

The Development of Cooked Meat Cured without Nitrite as a Preservative Ingredient.

*A Thesis Presented as Partial Fulfilment for the Award of
Master of Science in Food Business Management and
Technology*

By

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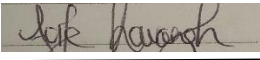
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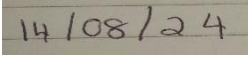
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Declaration

I, Aoife Kavanagh, hereby declare that the material included in this thesis submitted for assessment for the programme of MSc Food Business Management and Technology is entirely my own work, under the guidance of my supervisor, Mary O'Connor. This work has not been submitted for any academic award at this University, or any other University or Higher Education Institute. Any use of the work of others has been fully acknowledged by reference in both text and bibliography.

Signed: 

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Acknowledgements

I would like to take this opportunity to express my gratitude to all who supported me during the past year while completing my master's degree and thesis.

My sincere thanks to my supervisor, Mary O'Connor, for her exceptional support and guidance throughout my research.

I also want to extend special thanks to my workplace colleagues for their knowledge and assistance during this time.

Lastly, I am grateful to my parents and friends for their unwavering support.

Sincere thanks to all who contributed to this journey.

Abstract

This thesis explores the investigation into the development of cooked meat cured without nitrite as a preservative ingredient. The pursuit of effective and safer alternatives has been spurred by the potential health risks associated with traditional nitrite-based curing methods. This research tackles the pressing need to identify viable nitrite alternatives that preserve the key qualities of meat while meeting consumer demands and complying with regulatory standards

The evaluation of this research topic was carried out through an in-depth analysis of peer-reviewed scientific papers and studies. The primary focus was on examining the effectiveness of alternative curing agents in replicating nitrites critical functions, particularly in terms of microbial control and shelf-life extension. The study explored the impact of these alternatives on sensory attributes and their economic viability, both from the perspective of consumers and within the broader context of food manufacturing.

Nitrite-free meat curing revealed that alternative ingredients performed exceptionally well, achieving a 24-day shelf life comparable to that of traditional nitrite-based methods. By strategically incorporating these alternatives into product formulations, the study effectively maintained critical attributes such as microbial safety and sensory quality. Sensory evaluations demonstrated that, in blind taste testing, the nitrite-free product garnered superior ratings compared to its traditionally cured equivalent. Economically, while the production of nitrite-free meats involves elevated costs, a growing willingness exists amongst consumers to absorb higher costs in pursuit of healthier options.

The investigation into the development of cooked meat cured without nitrite as a preservative has produced encouraging findings. The alternative ingredients tested exhibited remarkable performance when integrated into formulations, showcasing the food industry's potential to eliminate nitrites effectively. This underscores the viability of achieving the desired preservative effects and maintaining product quality without relying on traditional nitrite-based methods. Future works should focus on the continuous improvement of this innovative technique, strengthening the concepts economic viability and ensuring its alignment with progressive regulatory frameworks within an ever-evolving consumer landscape.

Abbreviations

AICR	American Institute of Cancer Research
CAGR	Compound Annual Growth Rate
EU	European Union
FSAI	Food Safety Authority of Ireland
HPP	High Pressure Processing
IARC	International Agency for Cancer Research
MAP	Modified Atmospheric Packaging
RDA	Recommended Dietary Allowance
RTE	Ready To Eat
TPP	Tomato Pulp Powder
TVC	Total Viable Count
WCRF	World Cancer Research Fund
WTP	Willingness to Pay

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Chapter One

Introduction

The focus of this thesis is to evaluate the development of cooked meats cured without nitrite as a preservative ingredient within the food industry. Nitrite-free cooked meat product development will be investigated to assess efficacy of alternative ingredients in maintaining product quality whilst also assessing nitrite free preservation methods influence on sensory attributes and consumer preference. This research aspires to deliver an in-depth evaluation of novel curing strategies and their potential to fulfil both industry benchmarks and evolving consumer preferences. The introductory chapter will provide an overview of nitrite use in meat curing, highlighting related regulatory and health issues. It will analyse consumer preferences and market trends, while evaluating alternative curing ingredients and methods.

1.1 Definition of Cooked Meats

Recognised as an indispensable aspect of human nutrition by leading health and dietary organizations, meat is renowned for its nutrient-rich composition and can be viewed as the foundation of a well-balanced diet due to being a substantial source of high-quality protein, essential vitamins, and minerals, providing consumers with comprehensive sustenance and promoting overall health (Leroy *et al.*, 2023). Meat products refer to items that, through various processing or further refinement methods, have been altered to such an extent that their original form as fresh meat is no longer recognizable (European Union, 2004). These processed meats often contain added ingredients such as sodium and/or potassium salts of nitrates and nitrites, which are used for preservation and flavour enhancement. In Ireland, pork is the predominant choice in the retail sector, reflecting both traditional preferences and market demand (Molina *et al.*, 2024). Prior to consumption, cooking of raw meat pieces is required. Cooked meat products undergo meticulous seasoning, thorough cooking and are typically packaged in convenient, ready-to-eat formats for ultimate consumer satisfaction (Cruz-Romero and Kerry, 2011). Food preservation is crucial for prolonging shelf life, safeguarding safety, and maintaining product quality. By decelerating spoilage and microbial growth, it effectively curbs waste and mitigates the risk of foodborne illnesses. Preservation methods also sustain nutritional value and enhance convenience through ready-to-eat options. Economically, it reduces financial losses associated with spoilage and bolsters food security by facilitating extended storage and distribution. The cooking process coagulates and denatures protein, assists in proteolytic enzyme inactivation, modifies appeal and texture, assists in shelf-life longevity and diminishes the presence of potentially hazardous microorganisms (Oz, Aksu and Turan, 2017). The application of cooking processing methods requires a comprehensive and

holistic approach that takes alterations in sensory and nutritional characteristics, as well as consumer preferences into account. An integrated strategy is essential in ensuring methods aligns with desired sensory attributes, nutritional value, and overall appeal of the final meat product (Gómez *et al.*, 2020). This broad category of cooked meat products, which includes an array of offerings such as ham, beef, chicken, turkey, and sausages, presents extensive opportunities for industry innovation. The sector stands poised for significant advancements through the exploration of novel flavours, innovative packaging solutions, diverse cooking methods, and alternative ingredients. By tapping into these avenues, the meat industry can develop unique and appealing products to capture new market segments and meet the evolving preferences of consumers.

1.2 History of Cooked Meats

The historical significance of meat as a dietary staple is profound, likely dating back to the very dawn of our genus, symbolising not only sustenance but also cultural importance across a myriad of diverse cultures and societies throughout history (Ederer and Leroy, 2023). Approximately 3 million years ago, early hominins began consuming more meat. This dietary change significantly influenced their evolution, as the nutrient-dense meat contributed to the enlargement of their brain size and supported the development of more complex bodily functions (Leroy *et al.*, 2023). In ancient civilisations such as Egypt, China, Greece, and Rome, meat was not only a fundamental dietary sustenance but also a symbol of social status and affluence. The use of preservation techniques, including smoking and salting, reflect a tangible representation of their culinary culture, highlighting the importance of meat in their societies.

In medieval times, meat also served as social stratification with consumption varying drastically amongst class. Diverse techniques, including fermentation and dehydrating, were implemented in Asia and the Middle East. During the early modern period, European colonization facilitated the global dissemination of meat products and preservation techniques, with this era also offering substantial improvement in meat preservation through the introduction of canned meats (Petrick, 2009). Refrigeration was subsequently implemented, which further revolutionised meat preservation by enhancing meat storage and enabling transportation. Contemporary developments in meat cooking and preservation technologies, shaped by dynamic consumer trends, have been instrumental in global meat production increases with the ascent anticipated to persist in emergent economies such as China, India, Brazil and Russia.

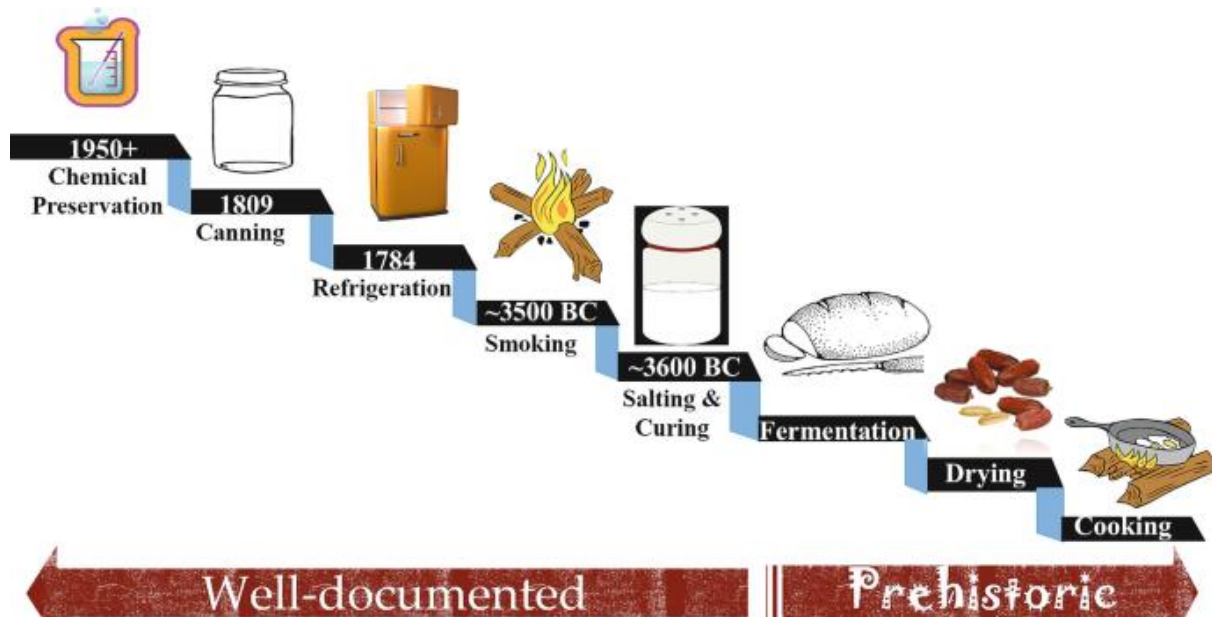


Figure 1.1: Historical timeline demonstrating the evolution of Meat Preservation Techniques (Joardder and Masud, 2019).

1.3 Cooked Meats Process

An intricate and technologically advanced operation within the pre-cooked meats industry, the cooked meats process encompasses several pivotal stages, each meticulously orchestrated to convert raw meat into a fully prepared, ready-to-eat product. Brine Injection involves the strategic introduction of a specially formulated brine solution into the raw meat, with the primary objective of achieving a uniform distribution of salt and other seasoning components throughout. By doing so, brine injection accelerates the equilibrium between the salt concentration in the meat and that in the brine solution, thereby facilitating the alteration of protein-ion interactions within the meat. The brine injection process is designed to influence the structural properties of the meat. Specifically, it affects the expansion of the protein matrix within the meat fibres, which in turn enhances the meat's tenderness and its ability to retain moisture. This is particularly important in pre-cooked meats, where maintaining an optimal texture and juiciness is essential for consumer satisfaction. The brine solution typically contains a blend of water, salt, and other functional ingredients, such as phosphates or flavor enhancers, tailored to meet the specific requirements of the product being processed.

The injection process is facilitated by advanced apparatus meticulously engineered for optimal precision and operational efficiency. This specialized equipment encompasses precision-engineered needles or compressors, which are adeptly designed to administer the brine solution

into the meat with exacting accuracy. Brine is introduced into the meat under controlled pressure and volume parameters, ensuring an even and uniform distribution throughout the meat matrix. The selection of apparatus and the fine-tuning of injection parameters are pivotal determinants of the brine infusion's efficacy, significantly impacting the overall quality and consistency of the final product. Nevertheless, the injection process is accompanied by obstacles, particularly a significant increase in drip loss. To address this challenge, it is imperative to meticulously optimize the processing conditions, including the brine concentration, injection pressure, and resting time, to minimize drip loss and achieve the desired balance between tenderness, flavor, and moisture retention (Kim *et al.*, 2020).



Figure 1.2: Precision Injection System in Meat Processing (Philipsen and Moeslund, 2019)

Following the injection process, tumbling is employed. Tumblers are precisely calibrated to precise time and speed parameters. The meat is thoroughly mixed with brine as the tumbler rotates, ensuring an even distribution. This rotational agitation not only improves tenderness by breaking down connective tissues but also facilitates flavour enhancement by equitably dispersing ingredients. Furthermore, tumbling improves moisture retention and guarantees that the product achieves a consistent texture and flavour profile. A 4-hour holding interval between tumbling and cooking is essential in meat processing, allowing flavours to thoroughly permeate the meat, contributing to a succulent final product. This waiting period also allows the brine to redistribute, leading to a more uniform taste throughout the meat. After holding, the meat is subjected to cooking at an internal temperature of 72°C (162°F) for a minimum of 2 minutes, followed by a rapid cooling process to below 5°C. As stipulated by the Food Safety Authority of Ireland (FSAI), this essential step ensures the safety of food by eradicating any potential

bacterial pathogens and facilitates the attainment of a 24-day shelf life of pre-cooked meats (FSAI, 2024).

1.4 Curing

As the global population expands, there is a growing need for fresh and nutritious food to maintain human health and well-being. Consequently, the significance of food preservation intensifies. Food preservation encompasses a diverse array of sophisticated technologies and scientific methodologies designed to extend the shelf-life of food products. These techniques aim not only to prolong the edibility of food but also to ensure that it remains free from pathogenic microorganisms, thus safeguarding its safety for human consumption (Sancho-Madriz, 2023). Shelf life is a critical concept in food preservation, referring to the length of time a food product remains safe to consume while preserving its intended sensory attributes, such as taste, texture, and appearance. It also encompasses the maintenance of the product's physical integrity and adherence to label declarations and nutritional claims, ensuring that the product meets consumer expectations and regulatory standards (Kaale *et al.*, 2011). Food preservation has evolved significantly in tandem with human civilization progression. Initially, techniques such as dehydration, salting, fermentation, and later smoking, were developed as essential techniques to combat spoilage and extend the usability of food. These traditional methods established foundations for more advanced preservation technologies. With the advent of rapid industrialization and the adoption of lean manufacturing principles, contemporary food preservation processes have attained enhanced sophistication. Advanced processes such as chilling, canning, and thermal treatment have emerged, driven by technological advancements and the need for enhanced efficiency in food production and distribution.(Saravanan *et al.*, 2021).

Curing entails the incorporation of nitrite and nitrate salts, in conjunction with edible salt (NaCl) at varying levels and points throughout the processing of meat products (Pegg and Honikel, 2014). Deeply ingrained in diverse culinary traditions, curing is an ancient preservation technique, dating back to 3,000 B.C, that remains extensively practiced today (Pegg and Honikel, 2014). Achieving two primary objectives, curing extends a products shelf-life through water activity reduction to ensure microbial stability at room temperature and assists in the enhancement of favourable organoleptic properties (Rodrigues *et al.*, 2023). Undergoing extensive growth as of late, the cured meat market is directed by increasing demand for protein-rich, convenient, and flavourful culinary options. With artisanal varieties,

innovative products, health and wellness and convenience and snacking spearheading consumer interest, the realm of cured meats has the scope to focus on premium and distinctive offerings that prioritise quality and craftsmanship.

1.4.1 Traditional Curing Methods

Having been perfected over centuries, timeless traditional curing techniques can be categorised into dry, wet, and mixed curing. Providing a harmonious blend of preservation and taste that remains revered in culinary traditions, salting, smoking, drying and fermentation have evolved to enhance both the longevity and rich flavours of meats, ensuring their enduring prominence in a wide array of cultural cuisines. Accomplished by reducing water activity through salt addition and drying, dry curing encompasses the application of curing agents or salt to the meats surface followed by the combination of salt with natural juices exuded by meat to generate a curing solution (Zhou, Hu and Wang, 2022). The Dry Curing process consists of 3 stages; 1) A salting stage that enables salt penetration through the meat via solubilization within natural meat exudate 2) Post-salting that permits diffusion and equitable distribution throughout the unit and 3) A drying stage, often referred to as ripening, to enable reduced water activity and valuable biochemical reactions (Toldrá, 2014). Requiring significant time, slow ripening enables a greater rate of enzymatic degradation and assists in the development of distinct sensory and textural properties obtained through proteolytic and lipolytic action. The characteristic aroma of dry-cured ham arises from the breakdown of amino acids and lipolytic and oxidative degradation. The combination of reactions generates volatile compounds during ripening at higher temperatures. Consequently, product quality undergoes notable enhancement (Gonzalez and Ockerman, 2007).

