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NATURAL INHIBITORS IN SOUS VIDE COOKING - A CRITICAL REVIEW

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Abstract

Sous vide (SV), a culinary technique that involves vacuum sealing food and cooking it at precise temperatures, has been celebrated for improving food's texture, flavor, and nutritional content. Integrating natural inhibitors is a crucial strategy for enhancing food safety, shelf life, and health benefits by fighting microbial growth. This review examines the combined effects of SV and natural inhibitors on various food types, including meats, seafood, and vegetables. It highlights significant progress in food safety, with natural additives helping to reduce pathogen resistance and curb bacterial spread, thus improving the overall safety and sensory appeal of meals. Moreover, it discusses the challenges and opportunities in refining the use of natural inhibitors in SV cooking, such as achieving the right balance between flavor and microbial management. The adoption of SV varies globally, reflecting its adaptability in different culinary traditions. The review suggests future research avenues, like exploring new natural inhibitors, cooking conditions, and their effects on consumer health, emphasizing SV's role in modernizing cooking practices to meet demands for quality, and safety.

Key words*: culinary innovation, food safety, natural inhibitors, sensory quality, sous-vide.*

INTRODUCTION

In the evolving landscape of culinary innovation, SV cooking emerges as a paragon of modern culinary technique, blending the precision of scientific methods with the traditional artistry of cooking. This technique, denoted as "under vacuum" in French, entails vacuum-sealing food and cooking it in a water bath at carefully regulated temperatures, celebrated for its ability to maintain the food's integrity and amplify its flavors (Avató et al., 2022). Initially buoyed by the collaborative efforts of American and French chefs to enhance cooking consistency and quality, SV cooking has transitioned from a niche method in gourmet kitchens to a globally acknowledged culinary practice, marking a significant shift in food preparation approaches (Toon, 2018).

The hallmark of SV cooking lies in its distinctive temperature control and vacuum sealing method, offering unparalleled control over the texture, flavor, and nutritional value of food (Berdigaliuly et al., 2022; Song et al., 2023). This innovative cooking method enhances the sensory quality of culinary creations and introduces a novel way to incorporate natural inhibitors into food products, advancing food safety, extending shelf life, and improving nutritional content (Zakrzewski et al., 2023). The integration of natural inhibitors, such as oregano and citric acid, has shown potential in increasing the thermal sensitivity of bacteria in salmon (Dogruyol et al., 2020), while thyme and rosemary essential oils have showcased antimicrobial effects against *Listeria monocytogenes* in SV turkey and rainbow trout (Amoroso et al., 2019; Kačániová et al., 2021).

SV cooking's efficacy in preserving the nutritional and sensory qualities of food is robustly supported by literature. Its benefits extend to enhancing shelf life, a critical consideration in today's market that demands convenience without quality compromise. By

employing low-temperature cooking, SV prevents the degradation of vital nutrients and bioactive compounds, enhancing food product longevity (Czarnowska-Kujawska et al., 2023). Further studies, such as those by Kaya et al. (2022), underscore the method's role in inhibiting bacterial growth and extending the shelf life of various food products.

The incorporation of natural inhibitors in SV cooking not only enhances food safety by preventing microbial growth but also enriches food with health-beneficial compounds. This synergy between SV cooking and natural inhibitors meets modern consumer preferences for food products that deliver health benefits beyond basic nutrition. For instance, the use of sage has been shown to improve food's oxidative stability and sensory properties, highlighting the method's dual function (Çetinkaya, 2020; Onyeaka et al., 2022).

As the market landscape evolves, a noticeable shift towards food products reflecting health, sustainability, and convenience values is evident. SV cooking, especially when coupled with natural inhibitors, adeptly responds to this trend, offering solutions that cater to contemporary consumer needs. This method extends shelf life, ensures food safety, and enhances nutritional quality, heralding a new era in culinary practices and signifying a transformative shift towards food innovation (Toon, 2018; Pongsetkul et al., 2023).

The current literature and emerging trends provide comprehensive insights into optimizing cooking conditions and identifying new natural inhibitors, guiding innovative culinary practices that prioritize health and sustainability. This review delves into the complex interplay between SV cooking and natural inhibitors, highlighting their combined impact on food safety, nutrition, and sensory qualities, taking into account current studies, future outlook of the development of this novel technology.

