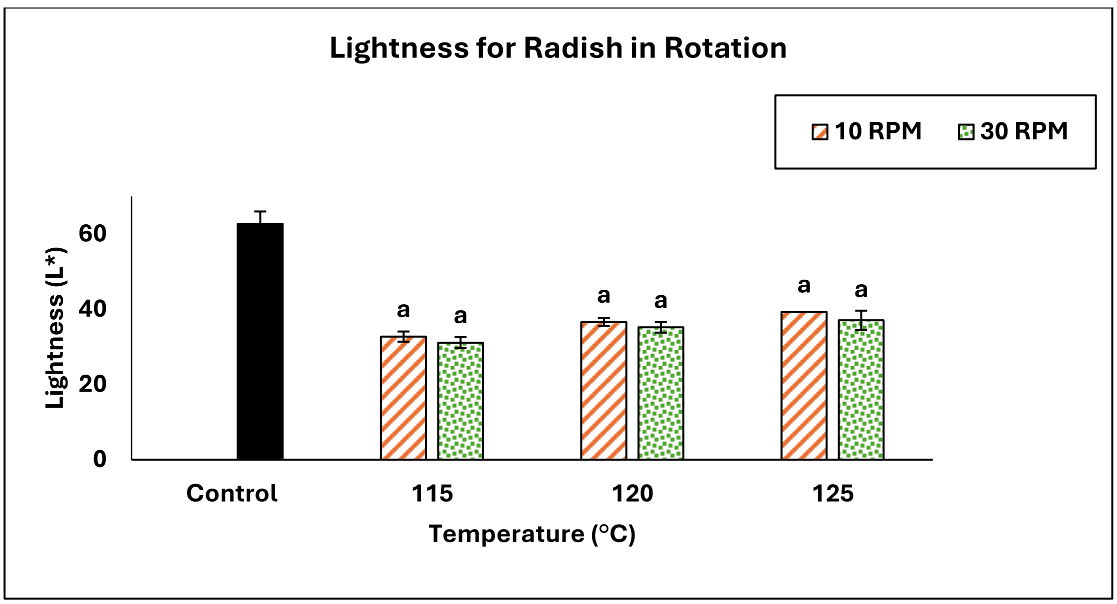

Figure 5.10 Lightness (L^{*}) of radish in rotational thermal processing vs process temperature at various RPM. Letters of significance indicate significance (p< 0.05) between reciprocation frequencies.

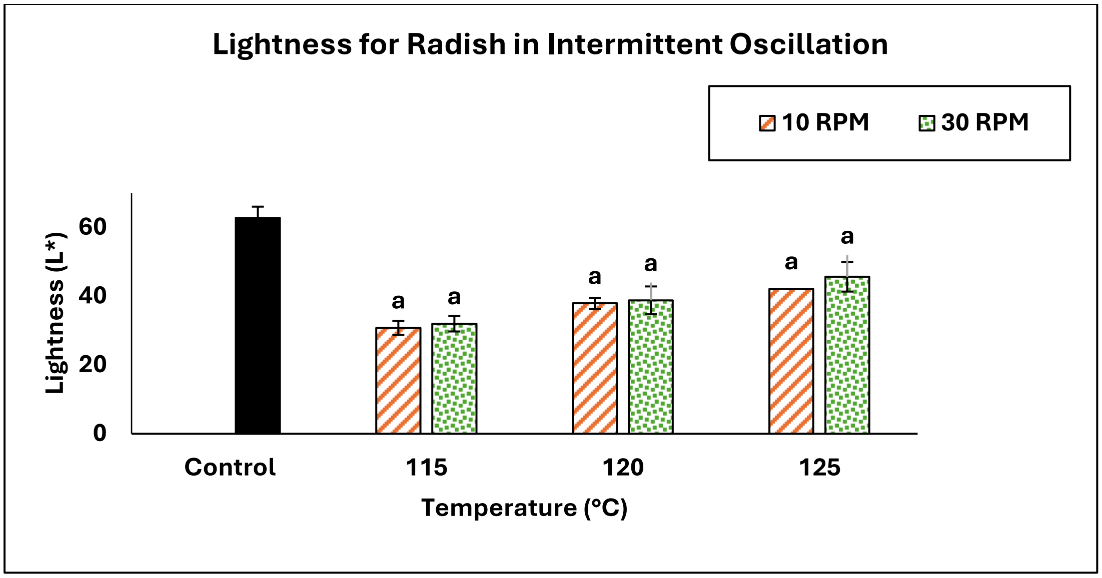

Figure 5.11 Lightness (L^*) of radish in intermittent oscillation thermal processing vs process temperature at various RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

b. Yellowness

Figure 5.12 and 5.13 shows the analysis of the b* (yellowness) values for radish processed under end-over-end (EOE) rotation and EOE intermittent oscillation based on the data provided. The discussion incorporates findings from Yu et al. (2023) to explain the trends.