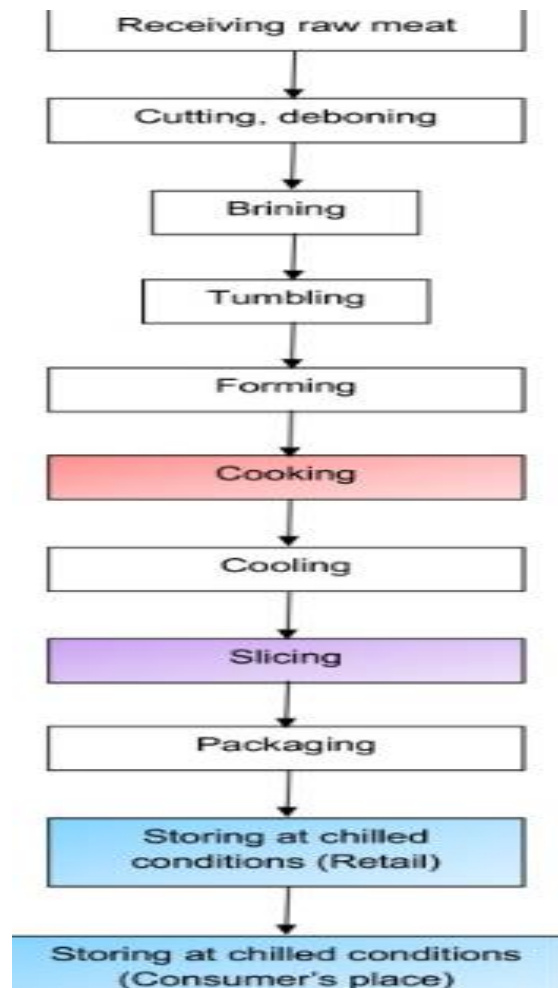


Figure 1.3: Schematic flowchart illustrating processing of cooked ham (Zwietering *et al.*, 2016)

Wet curing has eclipsed dry curing and stands currently as the prevailing standard in industry for cured products. Becoming the preferred method for food-producers seeking improved efficiency and scalability within production, this paradigm shift is driven by wet curing's enhanced versatility and the significant reduction in processing time it offers (Keenan, 2016). The Wiltshire Curing process is extensively documented and boasts a rich historical legacy in the context of pork products. It can be defined as the injection of curing solution into meat followed by an immersion cure consisting of microbiological starter culture for 3-10 days. The European Union (EU) acknowledges this traditional process in Regulation 1333/2008 Annex II in the food category 8.3.4.1 (European Union, 2008). Encompassing the injection of curing solution into 8-10% of the pork muscle, the meat receives mechanical tenderization through puncturing via injection. In turn, meat undergoes complete submersion in 'live brine' for 4-5 days, with Wiltshire Brine being preserved and replenished to sustain a thriving live bacterial

population controlling nitrogen metabolism within the brine (Marcinkowska-Lesiak *et al.*, 2022). Bacteria concentrations within Wiltshire brine have been determined at a range of 10^6 – 10^7 CFU/ml (Woods and O’Gara, 2019). Scarcity of research on brine used for meat curing has led to significant voids in our comprehension of this traditional method. To entirely elucidate and characterise the process, it is necessary to conduct more extensive and detailed investigations to narrow the disparities of knowledge. An integrated approach, Combination curing merges dry and wet curing to optimise their respective benefits.

1.4.2 Non-Traditional Curing Methods

Non-traditional curing methods that deviate from conventional curing methods are innovative applications such as Vacuum Tumbling, Injection Curing, Electrolytic Curing, and Enzyme-Enhanced Curing. Modern insights into food science and advanced technologies are immensely advantageous when applied to curing processes, developing the efficacy, safety, and flavour of the final product. Tumbling is a reputed physical-mechanical technique that readily penetrates muscular cell membranes and reduces the curing duration through rupturing (Conde *et al.*, 2012). A vacuum tumbler is typically employed to boost cure penetration into the product with the complementary impacts of the vacuum and mechanical movements of tumbling demonstrated in the distribution of liquids from the pores and the extraction of meat proteins to its exterior (Bosse *et al.*, 2017). Consequently, vacuum tumbling stimulates the relaxation of muscle fibre structures, thereby enhancing product quality by ensuring an even dispersion of cure throughout the meat (Szerman *et al.*, 2007). Salt can be administered to meat products externally via submersion, and internally via injection. Injection with a condensed pattern typically prevails within industrial production due to the duration required for salt diffusion. To accomplish the desired salt content for a given quantity, primary process parameters including injection speed and pressure are modified, with many meat products being homogenous and typically comprising of an assortment of various muscles and tissues that each absorb brine differentially considered (Philipsen and Moeslund, 2019).



Figure 1.4: Industrial Vacuum Tumbler – Derived from Internal Company

Utilised as a progressive approach and substitute to mechanical tenderization, enzymatic activity efficiently develops a products desirable characteristics. Proteolytic enzymes, often referred to as protease, catalyse the hydrolysis of proteins into amino acids and peptides, with 60% of commercial enzymes implemented within the food industry reported as protease (Wu *et al.*, 2017). Recently, the use of external enzymes for meat tenderization has garnered growing interest among food technologists and meat scientists due to their exploitable properties. An amalgam of bacterial collagenase and plant exogenous proteases such as bromelain, papain, ficin, actinidin, and zingibain, are typically included within the tenderizer applied to meat (Abdel-Naeem and Mohamed, 2016). These proteases hydrolyse peptidic linkages within meat proteins, degrading muscle proteins in connective tissues and ultimately forming peptides and amino acids that diminish meat toughness (Fernández-Lucas, Castañeda and Hormigo, 2017). Enzymatic action not only enhances texture and flavour development but improves moisture retention and yields consistently efficient production during curing.

1.5 Nitrite & Its Role in Cured Meats

Nitrite (NO_2^-), consisting of one nitrogen and two oxygen atoms, is a ubiquitous precursor within the biological nitrogen cycle and serves a wide array of industries including pharmaceuticals and food processing. In humans, nutrition and endogenous synthesis are the primary sources of nitrate and nitrite with a nitrate-nitrite-NO balance maintained via circulation, reduction and partial excretion (Qin *et al.*, 2012). A fundamental biogeochemical system that explicates the morphology of nitrogen across an array of ecosystems, the Nitrogen

Cycle consists of complex interconnections within nitrogen reservoirs which are primarily regulated by nitrogen fixation and denitrification (Gruber and Galloway, 2008). As seen in Figure 1.3.1, nitrite plays a critical intermediary role by facilitating the conversion of Ammonia (NH_3) to Nitrate (NO_3^-), ensuring Nitrogen's (N) availability in maintaining ecological equilibrium. Sodium Nitrite (NaNO_2) is applied as an antidote for cyanide poisoning, functioning through the conversion of haemoglobin to methaemoglobin which binds to cyanide, ultimately enhancing activity of the endogenous detoxification system and enabling excretion (Bhattacharya and Flora, 2015). Furthermore, nitrite reacts with aromatic amines in the presence of an acid to form diazonium salts, which are essential precursors in the production of azo dyes, pigments, and diverse organic compounds.

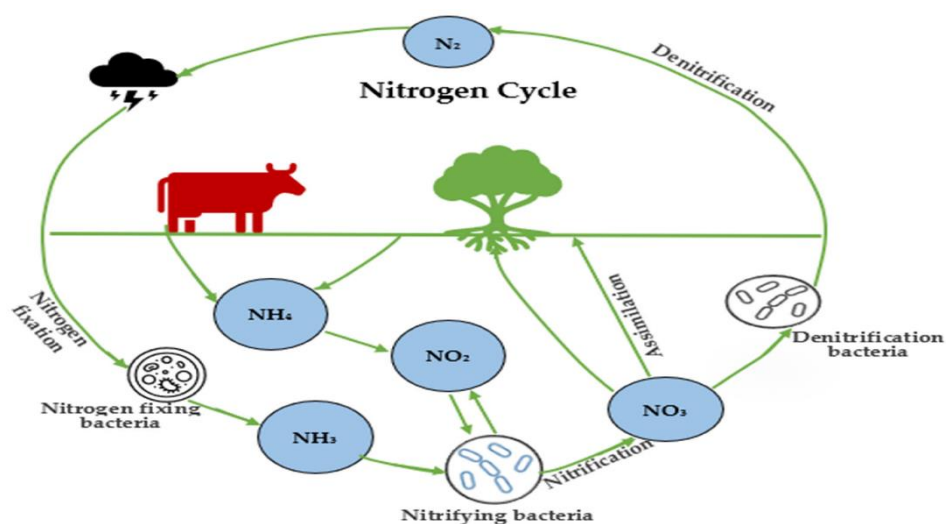


Figure 1.5: Graphic illustration of The Nitrogen Cycle (Shakil *et al.*, 2022)

Amongst the preservative additives utilised throughout the meat curing process, nitrite salt is a prominent contributor with its significance derived from its multifarious functions, enhancing both safety and quality. Nitrite, when incorporated into the curing process at concentrations typically below 15ppm, plays a crucial role in ensuring food safety. This is achieved through its potent antimicrobial properties, which effectively inhibit the growth of harmful bacteria, such as *Clostridium botulinum*. This bacterium is notorious for its production of botulinum toxin, a highly potent and potentially fatal compound known to induce severe cases of food poisoning (Badea *et al.*, 2004). In addition, nitrite significantly enhances the sensory attributes of cured meat products. Responsible for catalysing the formation of nitroso myoglobin, nitrite enables the chemical complex that imparts a distinctive and desirable pink to red hue to the

meat which extends beyond visual appeal by playing a crucial role in shaping consumer perception and product acceptance. Through its role in mitigating lipid oxidation, nitrite plays a vital part in maintaining the meat's freshness, curbing rancidity, and prolonging the product's overall shelf life. This antioxidative function is essential for protecting the meat against the degradation of its flavor, texture, and nutritional integrity over time.

1.5.1 Antimicrobial Effect & Shelf-life Extension

Foodborne pathogen and spoilage bacteria proliferation can be inhibited by nitrite in processed meats through an assortment of mechanisms including the generation of nitrous acid and nitric oxides, the impediment of oxygen consumption and energy production, and the disruption of essential bacterial enzymes such as aldolase required for metabolism (Weiss *et al.*, 2010). Nitrites are recognised for their bacteriostatic and bactericidal properties against pathogenic bacteria including *Salmonella enterica* serovar Typhimurium, *Listeria* spp., and *Clostridium botulinum* (Majou and Christieans, 2018). Even at concentrations as low as 4×10^{-5} to 8×10^{-5} g/g, nitrite impedes the growth of *Clostridium botulinum*, which is a fatal illness that is characterised by potential paralysis, respiratory failure and death (Ferysiuk and Wójciak, 2020). Nitrite's ability to inhibit microbial growth is primarily due to its capacity to generate nitric oxide (NO), rather than the nitrite itself. NO effectively reacts with microbial proteins that contain iron-sulphur clusters, leading to a generation of protein-bound dinitrosyl dithiolato iron complexes. These iron-sulphur complexes are vital to produce ATP in *Clostridium* species, as ferredoxin is employed for this function. The key cause of the inhibition of *Clostridium* vegetative cell proliferation is this reaction. Aerobic and facultative pathogens that are present in cured meat products exhibit comparable effects (Crack and Le Brun, 2021).

Nitrite functions as an antioxidant in food preservation. A molecule that is sufficiently rigid to donate an electron to a ravaging free radical and counteract it, thus lowering its ability to cause damage, is referred to as an antioxidant. The oxidative degradation of lipids, commonly referred to as rancidity, is the consequence of lipid oxidation, a highly intricate series of free radical reactions between fatty acids and oxygen (Mozuraityte, Kristinova and Rustad, 2016). The primary non-microbial cause for quality loss, lipid oxidation is rapidly progressive and requires meticulous control to minimise economic loss within industry with the fundamental objective of stakeholders and researchers to comprehend mechanisms to allow efficient control (Amaral, Silva and Lannes, 2018). Mechanisms that nitrites undergo include free radical scavenging, NO formation, metal ion chelation and redox balance maintenance. The primary

mechanism by which these antioxidants prevent, or stall cellular harm is through their ability to scavenge free radicals. Antioxidants can successfully curtail the chain reaction prior to the compromise of vital compounds (Lobo *et al.*, 2010). Nitrite stabilises the heme Fe and functions as a chelating agent for metallic ions, which are the primary prooxidants in meat (Shakil *et al.*, 2022). Nitrite has been demonstrated to possess antioxidant properties at quantities as low as 40 mg per kg (Al-Shuibi and Al-Abdullah, 2002). The addition of 50 ppm sodium nitrite to meat products has been observed to result in a 65% decrease in lipid oxidation (Girouard, Frenette and Sullivan, 2011). Nitrites significant combination of antimicrobial and antioxidant properties render them valuable to produce cured meat products due to their weighty contribution to shelf-life extension and food safety.

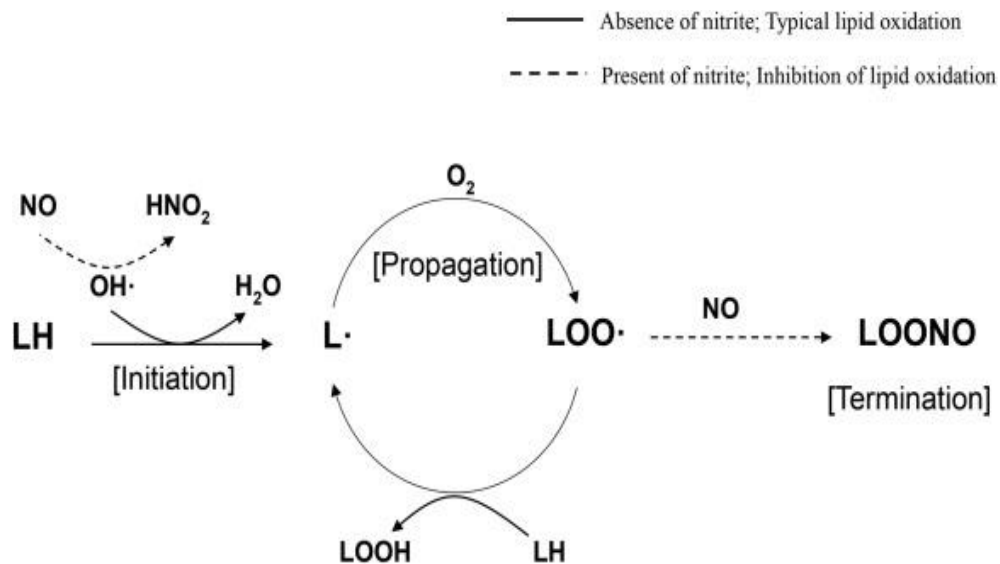


Figure 1.6: Illustration of Nitrites Antioxidant ability to stabilise lipid radicals during Lipid Oxidation (Jo *et al.*, 2020).

1.5.2 Colour & Flavour Development

Colour plays a pivotal role in consumer decision making due to its contribution to visual appeal, perceived quality, flavour expectation and function as a safety indicator. Vivid colours, such as bright red or pink, indicate freshness and sufficient cooking, whereas drab or brownish hues may suggest spoilage or inadequate cooking. These colour signals allow consumers to effectively gauge the safety of meat, thereby reducing the risk of the ingestion of spoiled or unsafe products. Meat is infused with a sodium nitrite infusion that rapidly converts to NO. Nitroso myoglobin, which is red in colour, is produced when nitrite reacts with myoglobin, a

primary haemoprotein responsible for meats colour. In fresh meat, myoglobin is in one of three states of dynamic equilibrium: deoxy myoglobin, oxymyoglobin, and metmyoglobin. These states are impacted by the redox state of iron in the heme group and the level of oxygen (Pujol *et al.*, 2023). The subsequent heating of meat that contains the NO-myoglobin complex results in chemical reactions that convert myoglobin to a compound known as nitrosylhemochrome. This results in the distinctive pink hue of cured meats (Zeece, 2020). In essence, the development of the cured colour in meat necessitates a negligible amount of nitrite, typically between 2 and 14 ppm. The residual nitrite content of cured meats decreases over time due to storage oxidation, light and oxygen exposure, consequently becoming discoloured. The presence of sufficient residual nitrite and reducing compounds can impede this process with a residual nitrite concentration of 10-15ppm beneficial to serve as a repository for colour replenishment (Sindelar and Milkowski, 2011).

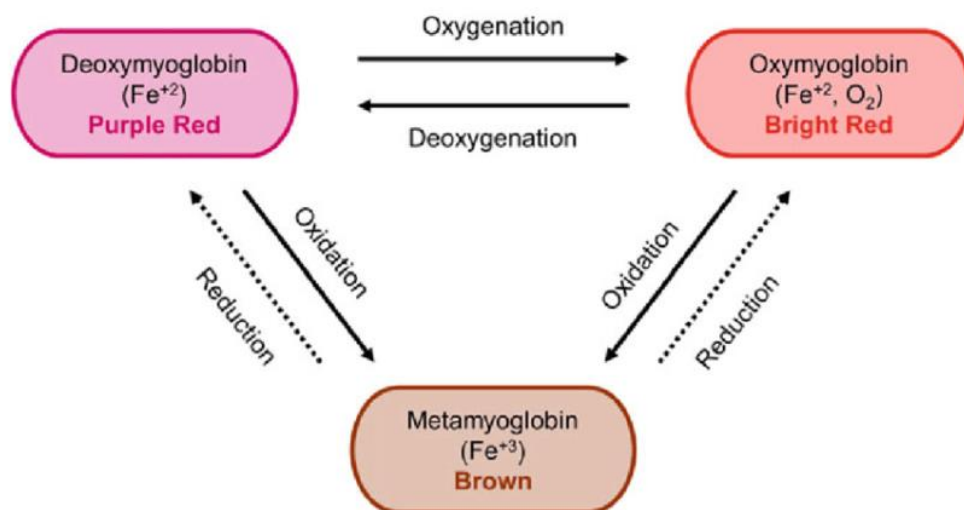


Figure 1.7: Myoglobin in one of three states of dynamic equilibrium (Senoptica , 2022)

The flavour of food is a critical qualitative attribute that influences consumers' purchasing decisions. It is the outcome of the interplay between chemesthetic sensations, aroma, and taste. The five fundamental tastes—sweet, salty, bitter, sour and umami—are distinguished by the non-volatile compounds that are present in food (Menis-Henrique, 2020). The flavour continuum has been shown to be simplified by nitrites antioxidant activity. The synthetic process of specific flavour compounds is not influenced by nitrite; however, it inhibits the formation of aldehydes through lipid oxidation, which obscures the sulphur-containing molecules that impart the flavour of cured meat (Shakil *et al.*, 2022). Sensory research

demonstrates that the flavour of cured meat is not solely a result of the diminished rate of lipid oxidation; it is also the result of the fusion of nuanced cured aromas and flavours, in conjunction with the scarcity of putrid flavours (Ursachi, Perța-Crișan and Munteanu, 2020).