MATERIALS AND METHODS

This review article employs a comprehensive literature survey aimed at elucidating the interplay between SV cooking techniques and the integration of natural inhibitors for enhancing food safety, nutritional quality, and sensory attributes. The methodology followed to compile and analyse the current body of knowledge in this domain involved several systematic steps outlined below.

An extensive literature search was conducted across multiple scientific databases, including Google Scholar, PubMed, ScienceDirect, and Wiley Online Library, to gather relevant research articles, reviews, and case studies published up to 2024. The search strategy incorporated a combination of keywords related to "sous vide cooking", "natural inhibitors", "food safety", "sensory quality", and "culinary innovation" among others.

The inclusion criteria for the selection of articles were:

- Peer-reviewed articles and reviews published in English.
- Studies that specifically address the use of SV cooking techniques and/or the incorporation of natural inhibitors (e.g., essential oils, grape seed extract, citric acid).
- Research that provides empirical data on the effects of SV cooking and natural inhibitors on the microbial safety, nutritional content, and sensory properties of food products.
- Articles that discuss the commercial application, consumer perception, and regulatory considerations of SV cooking with natural inhibitors.

Exclusion criteria eliminated studies that:

- Did not directly relate to SV cooking or the use of natural inhibitors.
- Lacked empirical data or provided insufficient detail on methodology and results.
- Were published in languages other than English without an available English translation.

Relevant information was extracted from each selected article, including the year of publication, authors, study objective, methodology (SV conditions, types of natural inhibitors used, food matrix involved), key findings, and conclusions. This data facilitated a comprehensive analysis of the state-of-the-art in SV cooking with natural inhibitors, focusing on their impact on food safety, shelf life, nutritional quality, and sensory attributes.

Special attention was given to studies that reported innovative applications of natural inhibitors in SV cooking, documented challenges in integrating these substances into culinary practices, or offered insights into

future research directions and commercial potential.

The extracted data were synthesized to highlight emerging trends, consensus, and discrepancies within the reviewed literature.

This methodology underscores our commitment to rigorously reviewing and interpreting current research on SV cooking and natural inhibitors, thereby offering valuable insights into innovative culinary practices that prioritize health, safety, and sustainability.

RESULTS AND DISCUSSIONS

Use of inhibitors in SV processing

Within the scope of sous SV cooking, the strategic incorporation of natural inhibitors, such as grape seed extract and a spectrum of essential oils including oregano, rosemary, coriander, laurel, and sage, embodies a holistic approach to culinary arts. This methodology not only prioritizes the enhancement of food safety by mitigating pathogen resilience and controlling microbial proliferation but also enriches the sensory profile of dishes, marrying the essence of natural flavours with the principles of modern culinary safety.

When coming to the essential oil impact of the SV processed matrix, several aspects have been addressed in different studies, targeting the bacterial growth, preservation, and shelf life (Table 1).

Table 1. Essential oils and inhibitors in SV cooking

Inhibitor	Matrix	Key Finding	Autor
Grape Seed Extract	Ground Beef	Reduced bacterial heat resistance; enhanced safety	Cosansu et al., 2019
Grape Seed Extract	Doner Kebabs	0,5-1% addition lead to reduced bacterial heat resistance, energy conservation and enhanced quality	Haskaraca et al., 2019
Grape Seed Extract	Fresh Strawberries	1% addition lead to shelf life of up to 30 days	Duran et al., 2016
Grape Seed Extract	Roasted Chicken	0.2-1% addition lead to lower bacterial count on treated meat	Guo et al., 2020
Grape Seed Extract (GSE)	Refrigerated salmon	0,8% addition lowered *Pseudomonas spp*. on the 7th day of storage compared to control without GSE	Alves et al., 2018
Oregano Essential Oil	Potatoes	Controlled bacterial growth; enhanced flavor and shelf life	Zavadlav et al., 2020
Rosemary Essential Oil	Fresh cut Potatoe	Positive effect on texture, and limited the growth of mesophilic bacteria and *Enterobacteriaceae* over the storage period	Rizzo et al., 2018
Rosemary Essential Oil	Tilapia	Effective in preservation and extending shelf life	Zavadlav et al., 2020
Rosemary Essential Oil	Cook-Chill Beef	Reduction and antimicrobial effect against *L. monocytogenes*, extended shelf life	Gouveia et al., 2017
Coriander Essential Oil	Rainbow Trout	Effective against *L. monocytogenes*	Öztürk et al., 2021
Coriander Seed Extract	Ground lamb	The appearance, odor, and overall acceptability were better than the control, and reduction of *L. innocua*	Omidi-Mirzaei et al., 2021
Laurel Essential Oil	Rainbow Trout	Effective in vitro against *L. monocytogenes*	Öztürk et al., 2021
Laurel Essential Oil	Sea Bass	Extended the shelf life and enhanced flavor profile	Abouel-Yazeed et al., 2015
Laurel Essential Oil	European Sea Bass	Extended shelf life but there was a diminishing in quality	Bolat et al., 2019
Sage Essential Oil	Cooked Fish Fillet	Extended shelf life, decreased lipid oxidation	Çetinkaya et al., 2020
Sage Essential Oil	Beef Tenderloin	Suggested reduction in *L. monocytogenes* survival	Gál et al., 2023
Citric Acid	Mediterranean Mussels	Enhanced microbiological quality, reduced spoilage and lipid oxidation	Russo et al., 2023
Lime Juice	Chicken Breast	It prevented pink discoloration for up to 14 days	Hong et al., 2016