The b* values, which indicate the yellowness of radish, exhibited a decreasing trend with increasing processing temperature across both EOE rotation and EOE intermittent oscillation. At 115°C, the highest b* values were recorded, with a reduction as the temperature increased to 120°C and 125°C. This increase is likely due to the degradation of carotenoid pigments and Maillard reactions that take place at longer thermal exposure, leading to a loss of the natural yellow hue of the radish (Yu et al., 2023).

When analyzing the effect of rotation speed, the b* values were generally lower at 30 RPM than at 10 RPM for EOE intermittent oscillation and higher for EOE rotation. In EOE rotation, the yellowness decreased by an average of 23% from 115°C to 125°C at 10 RPM, while at 30 RPM, the decrease was about 33%. A similar trend was observed in EOE intermittent oscillation, where the b* value at 30 RPM dropped by approximately 35% compared to 10 RPM.

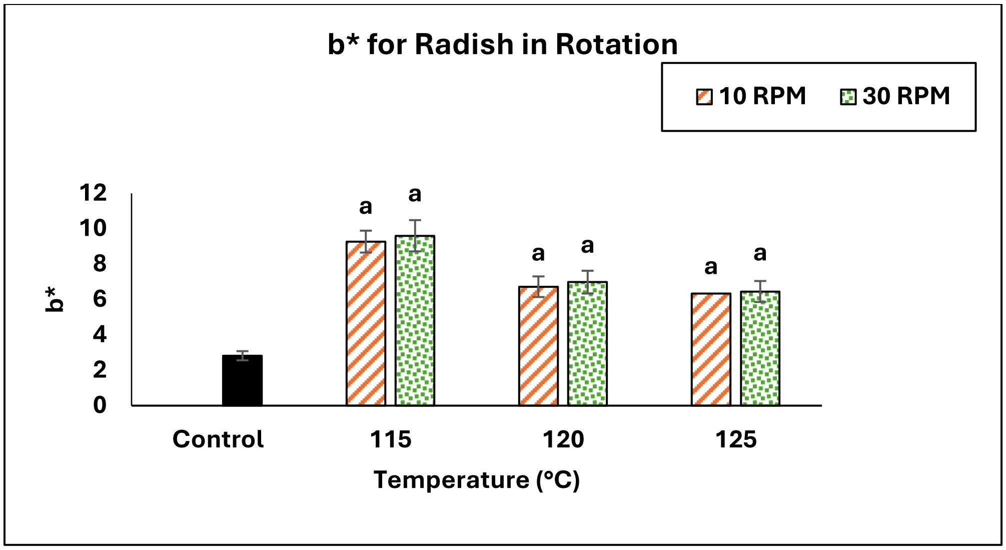

Figure 5.12 Yellowness (b^{*}) of radish in rotational thermal processing vs process temperature at various RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