1.6 Food Safety Aspect & Regulation

The meat industry is currently navigating a complex landscape marked by a range of challenges and controversy. These issues have become more pronounced due to ongoing research and developments as well as consumer knowledge regarding nutrition's pivotal role in overall health and well-being. Growing dissatisfaction among consumers is rooted in their deeper comprehension regarding meat components in relation to sodium, fat, chemical additives and preservatives. Additionally, heightened concern exists surrounding procurement and environmental impact of meat processing, including sustainability practices related to animal welfare, resource use, and ecological footprints (S *et al.*, 2023). This has prompted both consumers and health specialists to re-evaluate pre-cooked meat's role in contemporary diets and lifestyles. Consumer confidence in the safety and quality of food products is profoundly shaped by the robustness of food safety regulations. The establishment of critical standards and stringent protocols ensures product is meeting quality benchmarks, directly correlating to a greater sense of credibility amongst consumers. Consumer confidence in the security, traceability and quality of food products is significantly shaped by food safety regulations, with stricter regulations being correlated with a greater sense of credibility. Transparency and reliability within the food industry are significantly fostered through mechanisms such as Hazard Analysis and Critical Control Points (HACCP) and stringent labelling standards (Adams, 2024). These frameworks play a crucial role in ensuring that food products are safe, accurately represented, and consistently high in quality. Food manufacturers compliance with standards propels consistency within the industry through endorsing ongoing innovation, encouraging sustainable practices and driving operational efficiency.

1.6.1 Health Concern

Although primarily utilized as preservatives and for various technological purposes, the presence of nitrates and nitrites in food has garnered scrutiny due to the risk associated with the carcinogenic N-nitrosamine formation, and clinical symptom methemoglobinemia. Methemoglobinemia occurs due to high levels of methaemoglobin, resulting in a depletion in the bloods oxygen carrying capacity. Particularly perilous to infants under the age of six months, the condition leads to an underdeveloped methaemoglobin reductase system and

exhaustion of gastric acid production (Ward *et al.*, 2018). N-Nitrosamines are a group of compounds that are infamous for their pervasive presence in the world and for their formidable carcinogenicity, regarded as one of the three most potent carcinogens in the globe (Beard and Swager, 2021). Nitrosamines have been identified in a wide array of food products, spanning cured meats, processed fish, chocolate-flavoured beverages, and alcoholic beverages. Meat and its processed derivatives are recognized as the most significant contributors to human exposure to nitrosamines (EFSA, 2023). Approximately 300 N-nitrosamine compounds have been identified thus far and can be categorised into volatile and non-volatile compounds. N-nitrosodimethylamine (NDMA), N-nitrosodiethylamine (NDEA), N-nitrosopiperidine (NPIP), N-nitrosopyrrolidine (NPYR), N-nitrosomorpholine (NMOR), N-nitrosomethylethylamine (NMEA), N-nitroso-di-n-propylamine (NDPA), and N-nitrosodibutylamine (NDBA) are volatile components present within processed meats matrix that possess carcinogenic properties (Xie *et al.*, 2023). The International Agency for Cancer Research (IARC) classified processed meat as cancer-causing in 2015, with the World Cancer Research Fund (WCRF) and the American Institute of Cancer Research (AICR) executing comprehensive analyses suggesting the occurrence of colon cancer is connected to the increased consumption of processed meats (Xie *et al.*, 2023). Globally, a slight decrease in gastric cancer mortality rate was evident over previous decades, nevertheless in 2012, gastric cancer was the fifth most prevalent disease with 700,000 fatalities and one million new cases reported (Torre *et al.*, 2015).

The cellular breakdown of proteins in meat by endogenous proteases and microbial enzymes can produce secondary products, including peptides, amino acids, and biogenic amines, which act as precursors to N-nitrosamines (De Mey *et al.*, 2014). Prior to reacting with sodium nitrite, secondary products undergo further chemical modifications through deamination and cyclization to generate nitrosamines during thermal processing (IARC, 1997). Nitrosamines form synchronously with a spike in heating temperature with an optimal pH range for a nitrosation reaction ranging from 4.0 and 3.0. A study carried out by Song *et. al* (2015) involved the statistical combination of similar research studies to ascertain the effect of nitrate, nitrite and NDMA consumption effect on gastric carcinogenesis. Upon analysing the dose-response pattern for nitrates, nitrite and NDMA, the risk of gastric cancer was found to be reduced by the consumption of food that was high in nitrates, while the risk of cancer was increased by the high intake of nitrites and NDMA. Nitrates are generally considered to be essentially inert prior to their conversion to nitrites. As seen in figure 1.4.1.1 and figure 1.4.1.2, the risk of gastric

cancer increased by 7% for each 0.1 mg/day increase in nitrite intake as estimated in a linear dose-response model for nitrites. A nonlinear trend towards gastric cancer risks was observed with the adverse effects on humans becoming more apparent when the daily intake of NDMA reached 0.12 μg (Keszei *et al.*, 2013). These observations represent the significance of regulating and monitoring nitrite intake in dietary habits to effectively safeguard public health and to reduce the risk of cancer.

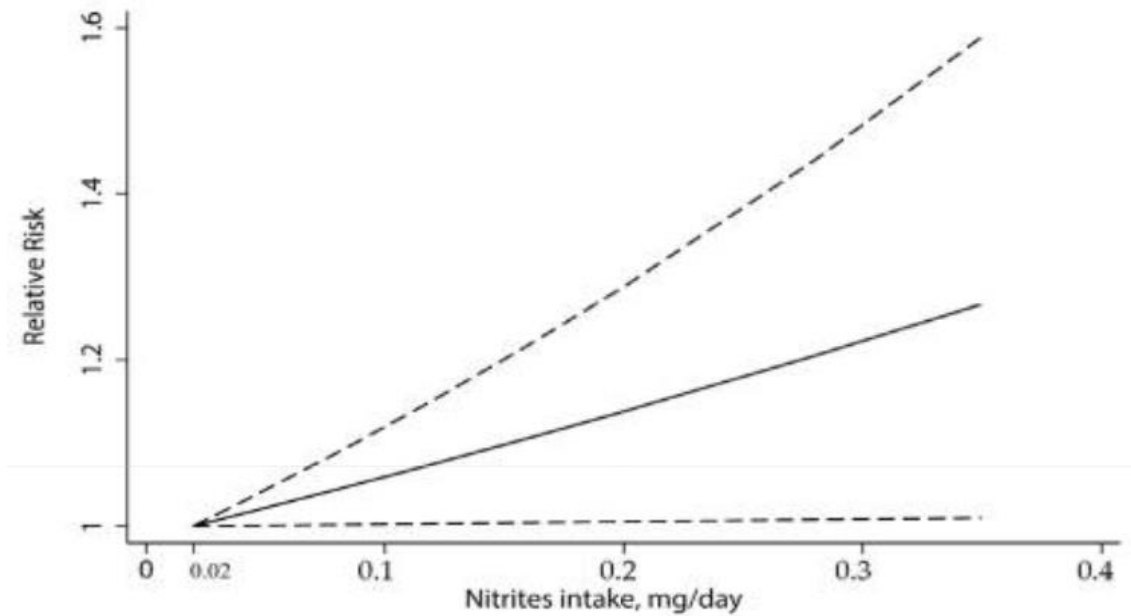


Figure 1.8: Dose response analysis of Nitrite Intake versus Relative Risk (Song, Wu and Guan, 2015)

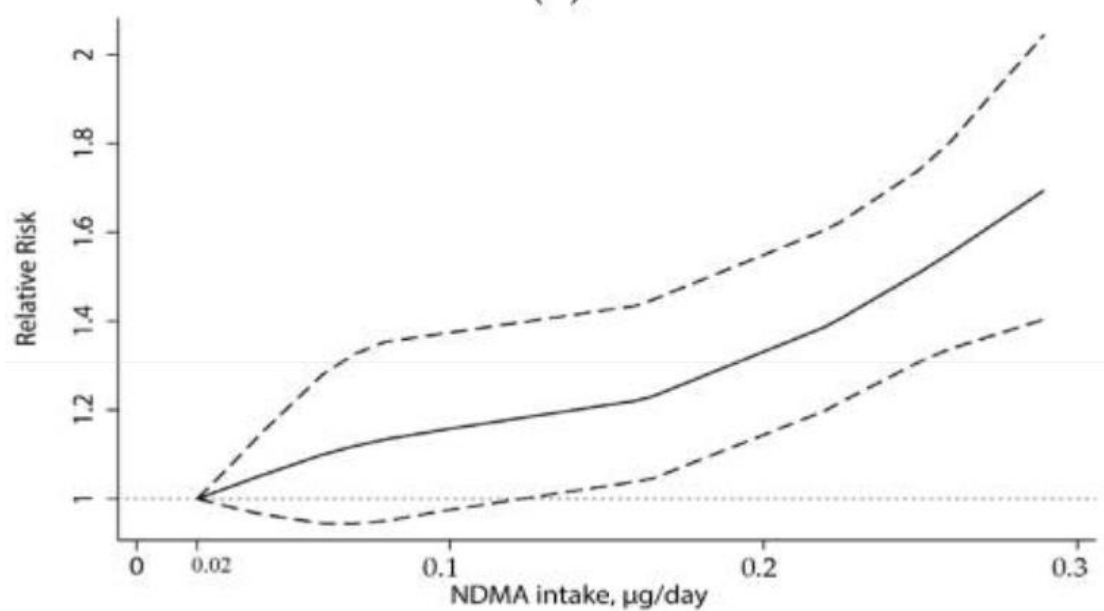


Figure 1.9: Dose response analysis of NDMA Intake versus Relative Risk (Song, Wu and Guan, 2015)

1.6.2 Regulatory & Compliance

The use of nitrites and nitrates as food additives has been considerably restricted by legislative changes implemented within the EU, with the FSAI, as the competent authority responsible for monitoring cured meats products adherence to food safety and authenticity standards. Regulation (EU) 1333/2008, which pertains to the use of nitrates and nitrites in meat products, has been implemented into Irish law by S.I. No. 330 of 2015. Divided into two groups based on their respective processes, cured meat products can be categorised into non-derogated and derogated. Non-derogated products are primarily cured through an injection process that is preceded by a brief immersion cure. Wiltshire cured products are derogated as they are conventionally cured, undergoing immersion curing for 3-10 days, and have specified exemptions as outlined in Directive 2006/52/EC (EU Commission, 2008). The permissible maximum residual levels for nitrates and nitrites in the final product are those set for derogated products recognized as unique within specific EU Member States. The quantity of additives in cured meat products is regulated in accordance with the quantity that is introduced. As of present, the current admissible maximum in-going quantity of nitrate and nitrite is 150mg/kg. Nevertheless, the current limits may only be applied by meat processors until October 2025, because of recent modifications to EU regulations. As of October 2025, the maximum permissible level for nitrate ion addition to non-heated meat products is 90 mg/kg, while the threshold for input nitrite is reduced to 80 mg/kg for both heated and non-treated products (EU Commission, 2023).

Ireland's legislation aligns with that of its other European counterparts. In accordance with Commission Decision (EU) 2021/741, Denmark are continuing to enforce more stringent nitrite limitations after May 5, 2024 (EU Commission, 2021). French food manufacturers establish limits for each product type in the Code d'usage de la Charcuterie, which outlines the standards by which French governance and commissions serves. France's curing process is noted for its regional artisanal methods and specific standards for traditional charcuterie, consisting of diverse aging techniques, spice blends, and fermentation or smoking methods that maintain its market competitiveness at a global scale. These thresholds are 80% less than those of the EU and are coupled with novel processing and hygiene procedures to mitigate the risks posed by microbes (Louis-Sylvestre, Krempf and Lecerf, 2010). A law proposal bill was voted

in French Parliament in February 2022, initially aiming to ban nitrites within 5 years. The final proposition simply defined a calendar for reviewing nitrites levels in meat products and their labelling, with research conducted by the French National Health Agency indicating the toxicity of nitrites. The report concluded that 99% of the French population is not exposed to levels higher than the recommended dietary allowance (RDA) and only 20% of nitrites exposure is due to meat products. Its ultimate recommendation was to minimise the presence of nitrites in food to the greatest extent feasible. Following this report, the French government implemented an action plan and detailed the reduction of nitrites levels in the Code de la Charcuterie, applicable in 3 phases: immediate (by end of April 23), short term (within 6-12 months) and medium to long term (5+ years) (INRAE, 2023). Table 1.1 summarises the established limits.

Charcuterie Product	Market share	EU current limit of sodium nitrite (mg/kg)	France current limit of sodium nitrite (mg/kg)	Action plan limits		
				Immediate (End of April 2023)	Short term – to evaluate within 6-12 months	Long term – to evaluate within 5+ years
Cooked ham	28%	150	120	90	80	60-40-2-0
Lardons	14%	150	120	100	90	80-60-40-2-0
Raw sausages	15%	150	120	80	0	0
Cooked sausages	10%	150	120	100	80	80
Patés, rillettes	10%	150	120	100	90	80-60-40-2-0

Table 1.1. Code de la Charcuterie Nitrite Level Reduction Plan (INRAE, 2023).

The UK has maintained EU Regulation 1333/2008 on food additives in the wake of Brexit, and the current maximum permissible levels for nitrites and nitrates in meat products are identical to those in the EU. The UK Food Standards Agency believes that the current permissible levels of nitrites and nitrates are adequate to safeguard consumers. This is founded on the perspective of the independent committees that provide guidance to the FSA, including the European Food Safety Authority. In adhering to EU regulation, food manufacturers hold a requisite function in food safety, quality and compliance of reduced nitrite and nitrite-free products, allowing the pre-cooked meat industry to continue to thrive and sufficiently adapt to its new setting.

1.7 Consumer Insights & Perception

Within both the academic and corporate landscape, consumer behaviour and preferences regarding food consumption has emerged as a major focal point. Particular emphasis is placed on factors concerning cultural practices, economic influences, environmental impacts, societal considerations and health implications (Veiga *et al.*, 2023).

With consumer preferences pivoting towards more sustainable and health-conscious options, a profound transformation is unfolding in the food industry. This essential shift mirrors evolving lifestyles and dietary habits, signifying a groundbreaking transformation within the sector. By capitalising on consumerism, the food industry can streamline its efficiency, secure robust customer-relationships and establish itself for long-term prosperity within a highly competitive marketplace. Health consciousness and transparency have become key pillars amongst consumers, with approximately 74% of consumers concerned about the healthfulness of their food selections (IFIC, 2023). The discovery of carcinogenic and genotoxic N-nitroso compounds in processed meat products has had significant adverse repercussions on the meat industry, with the revelation generating heightened concern and eroding trust amongst consumers. The consumption paradigm of conventional meat is enduring profound aversion, with a united front required by the pre-cooked meats industry to reclaim consumer support.

Notoriously capricious operators of the market economy, the consumer and their dynamical perception is shaping the cooked meats industry. Consumer preferences and purchasing decisions are a formidable force for the food industry to contend with, being the largest beneficiaries within the market. The rapidly shifting and fragmented trends of consumer behaviour have presented an immense obstacle for food manufacturers due to its desultory mechanism. A multidimensional process, perception is the act of choosing, planning, and deciphering information inputs to generate context that facilitates the decision-making (Madichie, 2012). The perception of meat and meat products among consumers has been altered by the constantly shifting psychosocial constructs of the past few decades (de Araújo *et al.*, 2022). Numerous studies have shed light on the incorporation of these key dimensions including; health beliefs and attitudes, trust and confidence, cognitive dissonance, and ethical and environmental concerns, and stressed how they significantly shape consumer attitudes (Klink-Lehmann *et al.*, 2022). Consumer attachment to meat is fortified by its perceived quality and flavour, which cultivate a deep-seated affinity for the product. The primary determinants for consumer acceptability in meat palatability are typically tenderness and odour with the most

critical sensory attributes associated with in-mouth perception of texture, flavour and perceived appearance (López-Pedrouso *et al.*, 2020). The removal of ingredients that are deemed as unhealthy, leads to an enhanced overall perception of the product; nonetheless, this may also affect sensory properties, which could potentially obscure the way the customer views the product as seen in a focus group conducted amongst European consumers. Consumers conveyed reservations regarding the uptake of innovative meat products with reduced nitrites and natural extracts due to the prospective drawback in relation to taste, healthiness and product shelf-life. Ultimately, the qualitative study expressed the consumers value of a sensory experience of cured meats and are consequently averse to products that provide inferior sensory quality (Hung, Verbeke and de Kok, 2016). To effectively mitigate the impact of nitrite elimination from meat, comprehensive and systematic refinement to processing methods is fundamental while also placing emphasis on developing consumer confidence.

As indicated in the Nielsen Global Health and Wellness Survey, executed in 60 countries and polling approximately 30,000 shoppers, the most coveted food attributes are freshness, naturalness, and minimal processing (Román, Sánchez-Siles and Siegrist, 2017). The desire for more authentic and health-orientated products reflects a broader trend towards prioritizing nutritional integrity and environmental stewardship in food consumption. Consumers inclination towards natural antioxidants as a substitute of synthetic additives reflects an inherent trust in the value of ‘naturalness,’ regardless whether consumers are fully informed about their use within conventional meat products (De Andrade *et al.*, 2017). Nonetheless, a notable air of scepticism towards innovation concerning health attributes exists... Through open discourse, evidence-based incentives, and congruence with consumer values, it is possible to remediate consumer concerns to foster trust and acceptability for new products. Clean labels have the potential to serve as peripheral indicators and generate a halo effect amongst consumers via their transparent and simple representation of product. Consisting of clear claims such as “free from” and “natural,” simple ingredient lists and a health and well-being focus, clean labelling has the potential to exert profound impact on purchasing decisions and assist in achieving indispensable competitive advantage (Cao and Miao, 2022). The use of the traffic light system is another consumer-centric approach utilised to support informed decision-making. Providing detail regarding the content of essential nutrients per 100g/serving, the mechanism classifies nutrient content as low, medium or high in accordance with predetermined standards through graphical interpretational aids obtained from traffic lights (Machín *et al.*, 2018). This transparency bolsters the successful introduction of a nitrite-free

meat product into the marketplace, reinforcing its appeal as a healthier alternative to conventional products whilst demonstrating responsiveness to supporting informed consumer decisions.

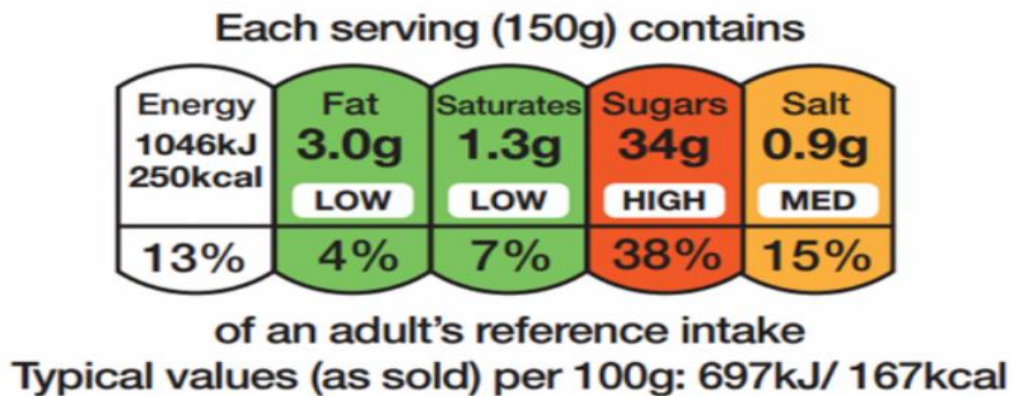


Figure 1.10: Traffic Light Label (Food Standards Agency, 2020)

In 2022, 63% of Irish consumers ranked cost as the most significant factor when considering food purchases, with 54% ranking taste and 52% ranking product safety. It is noteworthy that these findings surpass the average constraints across the entire EU (FSAI, 2022). Consumers' Willingness to Pay (WTP) is greatly affected by socioeconomic variables including education, income, gender and age and is driven by primary psychological factors such as health-consciousness, with 44% of consumers prepared to spend an additional 9% extra on wellness food products. (Ali and Ali, 2020). This percentage value has significantly improved in recent times due to social media platforms simplifying complexities of navigating food labelling and asserting confidence in making informed purchase-decisions via visual and interactive content. Nonetheless, the negative correlation that exists between price sensitivity and purchase intent highlights the necessity for manufacturers to strike a balance between pricing strategies and perceived value to successfully mould consumer purchasing behaviour.

1.7.1 Market Analysis

The global appetite for meat is continually on the rise, with worldwide meat consumption growing fourfold since 1961. At present, approximately 80 billion animals are slaughtered annually to yield 340 tonnes of meat for human consumption (Ritchie, Rosado and Roser, 2024). Attributed to the exponential growth of the human population, this surge has an

immense economic influence, with projections suggesting that the market will contribute over \$1.5 trillion by 2029 (Caputo *et al.*, 2024). Europe is a leading market for cured meats, boasting a production volume of 14.5 million tonnes and a market turnover surpassing €62 billion. Germany contributes 25% to European production, followed by Italy at 10%. Spain, France, and Poland each account for 9%, while the UK closely follows, supplying 8% of production (SIAL, 2024). The market is projected to reach €330.2 billion in 2024 with substantial growth anticipated in forthcoming years as illustrated in Figure 1.11. The Irish livestock market is an ever evolving and integral component of the nation's economy that experiences consistent advancement fuelled by resilient export performance and secure domestic consumption. The Irish Meat Processing industry ranks 8th in Europe and has an industry market size of €4.6 billion in 2024. Employing over 11,000 people, it is experiencing an average annual growth rate of 0.5% from 2019 (IBIS World, 2023). Catering to diverse consumer preference, the Irish cured meats industry has effectively expanded its market reach beyond domestic borders by leveraging international markets. Ireland's positive reputation as authentic and premium has heightened the appeal and acceptability of its cured meats products, facilitating the smoother entrance into global markets.

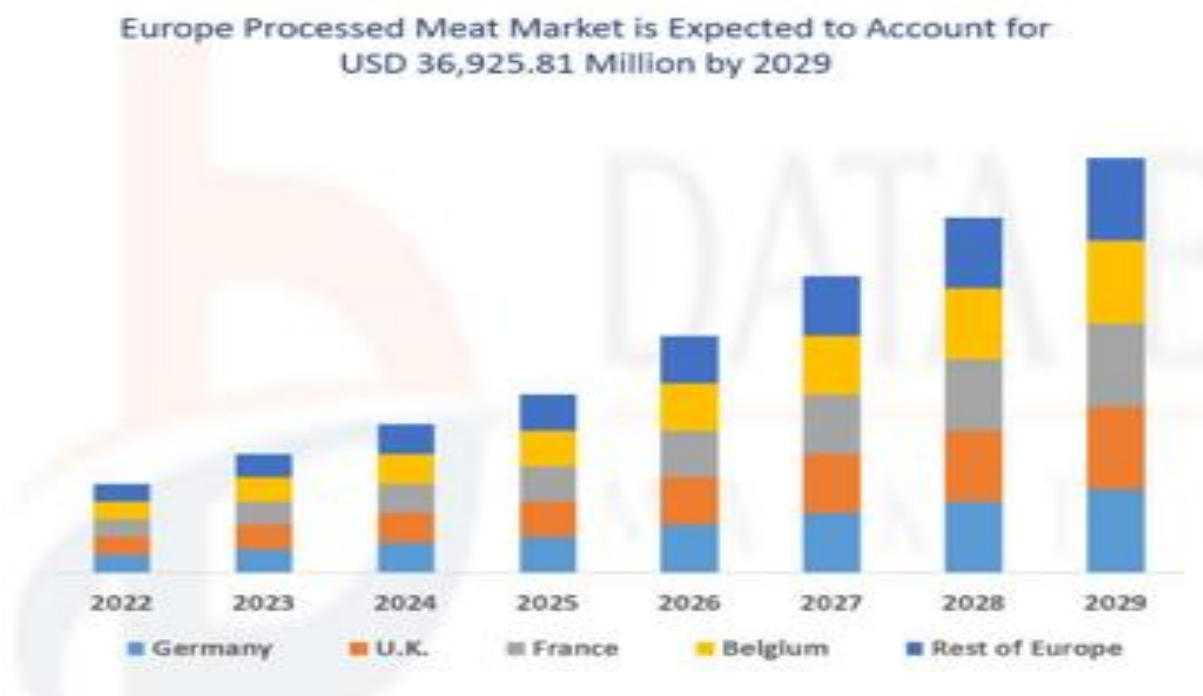


Figure 1.11: Europe Processed Meat Market Exponential Growth by 2029 (Data Bridge Market Research, 2022)

Amid heightened health awareness, the processed meats industry is currently witnessing a desire for nitrite-free alternatives, underscoring a nuanced and multifaceted market driven by

informed consumer preference. Key industry contenders are continuously expanding their regional presence and employing product development as a central focus to successfully consolidate market dominance within the rivalrous industry. Europe is pioneering the transition to nitrite-free meat products due to its proactive approach to health, innovation, and regulatory frameworks.

Embodying a secular, heritage, French cuisine has shaped global cuisine with an immense international influence. In 2022, nitrites and nitrates were used in 90% of French cured meats, with strong impetus applied by leading companies to explore alternative nitrite-free offerings (Dongo, 2022). Examples of companies who have spearheaded innovative benchmarks include 'Fleury Michon' who have launched a reformulated 140g nitrite-free ham product in November 2022 using vegetable extracts as an alternative, retailing at €3.58 (Fleury Michon, 2022). A diverse range of nitrite-free offerings exist within the French market with 'Giuseppe Citterio' launching an 80g salami offering retailing at €3.45 (Citterio, 2024). 'Herta' launched a 120g nitrite-free roast chicken offering within the poultry category, retailing at €1.80. Key players within the UK market include Sainsburys and Waitrose who offer both nitrite-free meat offerings whilst boasting high levels of animal welfare and sustainable packaging, catering to today's ethically minded consumer. "Finnebrogue Artisan," a Northern Irish company retailing within the UK, utilise a combination of natural fruit compounds, including concentrated apple juice, and sea salt to produce their nitrite-free product retailing at €3.89, "Naked Bacon." The assessment of value proposition requires consumer recognition towards the attributes that contribute to the price disparity that exists between nitrite-free and conventional meats, such as production methods, supply-chain complexities, premium marketing positioning and rigorous quality and regulatory control. This acknowledgement is fundamental in allowing appreciation of a nitrite meats value, justifying higher costs and supporting informed decision-making.



Figure 1.12: ‘Fleury Michon’ Nitrite-free ham offering available in the French Market (Fleury Michon, 2022).

1.8 Alternative Curing Ingredients & Methods

The imperative to develop and implement nitrite alternatives within the processed meats industry cannot be understated and is both urgent and essential. Considering forthcoming regulations, mounting health concerns and a demand for improved transparency and innovative offerings, the need for nitrite alternatives is further accentuated. Investment in this relatively unexplored research will have a substantial impact on both manufacturers and consumers by enhancing food safety and expanding market appeal, ultimately fostering a more consumer-orientated industry. Numerous researchers have concurred that a comprehensive approach that integrates scientific innovation, regulatory compliance, consumer education, and practical application is necessary to address the significant challenge faced by the industry in establishing a component that can fulfil nitrites multifaceted role (Bernardo *et al.*, 2021). The successful elimination of nitrites and incorporation of alternatives would provide several benefits to consumers, nonetheless, a careful balance must be struck between the enhancement of meat safety and maintenance of distinct characteristics of conventional products by meat processors (Hung, de Kok and Verbeke, 2016).

1.8.1 Alternative Ingredients

Plant extracts as nitrite alternatives harmonize seamlessly with contemporary consumer preferences for ‘naturalness,’ with the botanical ingredients serving as effective natural preservatives and antioxidants. Extensive research has revealed that an eclectic assortment of natural additives holds promise as viable replacements for nitrite. Vegetables such as celery, lettuce and spinach contain over 2,500 mg nitrate/kg, making them effective curing agents following conversion to nitrite by microorganisms (Colla *et al.*, 2018). As demonstrated in mortadella-type sausages at concentrations of 4.29g parsley powder extract/kg of sausage meat, parsley proves to be a viable nitrite alternative by providing an equivalent microbiological stability to traditionally cured products through the inhibition of *Listeria monocytogenes* and maintaining vibrant red colouring (Riel *et al.*, 2017). The application of 0.8% celery powder in sausage production are comparable to those of conventional methods in terms of sensory assessments, total microbial count, and pH. Product colouring is improved by celery powder, producing a more appealing hue because of its natural betalain pigment consistency (Horsch *et al.*, 2014). In a study by Patarata *et al.*, chorizo made with red wine and garlic proved more effective at destroying *Salmonella* during processing and was preferred over sodium nitrite control samples. Adding 7.5% red wine to the chorizo significantly enhanced its redness, achieving a color intensity similar to that attained with 150 ppm of sodium nitrite (Patarata *et al.*, 2020). Ozaki *et al.* integrated radish powder at concentrations of 0.5% - 1%, and oregano essential oil at 100 mg/kg into fermented cooked pork with results demonstrating that their inclusions markedly intensified the red hue of meat (Ozaki *et al.*, 2021). Research conducted by Aquilani *et al.*, investigated the impact of grape seed extract with olive pomace hydroxytyrosol and, chestnut extract with hydroxytyrosol on microbiological stability and colour of meat. Grape seed extract significantly enhanced the redness of meat, likely due to the formation of Zn-protoporphyrin, with the addition of extracts resulting in low microbial counts of *Listeria monocytogenes*, *E. coli*, *Clostridium spp.*, *Staphylococcus spp.*, and *Salmonella spp.*, over a 3-week period (Aquilani *et al.*, 2018). At a concentration of 1.5%, tomato pulp powder (TPP) improves the colour of pork luncheon rolls while maintaining their physicochemical integrity. In contrast to formulations with higher nitrite levels, lower nitrite levels produce sensory qualities that are comparable or superior when blended with TPP, imparting exemplary flavour and valuable carotenoids (Tan *et al.*, 2021). The incorporation of pomegranate peel extract, white kimchi powder, lemon extract powder, extracts from wild thyme by-products, and potassium bixinate into the meat industry represent cutting-edge

innovation (Bae *et al.*, 2021). Boasting a distinguished reputation because of its high polyphenol content, pomegranate peel extract is particular scientific interest due to its composition of a plethora of antioxidants, including phenolic acids and flavonoids, which confer an impressive array of health benefits such as anti-cancer, anti-mutagenic, anti-cardiovascular, and anti-inflammatory properties (Al-Gubory *et al.*, 2016).

Organic acids and their salts are being examined as pioneering alternatives to nitrite in the realm of meat processing. Lactate, sorbate, acetate, and benzoate are particularly noteworthy organic acids with their use substantiated by their capacity to reduce pH level to a threshold that effectively suppresses microbial growth (Shakil *et al.*, 2022). Sodium lactate adeptly mitigates lipid oxidation and off-flavouring through the synergistic collaboration with sodium chloride and extends shelf-life with sausages consisting of 1.8% sodium lactate maintaining integrity for 2 months instead of 1 (Bingol and Bostan, 2007). Furthermore, sodium lactate increases the activity of lactate dehydrogenase (LDH), which in turn facilitates the conversion of metmyoglobin to deoxy myoglobin. Consequently, the meat's vibrant hue is preserved (McClure *et al.*, 2011). Sorbate, propionate, and benzoate are additives that exhibit efficacy in reducing the proliferation of Gram-positive bacteria, including *Staphylococcus aureus*, *Listeria monocytogenes*, and *Clostridium botulinum*. The proliferation of *L. monocytogenes* is curtailed by a 0.1% compound of benzoate-sorbate and benzoate-propionate. However, replacement limitations persist, as sodium sorbate cannot fully substitute for sodium nitrite because of its inability to impart meats characteristic colouring (Shakil *et al.*, 2022). Overall, these innovative ingredient nitrite-alternatives offer promising results, nonetheless, additional research is necessary to enhance their efficacy and address any sensory and functional constraints.

1.8.2 Alternative Methods

Innovative technologies embody cutting-edge advancements in the field of cured meat products. These techniques, including High Pressure Processing (HPP) and Modified Atmosphere Packaging (MAP), offer unique mechanisms for elevating quality and extending preservation, presenting compelling advantages in food processing. Aligning with the broader question of exploring the development of cooked meat without nitrite as a preservative ingredient, these technologies offer advanced solutions to maintaining product quality whilst meeting market expectations and regulatory demands. Nonetheless, their implementation within a food business involves substantial financial investment.

HPP inactivates microorganisms and enzymes while preserving the nutritional and chemical integrity of the food, thereby avoiding any chemical residues and maintaining product quality by applying intense hydrostatic pressure with a holding time of 1.5 – 6 minutes (Khaliq *et al.*, 2021). Foods are vacuum-sealed and loaded into the HPP chamber, where they are subjected to high pressure via a water-based system. High-pressure pumps and intensifiers create the required pressure, which is maintained for 1.5-6 minutes. During this process, the temperature of the water increases by about 3°C for every 100 MPa of pressure. After depressurization, the temperature quickly returns to near its original level (Balakrishna, Wazed and Farid, 2020). As seen in Figure 1.6.2.1, the creation of a hostile environment inhibits microbial proliferation, thereby extending the shelf-life of cooked meat. From an economic perspective, extending the shelf-life of nitrite-free meat through HPP can significantly diminish waste and enhance profitability. Offering an environmentally conscious advantage by eliminating the need for chemical additives, HPP resonates with the growing consumer preference for sustainable and natural food processing techniques. This technology propels the development of nitrite-free cooked meat by ensuring that alternatives satisfy stringent health-conscious standards but also uphold their sensory attributes and safety across extended storage periods, effectively addressing the demands of today’s discerning and ever-evolving marketplace

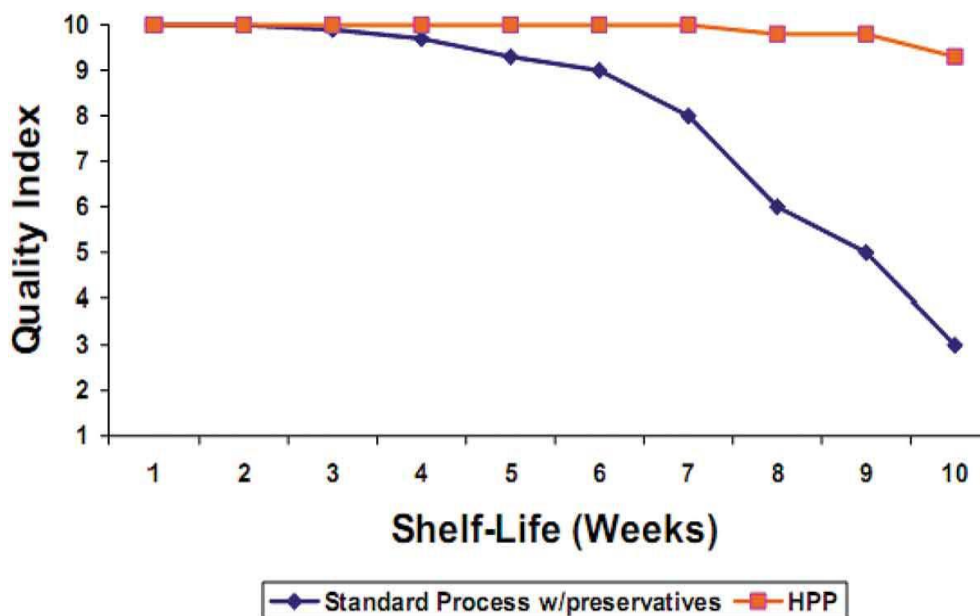


Figure 1.13: Impact of HPP on Shelf-Life Extension Compared to Control Ready To Eat at (RTE) Meat (Balakrishna, Wazed and Farid, 2020)

The ongoing transformations in the food industry to fulfil consumer expectations are evident in several innovative approaches, among which is the development and adoption of advanced packaging methods. MAP is an advanced packaging technology that involves adjusting the gaseous environment around food within its package. The initial step in the procedure is vacuum sealing which assists in the removal of excess oxygen and mitigates the likelihood of contamination. This is followed by the package being purged with a specific combination of gases that are specifically designed to meet the food product's requirements. This process utilizes three key gases: Oxygen, which preserves color and inhibits anaerobic growth; Carbon Dioxide, which curbs the proliferation of microorganisms, and Nitrogen, which maintains the structural integrity of the package by preventing collapse (Kandeepan and Tahseen, 2022). CO₂ plays a vital role in suppressing microbial proliferation, making its presence essential in packaging. Although CO₂ can impart a sour flavor, it is usually combined with other gases to counteract this effect (Zhang *et al.*, 2023). The manipulation of the gaseous environment is instrumental in achieving sufficient shelf-life, reflecting a commitment to sustainability by significantly minimizing waste and enhancing environmental stewardship within the food industry. This technique not only extends the shelf life of meat products but also aligns with the rising consumer preference for healthier, preservative-free options. By adopting MAP, producers can tackle contemporary challenges, drive innovation, and elevate industry standards towards a more eco-conscious future.