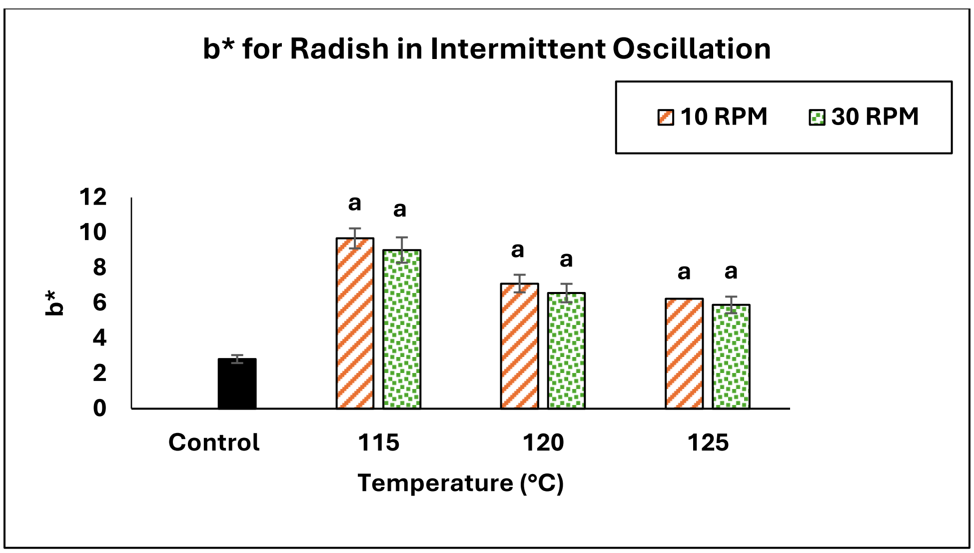

Figure 5.13 Yellowness (b^{*}) of radish in intermittent oscillation thermal processing vs process temperature at various RPM. Letters of significance indicate significance ($p < 0.05$) between reciprocation frequencies.

5.6 Conclusions

The comparison between end-over-end (EOE) rotation and EOE intermittent oscillation for processing radish in water revealed distinct differences in heat transfer efficiency, texture retention, and color stability.

At lower rotational speeds (10 RPM), EOE rotation resulted in higher process times and moderate textural degradation, aligning with previous findings that suggest limited agitation reduces heat penetration but preserves structural integrity (Yu et al., 2023). However, at 30 RPM, the process time did not decrease significantly due to increased particle adherence to the container walls, leading to reduced convective mixing and inefficient heat transfer. This phenomenon, also observed in prior studies (Clifcorn et al., 1950), indicates that excessive rotational speed can hinder fluid movement, prolonging heating times and accelerating textural softening.

In contrast, EOE intermittent oscillation exhibited superior heat transfer efficiency across all speeds. The periodic reversals in motion, coupled with dwell time, enhanced internal mixing and improved convective heat transfer, resulting in a consistent decrease in process time with increasing RPM. Unlike continuous rotation, which promoted particle settling and reduced fluid circulation, intermittent oscillation minimized thermal resistance and improved heating rate index (f_h) and heating lag factor (j_{ch}), as supported by previous research on oscillatory agitation systems (McNaughton, 2018). The improved heat penetration in oscillatory processing also contributed to better structural retention, minimizing excessive softening observed at higher temperatures.

In terms of color stability, intermittent oscillation preserved lightness (L*) and redness (a*) more effectively than rotation. Higher rotational speeds in continuous rotation accelerated pigment degradation and increased moisture loss, whereas the controlled motion of oscillation limited oxidative damage and better maintained natural color. This aligns with findings from Yu et al. (2023), which indicate that high-temperature short-time (HTST) processing with optimized agitation can minimize color loss in thermally processed vegetables.

Overall, EOE intermittent oscillation proved to be the more efficient processing method, particularly at higher rotational speeds, where traditional EOE rotation led to prolonged process times and excessive softening. The improved heat transfer dynamics, superior texture retention, and better color stability make intermittent oscillation a more favorable technique for optimizing the thermal processing of radish in liquid media. Future studies should further explore the impact of oscillation parameters, such as dwell time and angular displacement, on heat penetration and quality retention to refine processing conditions for industrial applications.

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CHAPTER 6

GENERAL CONCLUSIONS

This thesis presents a comprehensive study on the application of agitation thermal processing (RATP and EOE rotation & intermittent oscillation) to evaluate its effects on heat penetration, process time, and quality retention in food products, specifically salmon, Nylon spheres and radish. Through extensive experimentation and data analysis, significant findings have been obtained that shed light on the benefits and challenges of using agitation in thermal food processing.

For the first objective, focused on salmon, it was found that reciprocating agitation significantly improved the heat transfer efficiency and reduced process time compared to static processing methods. The optimal conditions, involving a frequency of 1 Hz and a temperature of 125°C, yielded the best results in terms of process efficiency and quality retention. The study demonstrated that RATP leads to faster microbial inactivation while maintaining the texture and color of the salmon, ensuring a product that retains much of its sensory attributes. However, excessively high frequencies resulted in diminished textural integrity, indicating the importance of finding a balance between processing efficiency and quality preservation.

Overall, the application of RATP in salmon processing proves to be an efficient method for improving heat transfer, reducing processing times, and enhancing product quality. However, careful consideration must be given to the choice of processing conditions, as excessive agitation or high temperatures can lead to undesirable changes in texture, especially for plant-based products. Further studies and optimization are required to fine-tune these conditions to achieve the best balance between processing efficiency and quality retention.