Chapter Two

Materials & Methodology

This chapter of the thesis provides a comprehensive exploration of the research framework and methodologies that were implemented to investigate the development of cooked ham cured without nitrite as a preservative ingredient. The materials used are described, including their constituents and origin and the procedural approach utilised encompassing preparation and processing techniques. The data collection and documentation methods are also elaborated upon, including sensory evaluations, shelf-life assessments, and the conditions under which experiments were conducted. By providing a comprehensive and precise account of the study's execution and the methodologies employed to deduce its findings, this section ensures research transparency and validity.

2.1 Methodology – Study Design

The design of the study was established to investigate the impact of nitrite on the development of cooked meat and to evaluate the impact of its removal as a preservative on the final product. The study seeks to assess the development of healthier meat products that meet consumer expectations and adhere to regulatory standards, ensuring they are appealing, safe, and marketable. The research methods used include reviewing published, peer-reviewed scientific papers, as well as examining resources from governmental and non-governmental organizations. The primary research took place with a case study investigating the development of cooked meat cured without nitrite as a preservative ingredient in the pre-cooked meat industry. A particular focus was placed on pre-cooked ham. Shelf-life testing, light trials and taste-panel data were included in the study.

2.1.1 Thesis Outline of Research

The thesis research question is intended to investigate the effectiveness and implications of replacing conventional nitrites with alternative curing agents in cooked meats. It aims to assess the impact of these novel ingredients on the quality, safety, and shelf life of the product, as well as address health concerns associated with the use of nitrite. The objective of this investigation is to evaluate the practicality, efficacy, and consumer acceptability of these alternatives to identify viable alternatives that maintain or improve product standards.

Chapter 1 provided a comprehensive analysis of traditional and non-traditional curing methods in meat processing. It investigated the critical role of nitrites in the preservation of meat, emphasising their chemical functions and safety concerns. The chapter also examined the

current regulatory frameworks that govern the use of nitrite, evaluates alternative curing agents and methods, and reviewed consumer attitudes and market trends in relation to nitrite-free products. The fundamental overview established the groundwork for a more comprehensive examination of innovative methods for curing meat without the use of nitrites. The methodology employed to address the research question will be detailed in Chapter 2 and will also provide a comprehensive account of the experimental approaches that were selected. A full overview of findings, including shelf-life testing results, sensory evaluations conducted through flavour panellists and a comparative analysis of production costs relative to traditional products, will be presented in Chapter 3. In Chapter 4, results will be thoroughly analysed, with a focus on the integration of nitrite-free products within food manufacturers and amongst consumers. The thesis will be concluded in Chapter 5, which will include a synthesis of the most significant discoveries and strategic proposals for future research and development.



Figure 2.1: Visual comparison of Nitrite-Free ham under Development vs. 2-Part Traditionally cured ham

As part of the research into investigating the development of cooked meat cured without nitrite as a preservative ingredient, alternative ingredients were utilised: Replacer 1, Replacer 2 and Replacer 3. These ingredients were selected to replace traditional nitrites and address specific challenges associated with flavor enhancement, color stability, and shelf-life extension. All three alternatives were integrated into a single formulation, each contributing distinct functions to achieve an effective replacement for traditional nitrites.

2.1.2 Scope

The scope of the research question encompasses a comprehensive investigation into the development of cooked meat cured without the use of nitrites as a preservative ingredient

to comply with imminent food safety legislation. The study incorporates an investigation of the effect of alternatives on the sensory attributes of meat, including flavour, texture, and colour, as well as the examination of consumer perception and acceptability of nitrite-free cured meat products. The scope of the study assesses the economic feasibility and practical implementation of innovative methods in the meat processing industry, while comparing their effectiveness to traditional nitrite-based techniques.

2.1.3 Data Inclusion

The research papers utilised in the study were obtained from both governmental and non-governmental sources and were subjected to peer review. They were collected from databases including Science Direct, Google Scholar, Elsevier, Springer Nature, and MDPI. Key words entered databases included “Traditional Curing”, “Nitrite and its role in cured meats”, “Nitrosamine formation”, “Health Aspect”, “Regulatory Standards”, “Consumer Perception”, “Alternative Ingredients” “Comparative Analysis”.

2.1.4 Data Exclusion

The study did not include data from studies that were not peer-reviewed. The study did not incorporate data that was not supported by evidence.

2.2 Materials

Three alternative replacement ingredients were utilised in the investigation into the development of cooked meat cured without nitrite as a preservative ingredient. All three alternative ingredients are combined in the product formulation to create a nitrite-free product that delivers the sensory attributes desired by consumers.

Replacer 1 is a formulation that combines natural flavors derived from fruit and spice extracts rich in polyphenols with ascorbic acid. This blend enhances the odour and flavor of nitrite-free meat products. The formulation creates a regenerative antioxidant system that stabilizes oxymyoglobin, preserving the natural red color of uncured meat and preventing browning caused by oxidative stress. Replacer 1 is free from nitrites with residual levels below detection limits and no nitrosamine formation. Used at 1% in whole muscle RTE meat products, it ensures desirable color and quality.

Replacer 2 is a series of fruit and spice extract blends, rich in natural polyphenols. These extracts safeguard the original sensory attributes of heat-treated meat products and support a bio preservative system. By preserving the meat's flavor, texture, and overall quality, its formulation upholds sensory excellence and extends shelf-life.

Replacer 3 is a phosphate alternative that enhances juiciness and natural yield in both fresh and cooked meat products. This unique blend of yeast and citrus extracts eliminates the need for phosphates by improving the natural binding capacity of meat. It works by opening the protein structure and counteracting rigor mortis, which increases the meat's surface area for better marinade absorption. It delivers exceptional juiciness and tenderness, prevents overcooking by retaining moisture during cooking, and improves meat binding. It also eliminates the soapy chemical flavors associated with phosphates and enhances the meat's savoury taste. The product has a faster brine pick-up compared to phosphates, with a recommended usage of 0.5 to 1.0%.

The ingredients were sourced from certified suppliers, ensuring high quality and effectiveness in the formulation and were incorporated into the formulation of a 2-part ham product through meat processing stages of brining, injection, tumbling, curing, cooking and cooling.

2.2.1 Study Range

The study range specifies the scope of analysis for meat products formulated without nitrites, focusing on two-part meat matrix of ham. It includes an exploration of the alternative ingredients, Replacer 1, Replacer 2, and Replacer 3, assessing their performance in replicating the characteristics of traditional nitrite-cured products in controlled processing conditions. The range encompasses the integration of alternative ingredients into formulation, the sensory evaluation criteria and shelf-life testing parameters.

2.2.2 Inclusions

The study includes a comprehensive analysis of meat formulated without nitrites, specifically focusing on 2-part meat matrix ham product. Key inclusions are the integration and evaluation of alternative ingredients: Replacer 1, Replacer 2 and Replacer 3. Controlled processing conditions, sensory evaluations, and shelf-life testing are included to assess the effectiveness of these alternatives in mimicking traditional nitrite-cured meat qualities. Additionally, all testing parameters related to quality and safety standards are incorporated within the scope of the research. The microbiological limits for shelf-life testing are detailed in Table X.X.X. This

table specifies the acceptable levels of microbial contamination that the products must meet to ensure safety and quality throughout their shelf life.

	Satisfactory cfu/g	Borderline cfu/g	Unsatisfactory cfu/g
TVC	<100,000	100,000 – 1,000,000	>1,000,000
E. Coli	<20	20-100	>100
Lactobacillus	Not Detected	N/A	Detected
Salmonella	Not Detected	N/A	Detected
Listeria species	Not Detected	N/A	Detected
Enterobacteriaceae	<100	100-10,000	>10,000
Clostridium perfringens	<10	10-10,000	>10,000
Coagulase-Positive Staphylococci	<20	20-10,000	>10,0000

Table 2.1: Microbiological limits for ready to eat foods as per FSAI Guidance Note 3 (Mulrooney, 2020)

2.2.3 Exclusions

The study did not include the use of synthetic preservatives or other chemical curing agents beyond nitrites, as the primary focus is on natural alternatives. The research also omits analyses of meat products that do not conform to the 2-part meat matrix structure, such as whole muscle meats.

Chapter Three

Results

The development of cured meat products devoid of nitrite as a preservative presents a formidable challenge, driven by the dual imperatives of ensuring robust preservation and safety, while simultaneously addressing escalating consumer apprehensions regarding nitrite consumption. Nitrites, which have been historically employed for their antimicrobial properties and for colour and flavour enhancement of cured meats, have been associated with potential health hazards through the formation of carcinogenic nitrosamines. A pressing need exists to uncover alternative preservation methods that maintain meat safety, uphold product integrity and satisfy evolving consumer preferences in accordance with upcoming regulation. A holistic strategy must be implemented to tackle this challenge, encompassing experimentation with alternative formulations, meticulous microbial testing, and thorough sensory evaluations. The information presented is derived from practical experience and data collected within a food industry context. This includes insights gained from hands-on work in product development, quality control, and sensory evaluation. The identities of the alternative ingredients utilized in the development of cooked meat cured without nitrite as a preservative ingredient remain confidential and cannot be disclosed due to ongoing work on this study. All three alternative ingredients are combined in the product formulation to create a nitrite-free product that delivers the sensory attributes desired by consumers.

3.1 Shelf-Life Testing

In conducting shelf-life testing, diverse process mechanisms were applied to gain an understanding on how variances affect overall product quality. This meticulous method enables the optimisation formulations and storage parameters, thereby guaranteeing that the product maintains quality and safety standards for the duration of its designated shelf life. Shelf-life results that are highlighted in green signify that the product has successfully passed, while those that are highlighted in amber indicate a borderline result. Results that are highlighted in red signal a failure. Shelf-life limits are delineated in Table 2.1. The corrective action is to conduct a comprehensive repeat series of laboratory tests if any results exceed the specified microbiological limits.

During the trials, 100 kg of meat was employed per batch, with each batch portioned into 80g packages, yielding 1,250 packs per trial. Product was packaged using MAP to assist in attaining a 24-day shelf-life. The 24-day period is aligned with the current manufacturing practices for

two-part Wiltshire cured sliced ham product. Unlike standard production processes, these trial samples were designated specifically for the Research & Development department. Prior to undergoing laboratory analysis and sensory evaluation, the samples were carefully stored under controlled chilled conditions of approximately 3°C. This careful storage ensured that the samples were kept in optimal conditions to accurately reflect their performance over time. Prior to testing, the integrity of the packaging was carefully assessed, focusing on factors such as sealing and overall appearance. Packs were sent to the laboratory for each test day in duplicates to ensure comprehensive and precise evaluation. The laboratory handles all product testing within the food business and is highly accredited, ensuring accurate analysis and consistent quality control. Shelf-life testing extended from Day 3 to Day 24, with a comprehensive suite of analyses performed to identify the factors that could lead to premature product failure. Due to the high cost of full-suite testing, it was conducted primarily at the end of the testing period. This approach is based on the rationale that if any issues were to arise, they would likely become evident towards the end of the product's shelf life.

	Day 5: 11/04/24	Day 10: 16/04/24	Day 15: 23/04/24	Day 20: 28/04/24	Day 22: 30/04/24	Day 24: 01/05/24 (2 days open)	Day 24: 01/05/24
TVC	12200	112000	7100000	31000000	236000000	20600000	27000000
Enteroc	<10	<10	<10	<10	<10	<10	<10
E.coli							<10
Salmonella							Not detected
Listeria							Not detected
Clostridium perfringens							<10
Staphylococci							<20

Table 3.1: Results of Shelf Life 1

Table 3.1 displays shelf-life results on a trial variant consisting of alternative ingredients: Replacer 1 and Replacer 3. Replacer 2 was deliberately omitted from this evaluation to assess its influence on product longevity. Product had borderline test results on day 10 for TVC and subsequently failed for TVC throughout the remainder of shelf-life test days.



Figure 3.1: Ham indicating spoilage after 24 Days of Shelf Life

After 24 days of shelf life, the nitrite-free ham displayed significant spoilage, including noticeable discoloration and off-odours, indicating inadequate preservation compared to traditionally cured ham

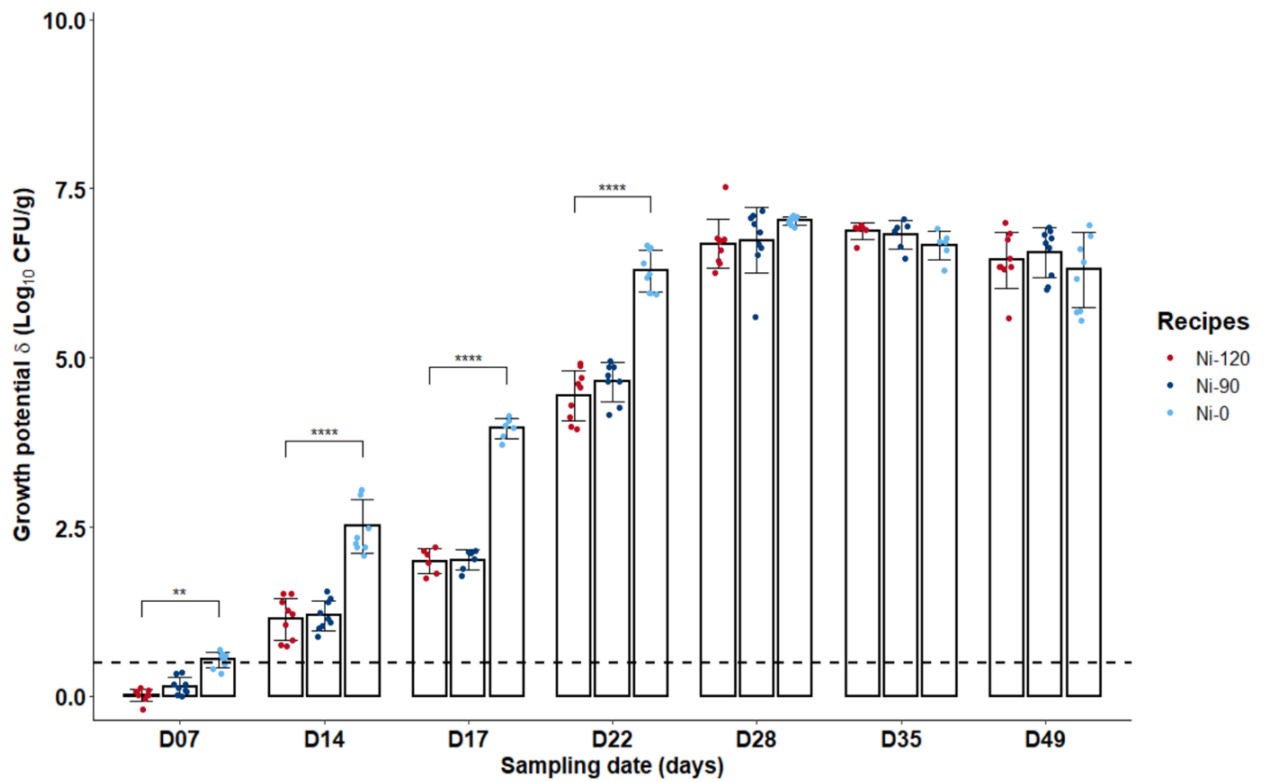


Figure 3.2: Growth potential of *Listeria monocytogenes* at various sampling times throughout the shelf-life of sliced cooked ham model products with different sodium nitrite concentrations (0 mg/kg vs. 90 or 120 mg/kg) (Guéraud *et al.*, 2023)

In a study conducted by Guéraud *et al.*, 2023 the impact of reducing, removing, or substituting sodium nitrite on microbiological growth in cured and cooked meat was evaluated. The results were illustrated using scatter plots with bars indicating the mean \pm SD (n = 3). Statistical significance was determined through an ANOVA test followed by pairwise comparisons using estimated marginal means, with significance levels denoted as **p \leq 0.01 and ****p \leq 0.0001. A dashed line on the plots indicates the threshold of 0.5 Log₁₀ CFU/g, above which the cooked ham model samples are susceptible to *L. monocytogenes* growth. Under the tested storage conditions, *L. monocytogenes* grew in sliced cooked ham with sodium nitrite up to 120 mg/kg, with levels exceeding 0.5 Log₁₀ CFU/g by day 14 across all three recipes. However, pathogen growth was significantly lower during the first 3 weeks in samples with 90 or 120 mg/kg of sodium nitrite compared to those with no nitrite (p \leq 0.01). There was no significant difference between 90 and 120 mg/kg nitrite (p > 0.05). Cooked meat without nitrite exhibited significant microbial growth (Guéraud *et al.*, 2023).

	Day 3: 11/04/24	Day 8: 16/04/24	Day 15: 23/04/24	Day 20: 28/04/24	Day 24: 02/05/24
TVC	<100	3600	278000	6100000	>300000000
Entero	<10	<10	<10	<10	<10
E.coli					<10
Salmonella					Not detected
Listeria					Not detected
Clostridium perfringens					<10
Staphylococci					<20

Table 3.2 Results of Shelf Life 2

Table 3.2 presents shelf-life results on a trial variant consisting of alternative ingredients: Replacer 1, Replacer 2 and Replacer 3. The Injection pattern during processing was altered to evaluate optimisation efforts aimed at enhancing product uniformity, flavour and tenderness and while minimising brine waste. Products created using the original injection pattern

exhibited patches of discoloration across several trials. To address this issue, the revised injection pattern illustrated in Figure 4.4 was implemented to determine if a more compact injection pattern could mitigate discoloration in the trial samples. The revised pattern increased the surface area available for injection, necessitating a reduction in the injection pressure to maintain a 15% injection rate. However, the decreased pressure resulted in incomplete distribution of the brine's ingredients throughout the meat, leading to heightened levels of discoloration. Product exhibited borderline test results on day 15 for TVC and subsequently failed for TVC on day 20 and 24 for shelf-life testing.

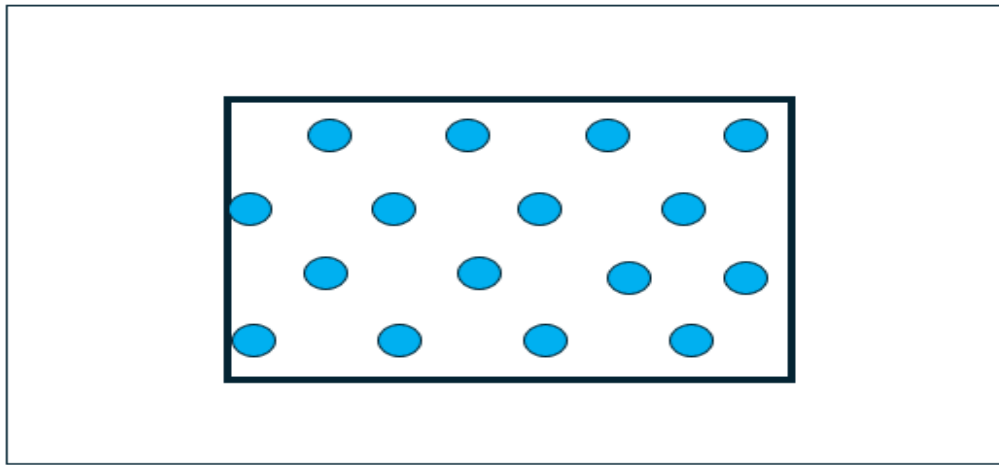


Figure 3.3: Original Injection Pattern implemented in Traditional Curing Methods

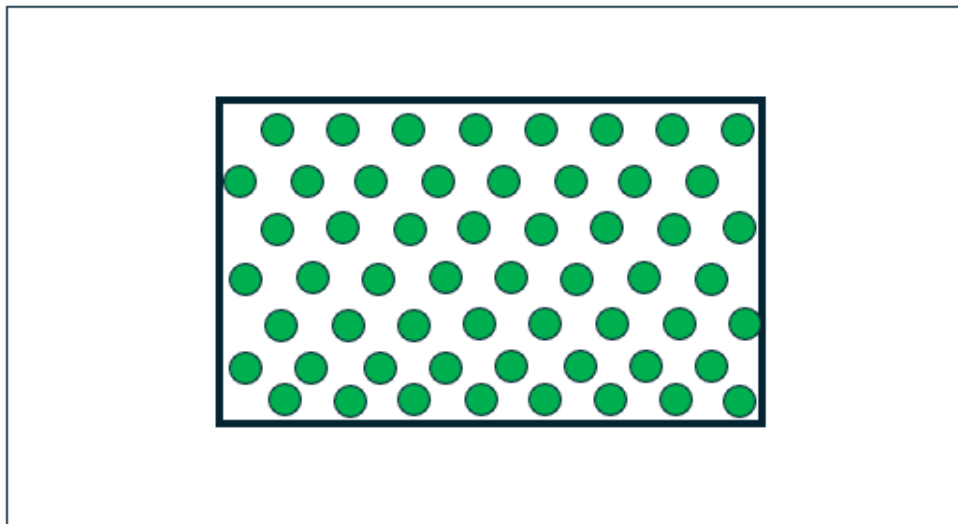


Figure 3.4: Revised Injection Pattern used in Trial 2

The revised pattern increased the surface area available for injection, necessitating a reduction in the injection pressure to maintain a 15% injection rate. However, the decreased pressure

resulted in incomplete distribution of the brine's ingredients throughout the meat, leading to heightened levels of discoloration.



Figure 3.5: Discoloration in Ham Resulting from Inadequate Brine Distribution Due to Revised Injection Pattern

In the results obtained by Shiroda et al. (2017), it was observed that *Salmonella*, capable of surviving in NaCl concentrations of up to 6%, exhibited an elevated risk in regions characterized by insufficient salt distribution (Shiroda *et al.*, 2014). Heir et al. (2010) found that Shiga-toxin-producing *E. coli* (STEC), which is sensitive to low water activity, exhibited an increased risk of outbreaks due to diminished pathogen control in areas with uneven curing (Heir *et al.*, 2010). In studies conducted by EFSA (2018), it was demonstrated that *Listeria monocytogenes*, a pathogen known for its ability to grow in NaCl concentrations as high as 10%, was able to proliferate in areas of the product where salt levels were inconsistent (EFSA, 2018). According to Peck and van Vliet (2016), uneven salt distribution can create anaerobic conditions in specific areas of the ham, which are ideal for the growth of *Clostridium botulinum*, a pathogen that produces botulism toxin (Peck and van Vliet, 2016).

	Day 5: 28/05/24	Day 10: 02/06/24	Day 15: 07/06/24	Day 20: 12/06/24	Day 22: 14/06/24	Day 24: 16/06/24 (2 days open)	Day 24: 16/06/24
TVC	200	200	16000	200000	650000	1300000	25000000
Entero	<10	<10	<10	<10	<10		<10
E.coli							<10
Salmonella							Not detected
Listeria							Not detected
Clostridium perfringens							<10
Staphylococci							<20

Table 3.3: Results of Shelf Life 3

Table 3.3 delineates shelf-life results on a trial variant incorporating alternative ingredients: Replacer 1, Replacer 2 and Replacer 3, with the efficiency of storage conditions and temperature control evaluated. The original injection pattern was reinstated, and product was stored in a repurposed blast-chill now functioning as a holding chill. Product exhibited borderline test results on day 20 and 22 for TVC and subsequently failed for TVC on the final day of shelf-life testing. At this stage, a comprehensive reassessment of the sample preparation methods is undertaken, prompted by the recurring failure to meet the specified shelf-life target of 24 days.



Figure 3.6: Paling in Ham resulting from incorrect storage conditions and temperature abuse

The image depicts paling in the ham, attributable to incorrect storage conditions. The improper storage led to uneven curing and color loss, resulting in a noticeable pale appearance

In a study conducted by Kreyenschmidt et al, 2010, aerobic plate counts of cooked cured ham increased substantially dependant on temperature storage conditions. At 25°C, aerobic plate counts exceeded 4 log CFU/g after 13 days. At 20°C, counts surpassed 4 log CFU/g after 13 days. At 15°C, counts exceeded 4 log CFU/g after 29 days (Kreyenschmidt *et al.*, 2010). Supporting these findings, Nieto et al, 2023, investigated the efficacy of natural ingredient combinations in controlling the growth of *Listeria monocytogenes* in cooked ham. The study demonstrated that storage at 4 °C significantly mitigated the proliferation of *Listeria monocytogenes* and other spoilage bacteria, achieving an extended shelf life of 17 weeks. This effectiveness is attributed to the use of antimicrobial agents such as natural citrus extracts, lemon, orange, grapefruit, and buffered dehydrated vinegar. Conversely, storage at 7 °C was less effective, leading to increased microbial growth and a reduced shelf life of 14 weeks (Nieto *et al.*, 2023).

	Day 5: 28/05/24	Day 10: 02/06/24	Day 15: 07/06/24	Day 20: 12/06/24	Day 22: 14/06/24	Day 24: 16/06/24 (2 days open)	Day 24: 16/06/24
TVC	1900	400	<100	700	1500	15400	100
Entero	<10	<10	<10	<10	<10	<10	<10
E.coli							<10
Salmonella							Not detected
Listeria							Not detected
Clostridium perfringens							<10
Staphylococci							<20

Table 3.4: Results of Shelf Life 4

Table 3.4 presents the shelf-life results for a trial variant that incorporated alternative ingredients—Replacer 1, Replacer 2, and Replacer 3. Following the reversion to the original injection pattern, storage under optimal conditions and additional salt, the product successfully achieved a shelf life of 24 days.



Figure 3.7: Comparison of Nitrite-Free Ham and Traditionally Cured Ham After 24 Days of Shelf Life

Following a 24-day shelf life, the nitrite-free product exhibited characteristics remarkably like those of traditionally cured ham. Despite the absence of nitrites, the nitrite-free ham demonstrated a comparable appearance, texture, and overall quality, demonstrating the alternative's efficacy in replicating the functional attributes of nitrite curing.

Several studies have explored the impact of salt concentration on microbial growth in meat products. Delgado-Pando et al, 2018, observed that lower salt levels in ham, 0.8% - 1.2%, led to increased numbers of lactic acid bacteria and total aerobic bacteria, indicating higher microbial growth (Delgado-Pando *et al.*, 2018). Fouguy et al, 2016, reported that reducing salt from 2.0% to 1.5% accelerated spoilage and promoted the growth of spoilage bacteria, although bacterial diversity decreased (Fouguy *et al.*, 2016). Additionally, Laranjo et al, 2017, found that in traditional Portuguese sausages, lower salt concentrations of 3% resulted in higher counts of mesophiles, staphylococci, and yeasts compared to sausages with higher salt of 6% (Laranjo *et al.*, 2017).

3.2 Sensory Evaluation

To guarantee consumer acceptance and product superiority, sensory evaluation is instrumental during the development of cooked meat products, quality control and standard shelf-life testing. The assessment of critical attributes such as appearance, texture, flavour and aroma, will assist in elevating the product's likelihood of success and aligning it with market preferences. Appearance is evaluated under standardized lighting conditions to assess color, uniformity, and visual defects. Texture is assessed through both sensory and instrumental methods with panellists rating attributes like firmness, tenderness and cohesiveness. Flavor is evaluated by tasting, with panellists rating attributes such as taste intensity and complexity and aroma is assessed by smelling the product under controlled conditions. A 1 to 5 scale was used to rate attributes: 1 is very poor, 2 is poor, 3 is average, 4 is good, and 5 is excellent. This scale assisted in standardizing the assessment, making it easier to evaluate and compare product qualities. A panel consisting of 8 to 12 individuals was used to secure results. Panellists involved in the study had experience in sensory evaluation from their work in the food industry and received specialized training to further refine their skills and ensure accurate assessments. Selection was based on their sensory sensitivity and consistency in detecting and articulating these attributes

For the execution of sensory analysis, insights into sensory profiles and consumer perception of nitrite-free versus existing products available within the UK retail market were assessed. Discrimination testing was designed to determine whether there was detectable difference between two or more samples, with a focus exclusively on identifying differences instead of attribute analysis.

	Appearance	Colour	Aroma	Texture	Flavour	Salt	Average
Consumer 1	5	5	5	4	4	4	4.5
Consumer 2	5	5	5	3	3	2	3.8
Consumer 3	5	5	5	5	5	5	5
Consumer 4	5	4	5	4	5	5	4.6
Consumer 5	5	5	4	1	3	4	3.6
Consumer 6	5	5	5	4	4	4	4.5

Consumer 7	5	4	4	4	3	2	3.6
Consumer 8	4	4	4	4	4	5	4.2
Consumer 9	4	4	4	4	2	3	3.5
Consumer 10	3	5	5	3	5	5	3.8

Table 3.5: Consumer Ratings of Sensory Attributes for Nitrite-Free Product

Table 3.5 presents the findings from a sensory evaluation of a newly developed nitrite-free product, assessed by a panel of ten consumers. The product under evaluation was safe for human consumption, having passed a 24-day shelf life and consisted of replacer 1, replacer 3 and replacer 3. Each sensory attribute was rated from very poor (1) to excellent (5), with average scores calculated accordingly.



Figure 3.8: Visual of Nitrite-Free Ham subjected to Sensory Evaluation

Figure 3.8 depicts the nitrite-free ham that was subjected to sensory evaluation as outlined in Table 3.5. The ham is shown in its final prepared state, highlighting its overall appearance and texture. The color is consistent with the evaluation results, with a smooth surface indicative of the sensory attributes assessed. The cross-sectional view provides insight into the internal texture, reflecting the product's quality as judged by the sensory panel.

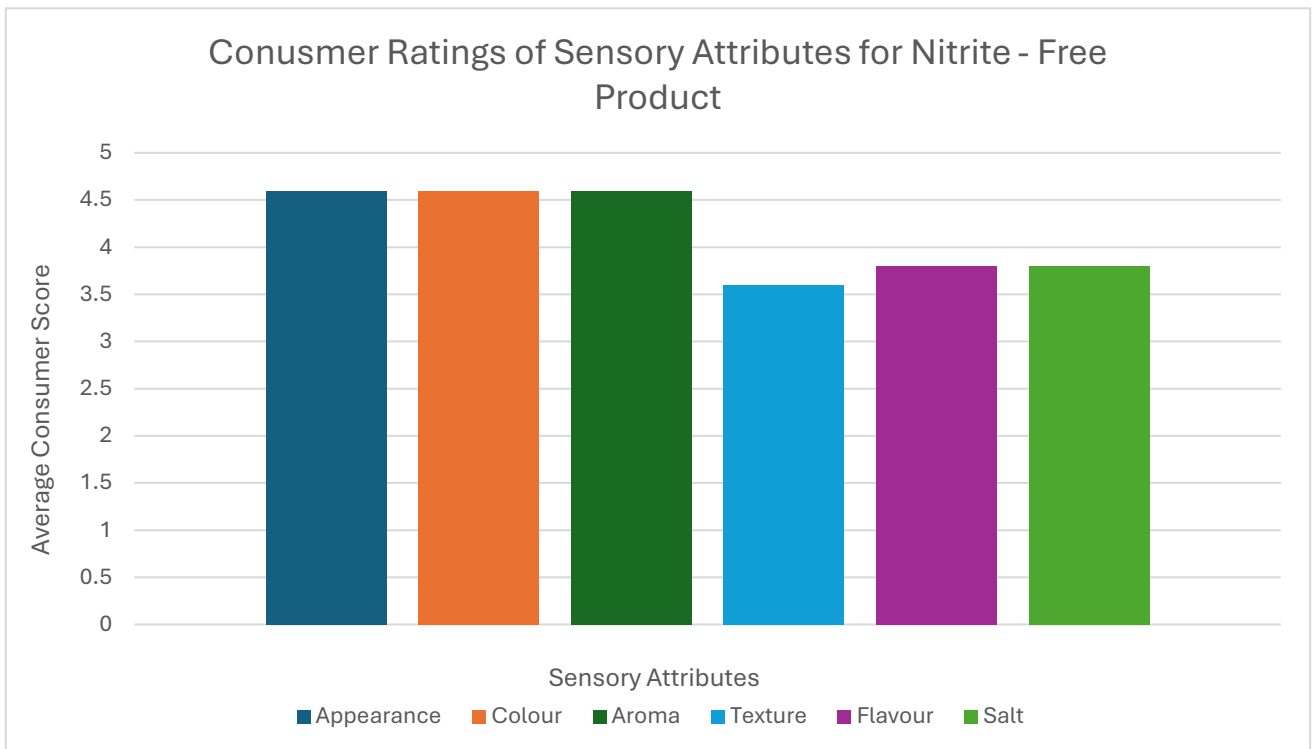


Figure 3.9: Bar Chart illustrating Consumer Ratings of Sensory Attributes for Nitrite-Free Product under development

Several studies have reviewed consumer perception on sensory qualities of meats eliminating synthetic nitrites and implementing natural alternatives. An investigation into the use of Swiss chard as a nitrite alternative in pork loins was conducted. The results indicated that an addition of 128.9ppm Swiss chard resulted in pork loins with no significant differences to the control (Kim *et al.*, 2019).

Jin *et al.* (2018) employed a range of natural ingredients, including celery powder, fruit extract powders, purple sweet potato powder, gardenia red, paprika, and blueberry powder, in the formulation of cooked sausages. Both descriptive sensory profiling and overall acceptability were assessed. The results indicated no significant sensory differences between the control sausages and those containing celery powder. However, the sausages featuring a blend of paprika and blueberry powders received significantly higher hedonic ratings (Jin *et al.*, 2018).

In a study conducted by Riel *et. al*, 2017, parsley extract was utilized in mortadella-type sausages to assess its impact on sensory attributes. The research involved descriptive sensory profiling and overall acceptability evaluations, with parsley extract added at concentrations corresponding to 60 and 120 ppm of nitrates. The findings revealed that sausages with these levels of parsley extract exhibited a color comparable to that of the control sausages and

achieved high overall acceptability. Notably, there were no reports of off-flavors associated with the parsley extract, indicating that it effectively maintained sensory quality while enhancing the product’s appeal (Riel *et al.*, 2017).

Vafania *et. al*, 2019, investigated the use of thyme essential oil nano encapsulated in chitosan-gelatine nanofibers in sausage formulations. Hedonic evaluations were conducted to assess the sensory attributes of the sausages, which included texture, color, odour, and flavor. The results demonstrated that sausages incorporating these nanofibers, along with 20 ppm nitrites and 400 ppm betaine, showed no significant differences in texture and color compared to the control sausages. Additionally, these sausages were preferred for their superior odour and flavor, indicating that the thyme essential oil nanoencapsulation enhanced the sensory qualities without adversely affecting the product’s appearance or texture (Vafania, Fathi and Soleimanian-Zad, 2019).