For the second and third objectives, the study initially examined heat penetration dynamics using non-food model particles (Nylon spheres) to establish fundamental thermal transfer characteristics under different agitation modes. The comparison between end-over-end (EOE) rotation and EOE intermittent oscillation in nylon-filled cans revealed that agitation plays a critical role in reducing processing times and improving heat penetration. At lower rotational speeds (10 RPM), EOE rotation demonstrated better heat transfer efficiency, with lower heating lag factors (j_{ch}) and a more controlled convective flow. However, as rotational speed increased, particularly at 30 RPM, the performance of EOE intermittent oscillation surpassed that of continuous rotation. The periodic reversals and dwell time associated with intermittent oscillation enhanced internal mixing, preventing particle stagnation and improving overall convective heat transfer. These findings reinforced that while both agitation methods are effective in reducing processing time, intermittent oscillation is particularly advantageous at higher speeds due to its ability to promote more uniform heat distribution.

Building on these initial results, the study transitioned to food systems by evaluating the thermal processing behavior of radish. The trends observed in nylon particles were largely replicated in the radish trials, confirming that EOE intermittent oscillation consistently achieved shorter process times and improved heat penetration. However, radish, being a high-moisture, fibrous matrix, exhibited additional quality-dependent responses to thermal processing. The texture analysis showed that EOE intermittent oscillation preserved firmness better than rotation, especially at elevated speeds. Additionally, the heating rate index (f_h) values for radish confirmed that oscillatory motion provided superior heat penetration, preventing excessive localized heating and reducing overprocessing effects.

Color stability analysis further validated the advantage of intermittent oscillation. Across all tested temperatures, oscillatory motion resulted in higher lightness (L*) values, indicating better color retention, while continuous rotation accelerated oxidative degradation and pigment loss. The higher retention of lightness (L*) and reduced degradation of yellowness (b*) in oscillatory processing further demonstrated its ability to minimize thermal damage.

Overall, the results demonstrated that while both EOE rotation and EOE intermittent oscillation effectively enhance heat penetration; intermittent oscillation provides superior process efficiency at higher speeds, particularly in preserving product quality. The consistency of results between nylon and radish underscores the applicability of these observations across different food systems, reinforcing the potential of intermittent oscillation as a preferred agitation strategy for optimizing thermal processing conditions.

The findings from this thesis have direct implications for improving the efficiency and quality of commercial thermal processing operations. The enhanced heat penetration and reduced process times achievable through reciprocation and EOE agitation techniques can be adopted to optimize processing schedules, lower energy consumption, and expand product shelf life without compromising safety. These methods are especially relevant for ready-to-eat meals, seafood products, and high-viscosity food systems where conventional static processing often fails to deliver uniform heating.

CHAPTER 7

FUTURE RECOMMENDATIONS

The first study focused on improving the quality of fish products, namely salmon, using RATP. For future research, the research can be expanded to more seafood products and check if the quality obtained is similar. Other quality factors can be included which are very particular to an individual product. Example: for salmon, one can compare a change in protein quality under static thermal processing vs RATP. This can show further advantages of the process.

RATP can be combined with an acidification process which can further improve the quality of the product. Since seafoods are fragile in texture, an optimal amount of acidification would be required to maintain the structural integrity and not affect the taste of the product. Some of the processes that can be used for acidification are high pressure processing. This could have some further improvement in the quality of the product.

The second study compares EOE rotation to intermittent oscillation. For my study, only one food matrix, radish, was used to study the comparison. This provides a proof of concept. This should be expanded in future to multiple food product categories to confirm the results of the research. Another major comparison could be made between all the agitation thermal processing techniques. RATP vs EOE rotation vs EOE intermittent oscillation vs biaxial rotation thermal processing. This research can further solidify the importance of agitation and compare which process is better and cheaper for the industry.

While the present work provides strong evidence supporting the benefits of reciprocation and EOE intermittent oscillation, it is limited by its lab-scale nature and the use of model particles (Nylon spheres and radish) to simulate heat transfer. Industrial-scale validation and real-time monitoring of internal food temperatures in irregularly shaped particulates remain to be explored. Additionally, only selected combinations of fluid media, temperatures, and agitation intensities were tested. Future work should investigate multi-phase foods, long-term storage effects post-processing, microbial inactivation kinetics, and compatibility with emerging packaging materials for broader industrial applicability.

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