Product ID	Appearance	Texture	Flavour	Salt	Average
Nitrite free Ham	17.7	13.6	14.7	13.8	14.95
Tesco Finest Wiltshire Cured Ham	11.6	18.7	15.4	13.6	14.83
Sainsburys crumbed ham	12.6	14.4	12.4	14.4	13.45

Table 3.6: Results of Taste Panel - Nitrite-Free Variant versus Traditionally Cured Products available in the UK Market

Table 3.6 presents a sensory evaluation comparison of Nitrite-Free Ham under product development ham products against Traditionally Cured Ham Products available within the UK Market. Various attributes, Appearance, Texture, Flavour, and Salt were analysed and rated on a scale of 1-20 with their average scores calculated. A small standard deviation of 0.834 indicates that the ham products are rated quite similarly overall. The average scores for each product are close to the mean, reflecting a consensus on quality.

1)



2)



Figure 3.10 Visuals of Sensory Evaluation Products: 1) Nitrite-Free Ham 2) Tesco Finest Wiltshire Cured Ham 3) Sainsburys Crumbed Ham

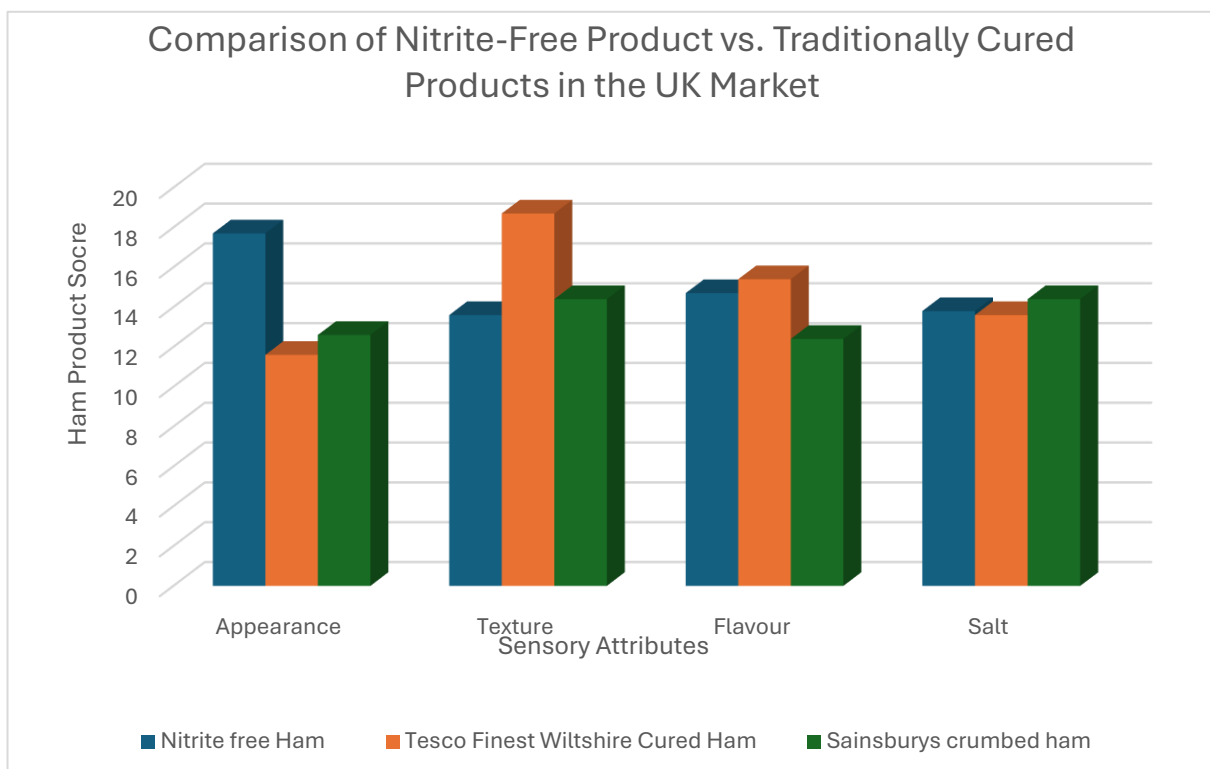


Figure 3.11: Bar Chart illustrating Consumer Ratings of Sensory Attributes for Nitrite-Free Product under development against Traditionally Cured Products available in the UK Market

The chart demonstrates that the nitrite-free ham attained the highest average rating of 14.95, exceeding the ratings for both Tesco Finest Wiltshire Cured Ham, 14.83, and Sainsbury's Crumbed Ham, 13.45. Nitrite-free ham distinguished itself in terms of Appearance and Flavour relative to the traditional products. Although it received a marginally lower rating for Texture, its superior overall average suggests it is perceived as a compelling alternative to traditional cured hams, excelling in appearance and flavour.

3.2.1 Discrimination Testing

Discrimination testing offers valuable insights into differentiation of products, a factor which is critical in the fine-tuning stages of product development and achieving acute product differentiation within the competitive market landscape. The Triangle Test sensory evaluation method was employed to discern whether detectable differences existed between two products. The test involved 41 participants who were presented with 3 samples, two of which were identical and one that was an odd sample. Samples were presented in randomized order to ensure validity and prevent any potential bias in the participants response.

ID	Product Variant
492	Lidl Thick Cut
173	Nitrite-Free
762	Nitrite-Free
Total Participants	41
Results	16 participants selected 492 and 25 selected 173 & 762 = 65% participants incorrectly identified the odd sample

Table 3.7 Results of Discrimination Testing

The discrimination test aimed to identify the odd sample among three product variants: Lidl Thick Cut (492) and two Nitrite-Free variants (173 and 762). Out of 41 participants, 16 correctly identified the Lidl Thick Cut as the odd sample, while 25 incorrectly selected one of

the Nitrite-Free variants. This resulted in a 65% incorrect identification rate, suggesting that a significant number of participants struggled to distinguish the odd sample.



Figure 3.12: Visual of Discrimination Testing with assigned product variant Identification Numbers

3.3 Cost Analysis

Product Description	Raw Mat.	Packaging	Ingred	Labour	Overhead	Total
Brady Family at the Deli Baked Ham 120g x 12	€0.70	€0.21	€0.03	€0.15	€0.09	€1.18
Nitrite Free Bearfields Family Delicatessen Honey 120g x 10	€0.70	€0.21	€0.12	€0.15	€0.09	€1.27
Difference	€0.00	€0.00	€0.09	€0.00	€0.00	€0.09

Table 3.8: Cost Analysis of Existing Brady Family Baked Ham vs. Nitrite-Free Ham

Table 3.8 provides a detailed cost analysis comparing existing product, Brady Family at the Deli Baked Ham 120g x 12, with new product, Nitrite Free Bearfields Family Delicatessen Honey 120g x 10. It outlines the expenses associated with raw materials, packaging, ingredients, labour, and overheads for each product, highlighting the variations in these cost components.

For this study, a comprehensive cost comparison was performed. The weekly production volume includes 1,080 cases, equivalent to 10,800 packs. This translates to approximately 1.5 tons of raw material per week, after accounting for an estimated yield loss of 15%. The weekly brine requirements consist of 225 kilograms for a 15% injection rate, plus an additional 160 kilograms for the injector setup, resulting in a total brine usage of 285 kilograms per week.

Calculation 4.2.1 Cost Comparison Analysis – Weekly & Annual Product Cost for Brady Family vs. Nitrite-Free Ham

Weekly Volume:

$$\text{Brady Family} = 10,800 \text{ packs} \times \text{€}1.18 = \text{€}12,744$$

$$\text{Nitrite Free} = 10,800 \text{ packs} \times \text{€}1.27 = \text{€}13,716$$

Annual Volume:

$$\text{Brady Family} = \text{€}12,744 \times 52 = \text{€}662,688$$

$$\text{Nitrite Free} = \text{€}13,716 \times 52 = \text{€}713,232$$

- Weekly additional cost of Nitrite-Free = €972
- Annual additional cost of Nitrite-Free = €50,544

Chapter Four

Discussion

The purpose and objective of the study was to investigate the development of cooked meat cured without nitrite as a preservative ingredient. Traditionally, nitrites have been utilized in meat curing to inhibit microbial growth and prolong shelf life; however, emerging scientific evidence has highlighted their potential carcinogenic risks, sparking health concerns among consumers and regulatory bodies. This study aimed to explore alternative preservation methods that can effectively substitute nitrites while ensuring the safety, quality, and longevity of the product. By evaluating range of curing formulations and their effects on microbial stability, flavor, and overall product performance, this research aims to advance nitrite-free curing technologies and offer insights into safer, natural preservation solutions that satisfy both consumer preferences and regulatory standards.

The study gave an overview on the cooked meats and curing process, outlining the complex stages of meat preparation, such as brine injection, tumbling, and the subsequent cooking and rapid chilling phases, elucidating the impact of each stage on the final product's desired attributes. The research investigated traditional curing methodologies, including dry and wet curing, and stressed their historical significance and efficacy in preservation. Furthermore, it delved into the innovative approach of non-conventional methods, such as vacuum tumbling, injection curing, and enzyme-enhanced curing. The review concluded that, despite the long-standing efficacy of traditional curing methods, non-traditional techniques offer attractive alternatives that can replace nitrite in the preservation of cooked ham whilst simultaneously addressing nitrite's health-risk association.

The pursuit of replicating the multitude of benefits of nitrite while mitigating its potential health risks is directly addressed through a comprehensive analysis of nitrites role in curing, encompassing its critical function in preservation and quality enhancement. As a formidable antimicrobial agent, nitrite effectively inhibits proliferation of pathogenic bacteria such as *Clostridium botulinum* and *Salmonella*. Additionally, nitrites antioxidant properties combat rancidity through the neutralization of free radicals. Contributing to food safety and product longevity, nitrites also play a role in product colour and flavour development. The mechanism by which nitrite reacts with myoglobin to produce nitroso myoglobin imparts meats vibrant hue while also enriching flavour through lipid oxidation suppression, render nitrites an indispensable component of meat preservation. This overview of nitrites accentuates the difficult challenge faced by R & D to effectively emulate nitrites significant role through alternatives, a difficulty that lies at the core of the investigation.

Amidst intensified scrutiny over nitrosamine formation, the meat industry grapples with mounting challenges and controversies. Driven by evolving dietary preferences and increased consumer awareness of nutrition and health, the place of pre-cooked meats within the modern diet is subject to examination. The IARC released evidence on N-nitrosamine compounds, generated during meat processing, and their association with an increased cancer risk, particularly gastric and colorectal cancer. Consequently, the investigation into the development of cooked meat cured without nitrite as a curing ingredient is a pertinent topic, causing the meat industry to refocus its R & D efforts to address these issues which are mirrored in the evolving legislative landscape across Europe. As of October 2025, new limits will be imposed throughout Europe, reducing the permissible levels of nitrate and nitrite in cured meats to 90 mg/kg and 80 mg/kg respectively (EU, 2023). The classification of cured meats into non-derogated and derogated products as well as the imposition of maximum permissible nitrite levels exemplifies the actions being taken to safeguard consumer well-being. Research corroborates that while current exposure levels are generally deemed safe, a recognized imperative remains to further diminish nitrite concentrations in food. A focus on health and regulatory adherence is pivotal to the research question with meeting these regulatory demands whilst reformulating products to meet desired attributes a critical aspect of R & D.

Nitrite-free products are well-positioned for launch, owing to the prevailing consumer preference for health, naturalness, and minimal processing. Consumers general gravitation towards 'free-from' offerings increases allurements towards nitrite-free. Although consumers seek health options, they also place high value on the cherished sensory attributes of conventional ham. Sensory analysis, as seen in the results chapter of this study, assesses texture, flavour, appearance and aroma and is a highly valuable approach providing consumer insight and guiding necessary formulation adjustments. Effective product development must adeptly address potential sensory disruptions to minimise consumer dissatisfaction, while simultaneously employing clean labels and transparent information to cultivate and sustain consumer loyalty and trust. Striking a balance between price and perceived value is essential, as consumers are prepared to invest more in health-oriented products but remain sensitive to pricing. Determining whether consumers are prepared to absorb the premium associated with nitrite-free products is a critical discussion for assessing the potential success of a nitrite-free product offering. The indicative costing conducted within this study illustrated the premium price-rate in comparison to Brady Family Traditional Ham.

With consumer preferences increasingly gravitating towards health-conscious alternatives, a thorough analysis of a nitrite-free offering within its emerging market is essential to assess the products development and feasibility. Market opportunities and gaps can be identified with insights facilitating a strategic approach when implementing product differentiation, pricing and market positioning. The global surge in meat consumption, driven by rapid population growth, has significantly elevated market dynamics. Europe's processed meats sector, a pivotal force in this expansion, is continually evolving and emerging as a leading player in the development of nitrite-free offerings. Ireland's impressive international outreach, ranking as 8th in Europe, signifies the remarkable achievement of such a relatively small nation in the global meat processing sector. France, the UK, Germany, and Denmark are pivotal components whose successes Irish market players should closely observe and imitate to establish a strong-presence within the competitive landscape of the nitrite-free market.

This research question is timely and essential considering prevailing trends in the processed meats industry, with the quest for alternative ingredients at an all-time high. Striving to adhere to regulatory standards whilst catering to consumer requests for transparency, natural plant extracts and organic acids are promising solutions, as supported by a body of research studies. Plant extracts such as celery powder and parsley extract are advantageous due to their effective preservative and antioxidant properties. Organic acids, including lactate, sorbate, acetate, and benzoate, exhibit substantial efficacy in lowering pH levels and curbing microbial proliferation. Similarly, essential oils and spices, such as oregano and garlic, offer remarkable antimicrobial benefits while enhancing the flavor and visual appeal of cured meats. Advanced processing techniques, including HPP and irradiation, are under investigation for their capacity to support meat safety and prolong shelf life, all while obviating the need for chemical preservatives. The use of cutting-edge innovations will not only contribute to safer meat products but will also support the industry's shift towards natural and sustainable practices. The transition towards alternatives for nitrites needs to be prioritized by government bodies and studies and viewed as a crucial element of societal responsibility to generate a healthier food-chain.

Shelf-life testing is a crucial facet of developing a nitrite-free product, serving a central role in verifying that the product upholds safety and quality standards throughout its entire lifespan. They are an appropriate method for obtaining precise estimates of the probability of microorganism growth, survival or inaction within the product (Iannetti *et al.*, 2017). Through

meticulous evaluation of the product's performance over time, this testing validated the efficacy of the diverse formulation methods employed during trials by ensuring that the product reliably meets expectations and preserves its intended quality and standards throughout its shelf life. This will assist in facilitating a successful market introduction as a new product.

Shelf-life prediction relies on various factors related to the product's composition, including pH, water activity, and salt content. Given the differences in composition across different products on the market, establishing a universal industry standard for pre-cooked ham is challenging. The shelf life of pre-cooked ham typically ranges from 10 to 23 days (Campden BRI, 2024). A 24-day target-range was determined by the current product packaging and was influenced by the shelf life of similar SKUs produced by competitors with comparable compositions. In terms of supply-chain logistics, the time between a product leaving the production facility and appearing on retail shelves can largely differ, potentially by up to 3 days. A product with a shorter shelf life could experience substantial deterioration by the time it reaches the retailer. Consumers typically prefer products with longer shelf lives for added convenience and reliability. Increased expiration rates in-store lead to reduced retail sales and elevated levels of waste with associated costs reverted to the manufacturer. These factors not only diminish profit margins but also introduce additional complexity to managing an efficient and cost-effective supply chain. The need for frequent restocking of short shelf-life products and the financial burden of high waste makes a 24-day shelf life increasingly desirable.

Shelf Life 1 consisted of a trial formulation with replacer 1 and 3 but excluded replacer 2 and exhibited borderline TVC results on day 10 with subsequent decline leading to unacceptable levels in following days. Intended to assess the influence of Replacer 2, the trial underscored its pivotal role in ensuring microbial stability and extending product longevity. The ham had evident signs of oxidation and bacterial growth as it was discoloured and had a slime-like texture. Upon opening the pack, a rancid odour was detected. The study conducted by Guéraud *et al.* (2023) investigated the influence of sodium nitrite on microbial proliferation. The results showed that *Listeria monocytogenes* grew extensively in nitrite-free cooked ham, surpassing the critical 0.5 Log₁₀ CFU/g threshold by day. Conversely, meats that contained sodium nitrite, even at lower concentrations of 90 mg/kg, exhibited a substantial decrease in pathogen levels during the initial three weeks ($p \leq 0.01$). Both studies coincide and have highlighted the critical role of sodium nitrite in the regulation of pathogens and the assurance of product safety, as its absence significantly enhances microbial proliferation (Guéraud *et al.*, 2023). Given the

substantial failures observed during initial trailing, the integrity of pack sealing emerged as an immediate concern. The integrity of the packs sealing was a vital test in the quality control process. An increase in oxygen levels within the pack can rapidly accelerate oxidative rancidity and lead to spoilage. All packs were subjected to MAP, with oxygen levels tested to ensure they remained below 1%, in adherence to factory standards. Conclusively, by conducting this procedure for every trial, any spoilage due to sealing issues could be effectively ruled out.

The results of Shelf-life 2 demonstrated the microbial effect of product following the alteration to the formulations brine injection pattern. The modified injection pattern was adjusted to evaluate improvements in product uniformity, flavor, and tenderness; however, an uneven distribution of the cure could potentially have been the cause of borderline TVC results on day 15 and subsequent failures on days 20 and 24. The revised injection pattern was designed to increase the surface area for brine infusion and potentially reduce discoloration. However, this new pattern required lowering the injection pressure to maintain a 15% injection rate. The reduced pressure compromised the effective distribution of the brine's ingredients, resulting in inadequate curing, which, paradoxically, exacerbated the problem of discoloration. The brine flow rate was increased while maintaining pressure within optimal levels. This elevated flow rate effectively ensured that brine reached all areas of the meat, achieving a more uniform distribution. The ham exhibited noticeable irregularities due to the uneven distribution of brine. This inconsistency was apparent in its texture and coloration with some areas of the ham showing a darker hue, while others remained pale. Findings have collectively found that inconsistencies in salt application can create localized environments where pathogens can persist with the EFSA highlighting that *Listeria monocytogenes* can thrive in areas with inconsistent salt levels, even in NaCl concentrations as high as 10% (EFSA, 2018). Similarly, Shiroda et al. found that *Salmonella* can survive in NaCl concentrations up to 6%. Incorporating nitrite at a concentration of 150 ppm into meat products effectively inhibits the growth of pathogenic microorganisms, such as *Clostridium botulinum* (Shiroda *et al.*, 2014). However, a lack of uniformity in salt application not only undermines effective microbial control but also fosters localized environments where the pathogen can proliferate, markedly heightening the risk of botulism contamination (Lopez *et al.*, 2021). To achieve even-distribution of vital ingredients within a unit, meticulous attention is required involving precise calibration of injection patterns and brining techniques, monitoring of processing variables such as time and temperature, and rigorous adherence to the recipe formulation.

Shelf-life 3 consisted of a trial variant that incorporated alternative ingredients Replacer 1, Replacer 2, and Replacer 3, which failed to meet the specified 24-day shelf-life target. The product, initially prepared with the original injection pattern and stored in a repurposed blast-chill unit now functioning as a holding chill, exhibited borderline TVC readings on days 20 and 22, and ultimately failed on the final day of testing. This outcome was surprising given the product reformulation factors seemed to be adequate. Upon examination, the ham exhibited a pallid and faded coloration, accompanied by a viscous, slimy texture. External factors were deemed to be at play. Despite seemingly sufficient storage conditions, the failure to meet the desired shelf-life can be attributed to certain factors regarding handling and environment management within the holding chill area. Optimal conditions were compromised due to the frequent use of the holding chill by personnel. Internal temperatures and humidity levels fluctuated because of movements and inconsistent door closures, jeopardizing product stability. Nieto et al, evaluated natural ingredient combinations for controlling *Listeria monocytogenes* in cooked ham. Their study found that storing the ham at 4 °C significantly reduced *Listeria monocytogenes* and other spoilage bacteria, extending shelf life to 17 weeks, thanks to antimicrobial agents like citrus extracts and buffered dehydrated vinegar. In contrast, storage at 7 °C was less effective, resulting in increased microbial growth and a shorter shelf life of 14 weeks (Nieto *et al.*, 2023). Concerns were raised that the chill chain might have been disrupted during transport from the site to the laboratory. To address this, samples were sent individually on each test day instead of in bulk. However, this change did not resolve the issue, and the product continued to fail early in its shelf life

Additionally, the potential for cross-contamination within a large manufacturing facility is highly likely. For trials that yielded failed results, samples were sliced and packed alongside other products during the production day. Consequently, there was a potential for compromised hygiene on the production line, possibly due to insufficient cleaning from previous batches. In a study conducted by Syne et. al, cross-contamination by *Listeria spp.* was observed during bacon sampling at a manufacturing site. Detected in multiple areas, including the pumped meat, the tumbler, and the slicing machine used for post-cooked items, it is plausible that *Listeria spp.* could have remained viable on post-cooking equipment and within the surrounding environment where favourable niches might have supported its persistence (Syne, Ramsubhag and Adesiyun, 2013). Subsequent trials were completed at the very beginning of the production day with intense cleaning applied to lines followed by quality pre-production audits.

Shelf-Life 4 represents a trial variant incorporating alternative ingredient; Replacer 1, Replacer 2, and Replacer 3. After reverting to the original injection pattern and applying additional salt while maintaining optimal storage conditions, the product achieved a successful shelf life of 24 days. Previous shelf-life challenges were overcome, demonstrating the critical contribution of added salt and replacer 2. The inclusion of extra salt likely enhanced preservation by suppressing microbial growth, while Replacer 2 significantly contributed to extending the product's shelf life, indicating its effectiveness in supporting product stability. The ham's appearance aligned closely with that of a traditionally cured product, achieving the intended goal of visual similarity. Studies have supported the effect of salt concentration on microbial growth in cooked meats with Delgado-Pando *et al.*, demonstrating that lower salt levels in ham at 0.8% - 1.2%, were associated with higher counts of lactic acid bacteria and total aerobic bacteria, indicating increased microbial growth (Delgado-Pando *et al.*, 2018). Similarly, Fougy *et al.*, reported that reducing salt from 2.0% to 1.5% accelerated spoilage and favoured the growth of spoilage bacteria, despite a decrease in bacterial diversity (Fougy *et al.*, 2016).

There is a mounting recognition of the need to reduce nitrate levels in meat, a concern that has been translated into EU legislation. The substantial impact of nitrates and nitrites on the sensory qualities of cured meats emphasises their crucial role and highlights the difficulties involved in finding suitable alternatives. A gap persists in comprehending the sensory characteristics and consumer acceptability of cured meats, attributable to shifting consumer preferences and ongoing advancements in food science, which have yet to be thoroughly explored in the existing literature. The systematic assessment of sensory attributes including taste, texture, appearance and aroma provided guidance for product development of the nitrite-free product. This approach facilitated refinement of processing formulations based on feedback and evaluation of consumer perception, enhancing optimization for market readiness and supporting overall acceptability.

The findings indicated in Table 3.5, presented the sensory evaluation carried out on the developed nitrite-free product with a successful 24-day shelf. Utilizing the same formulation as outlined in shelf-life 4, incorporating all three replacers and additional salt, the product was tested by a panel of ten participants. The product distinguished itself in appearance and color, achieving means of 4.6 and 4.7, respectively, with correspondingly low standard deviations of 0.5 and 0.4, suggesting a high level of consistent feedback. The evaluation of flavor, salt, and texture revealed significant variability. Both flavor and saltiness, with means of 4.0 and

standard deviations of 1.0 and 0.9, exhibited diverse consumer perceptions and potential inconsistencies in taste and seasoning. Texture, also averaging 4.0 but with a higher standard deviation of 1.1, underscores significant variability in consumer experience, with some finding the texture less satisfactory. The overall average score of 4.1, with a standard deviation of 0.7, reflects a generally favourable reception of the product, yet reveals significant variability in its sensory attributes. The evaluation highlighted both the potential and the limitations of the current formulation, pinpointing specific areas for enhancement including texture, flavour and overall acceptability. Studies have supported the sensory evaluation data of nitrite-free cooked ham while also highlighting areas where adjustments can be made, with high scores for appearance and color aligning with findings from Kim *et al.* (2019). The research demonstrated that natural alternatives, such as Swiss chard extract, can effectively maintain strong performance in these attributes, highlighting their potential to replicate the visual appeal of traditional nitrite-treated meat (Kim *et al.*, 2019). The variability in flavor and saltiness observed in the data is consistent with the findings of Jin *et al.*, 2018, which revealed that celery powder did not significantly affect flavor, whereas a blend of paprika and blueberry powders enhanced overall acceptability, highlighting the complexity of achieving a preferred as seen in the sensory evaluation results (Jin *et al.*, 2018).

The findings of the sensory evaluation seen in Table 3.6 demonstrate a striking contrast between the nitrite-free ham and its traditionally cured rivals in the UK market. The result of this evaluation is of particular importance with the nitrite-free product planned to retail within the UK market. The UK's sophisticated retail and distribution networks offer substantial visibility, laying a solid groundwork for future expansion into Europe. The Nitrite-Free Ham achieved the highest overall average score of 14.95, superseding both Tesco Finest Wiltshire Cured Ham of 14.83, and Sainsbury's Crumbed Ham of 13.45. This distinction is particularly significant considering the increasing consumer preference for healthier alternatives and the larger movement towards the reduction of synthetic additives in food products. The performance aligns with health-products gaining traction due to their ability to deliver sensory experiences that match or surpass those of traditional offerings. The results show how the offerings can effectively compete against all-ready established products with its favourable performance also displaying how it is suitable for market-launch. As the taste-panel was conducted in controlled workplace environment, the results may not fully reflect consumer preference within real-world conditions. The results do not capture the broader context of

aspects influencing consumer purchase-decisions including environmental influence such as packaging, product placement and promotional materials.

The findings of the discriminatory analysis, Triangle Test, as seen in Table 3.7, revealed that 65% of participants were unable to correctly identify the odd sample. Out of 41 participants, the study found that 16 correctly identified 492, Lidl Thick Cut, as the odd sample, while 25 participants mistakenly identified one of the nitrite-free variants, 173 or 762, as the odd sample. This result suggests that the nitrite-free products were not readily identifiable from the conventional cured product or from one another, thereby indicating that these alternatives are effectively replicating the functional properties of nitrite in meat curing. In addition to assessing packaging integrity, storage conditions, product appearance, and expiration dates were consistent to prevent any influence on the evaluation. Handling procedures and preparation methods were standardized, and the tasting environment was controlled to minimize external factors. A limitation to sensory analysis of nitrite-free meats is that a significant portion of research on newly developed cured meats with reduced or eliminated nitrate/nitrite levels has often neglected detailed sensory analysis. Most studies depend on conventional descriptive sensory profiling, often conducted by panels with insufficient or no specialized training. Overall, this result signifies Nitrite-free offerings potential to achieve strong consumer acceptance and build strong brand loyalty. The successful mimicking of nitrites critical function by alternatives represents a movement in food innovation, showcasing the potential for these alternatives to lead the way in both health-conscious consumer choices and industry practices.

Although the investment of visionary food businesses in nitrite-free offerings renders a sagacious and lucrative transition whilst underscoring a brands dedication to health, innovation and an expanding consumer demographic, it will also present considerable ramifications for financial and supply chain management. Due to the critical importance of deploying extensive R & D, procuring advanced technologies, recruiting specialised expertise, safeguarding the confidentiality of intellectual property, conducting market research and implementing comprehensive marketing strategies, innovation exerts significant costs and strain on businesses and their supply chain. Procuring nitrite-free alternative constituents within the supply chain requires a customised approach to address the unique challenges and demands of products, all while upholding rigorous sustainable practices. As the adoption of nitrite-free alternatives emphasises a commitment to ethical and sustainable stewardship, issues may arise

regarding the procurement of more expensive and rarer substitutes for conventional ingredients. This transition will require expansion and diversification of sourcing networks to incorporate these premium alternatives alongside the implementation of intricate contingency frameworks. Additionally, revisions to compliance procedures, stringent documentation and updated labelling and formulation approvals will be imperative to allow smooth integration and regulatory adherence.

R & D initiatives, including experimental trials, shelf-life evaluations and nutritional assessments is substantial, thereby amplifying production costs and impacting profit margins. Within operations, expenditure will rise due to the potential acquisition of new equipment, modification to manufacturing techniques and an implementation of strict quality control protocol. A thorough verification process is necessary to pre-empt potential issues and to ensure compliance with regulatory standards. To showcase exemplary quality and regulatory adherence, laboratory testing and certification validation are required, demanding significant investment. Relevant adjustments within the supply chain such as logistical modifications and establishment of new suppliers necessitate further investment. The successful product launch of nitrite-free ham is contingent upon strategic resource allocation, affecting both market presence and consumer acceptability. Leveraging target advertising, social media campaigns and in-store promotions enhance product visibility and amplify market reach. Initial hurdles include substantial marketing expenditures; however, prudent resource management can mitigate these costs over time, paving the way for sustained success. Effective strategies will not only cultivate brand loyalty but also drive sales.

Nitrite alternatives generally command a higher-price than traditional nitrites due to the utilisation of raw materials such as natural preservatives and plant-based substitutes, which are characterised by their limited availability and complex production processes. Cost can be further exacerbated by the complexity and advanced technology required for the manufacturing processes of these alternatives. As seen in Results Section 3, an indicative annual additional cost for producing Nitrite-free ham within a food manufacturer reflects a substantial financial impact, primarily attributable to the elevated expense associated with ingredients with an additional €0.09 per pack incurred. Brady Family ham was employed as a benchmark comparison, representing traditionally cured ham. On a weekly basis, the production cost of Brady Family ham 120g totals €12,744 for 10,800 packs, priced at €1.18 each, while the nitrite-free 120g alternative amounts to €13,716 with each pack priced at €1.27. This equates to an

incremental weekly production cost of €972 when manufacturing nitrite-free ham. Annually, this disparity becomes more pronounced, with the total cost for Brady Family ham amounting to €662,688 and the nitrite-free ham results in an annual cost of €713,232. The additional annual cost of €50,544 signifies the significant financial outlay associated with nitrite-free ham production. While the shift to nitrite-free alternatives is consonant with contemporary health and market trends, it is imperative for food businesses to rigorously assess the increased costs and strategically manage the supply chain, weighing these factors against the prospective advantages of long-term success.

In the evolving landscape of food choices, consumers are showing a notable readiness to bear higher costs for nitrite-free products. This trend is driven by an increasing awareness of health risks associated with nitrites in traditional curing. Consumer willingness to pay a premium for the more-expensive nitrite-free offering exists, reflective of a broader shift towards health and wellness. Retailing at €3.70 in France, consumers are prepared to absorb these additional expenses as part of their commitment to healthier eating and to support brands that align with values of transparency. Economies of scale are anticipated to reduce production costs as the market for nitrite-free alternatives expands. This trend is expected to result in these products becoming more affordable in the future, in addition to the increased competition and technological advancements.

Chapter Five

Future Work & Conclusions

5.1 Conclusion

The study investigated the development of cooked meat cured without nitrite as a preservative ingredient. As an essential part of the global food industry, the processed meats sector plays a pivotal role in shaping economic activities and influencing food supply chains on a worldwide scale. A particularly pertinent research topic due to consumer appetite for healthier alternatives and upcoming regulatory reforms, the transition towards nitrite-free meat curing has emerged as a prominent focus within the industry due to rising concerns regarding nitrites potential carcinogenic effect. Intensifying these concerns, consumers are increasingly shifting towards healthier dietary options, driving a growing demand for "clean label" products free from artificial or potentially harmful additives. This shift is further supported by proactive legislative reforms within the EU, targeting a reduction in permissible nitrate and nitrite levels in meat products.

Despite nitrites efficacy in ensuring microbial safety and enhancing sensory attributes the exploration of viable nitrite substitutes is necessary due to the significant health concerns that conventional nitrite-based curing techniques pose and in response to evolving dynamics. The investigation delved into innovative curing strategies, including the incorporation of plant-based extracts; Replacer 1, Replacer 2 and Replacer 3, into a two-part meat matrix formulation. The incorporation of the three replacers yielded remarkable outcomes upon reformulation, matching or even surpassing nitrite-cured products in terms of colour, flavour, texture and aroma, whilst achieving a 24-day shelf life. This demonstrated the efficacy of the alternative ingredients in replicating nitrites critical functions. Implementation of these replacers in the industry is strengthened by their impressive performance, which provides an optimistic path to healthier, nitrite-free meat products.

Economic factors play a crucial role in the shift towards nitrite-free curing methods with regulatory compliance imposing significant financial burden on food businesses. Investment into R& D, ingredient procurement, and advanced technologies is essential for the transition to nitrite-free curing methods. When establishing deadlines for businesses to comply with new regulations, governmental regulatory bodies must ensure realistic timeframes and acknowledge the economic pressures faced by the industry.

The alignment of nitrite-free products with personal health values and ethical considerations is a significant factor in its perception of superior value by many consumers. Nitrite-free meat

products are more expensive due to higher costs for natural preservatives, extensive R&D, smaller production volumes and increased regulatory compliance expenses. Nonetheless, consumers are willing to absorb these higher costs in their commitment to health and wellness.

A limitation that may hinder nitrite-free offerings adoption within the marketplace stems from a knowledge gap that affects multiple facets of the industry. Targeted education initiatives, regulatory support and collaborative partnerships are strategies that will assist in bridging this gap. The adoption of nitrite-free curing methods represents a pivotal shift in the evolution of the food industry. This development goes beyond simply replacing ingredients; it signifies a fundamental redefinition of industry standards that prioritizes environmental responsibility, consumer health, and transparency throughout the supply chain. The findings of this study highlight the significant promise of alternative curing methods and emphasize the need for ongoing research and innovation. These efforts have the potential to reshape policy frameworks, influence industry practices, and promote a healthier, more informed future for consumers worldwide.

5.2 Future Works

To develop nitrite-free meat curing, future research must focus on several critical areas. Continued exploration and refinement of these alternatives are essential for achieving widespread adoption and meeting both consumer expectations and regulatory standards in the evolving food landscape. Further research is imperative to thoroughly assess the effectiveness of alternative ingredients in replicating the critical function of nitrites in meat, given the relatively limited studies on this topic. In-depth analyses are required to gauge their impact on microbial safety and sensory characteristics. Rigorous shelf-life studies and nuanced sensory evaluations will be crucial in verifying that these substitutes uphold product integrity and quality throughout their intended shelf life.

Exploring more cost-effective production methods and ingredient sourcing is crucial for enhancing the economic viability of nitrite-free curing solutions. By optimizing formulations to reduce production costs without sacrificing quality, the industry can improve the affordability of these alternatives, thereby boosting consumer acceptance. Striking a balance between cost efficiency and product excellence will be essential for driving widespread adoption and ensuring that these innovative curing methods can effectively compete with traditional nitrite-based products.

The enhancement of consumer awareness can serve as a powerful tool for product development and its subsequent success post-launch. An informed consumer base plays a pivotal role in refining the research and development process by highlighting and addressing consumer preferences. This dynamic feedback loop will not only aid in the fine-tuning of product formulations but will also accelerate the evolution of nitrite-free curing technologies, ensuring that products align closely with consumer desires and market demands. Future research should encompass the environmental impacts of alternative curing methods compared to traditional nitrite-based techniques. This involves analysing ingredient sourcing, sustainability, and the carbon footprint associated with production. Such assessments are vital, as they align with the core values of health consciousness and sustainability that alternative curing methods aim to promote. Finally, a coordinated collaboration among researchers, industry stakeholders, and policymakers is crucial in ensuring that food manufacturers receive comprehensive guidance on meeting regulatory requirements and achieving successful market integration into the future.

Chapter Six

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