Studies like those of Cosansu et al. (2019) highlight the significant improvement in food safety these natural inhibitors bring, effectively reducing the heat resistance of pathogens and controlling bacterial growth, thereby extending the shelf life of perishable items like seafood. However, this approach is not without challenges; precisely calibrating the amount of each inhibitor to avoid overwhelming the natural flavours of the food can be a delicate balance. Overuse might lead to overpowering flavours or even ineffective pathogen control, and the cost or availability of high-quality natural additives could pose practical challenges, especially in commercial settings.

Plant extracts

In the field of food safety, the usage of ***grape seed extract*** (GSE) in ground beef offers significant advancements by markedly diminishing the heat resistance of *C. perfringens*, thereby enhancing food safety standards. Cosansu et al. (2019) highlight GSE's effectiveness, illustrating its role in substantially reducing pathogen survival rates during SV processing. This underscores GSE's potential as a formidable natural additive for augmenting both the quality and safety of SV meats. Complementarily, Haskaraca et al. (2019) further validate GSE's utility by demonstrating its impact when added at

concentrations of 0.5-1% to vacuum-packaged, cook-in-bag döner kebabs. This inclusion notably heightens the heat sensitivity of *L. monocytogenes*, with Weibull model analysis revealing an increased susceptibility of the pathogen to thermal processing (Duru et al., 2020). Such insights present GSE as an efficacious measure for the food industry to heighten SV processed döner kebabs' safety against *L. monocytogenes*, thus assuring consumer safety, maintaining product integrity, and contributing towards energy efficiency.

The implications of leveraging GSE within SV culinary methods are particularly pronounced in commercial contexts, where ensuring food safety is paramount. The natural origin of GSE aligns seamlessly with the growing consumer predilection for clean-label ingredients, positioning it as an invaluable asset to the SV cooking process (Weslie et al., 2021). By integrating GSE, not only does it bolster food safety mechanisms, but it also resonates with consumer demands for natural and safe food solutions, thereby enhancing the appeal and acceptance of SV cooking methodologies in the broader food industry landscape.

Adding to the significance of GSE in food safety, recent studies have extended its application beyond meat products. The utilization of antimicrobial agents such as nisin, natamycin, pomegranate, and GSE in chitosan coatings has proven effective in extending the shelf life of fresh strawberries by preserving their quality and inhibiting microbial growth (Duran et al., 2016). Similarly, the development of chitosan films with GSE and carvacrol microcapsules has demonstrated positive effects on the shelf life of refrigerated salmon by maintaining quality parameters and reducing microbial counts, indicating the broad applicability of GSE across different food sectors (Alves et al., 2018). Furthermore, a study on roasted chicken has shown that a 0.5% GSE solution, combined with modified atmosphere packaging, significantly reduces microbial growth and lipid oxidation, thereby extending shelf life and maintaining product quality (Guo et al., 2020).

These findings collectively highlight the potential of GSE as a versatile and effective natural preservative that can be adapted across various food processing methods to ensure food safety and extend shelf life, aligning with consumer preferences for cleaner label products. The integration of GSE into food safety protocols across different food categories not only underscores its efficacy in enhancing food quality but also its importance in advancing food preservation technologies to meet evolving consumer demands and industry standards.

Essential oils

Rizzo et al., (2018) conducted a study that demonstrated the efficacy of integrating 0.5% ***rosemary essential oil*** in SV cooking (105°C for 15 min) in preserving the nutritional profile of potato slices during storage. Their findings highlighted a notable increment in the ascorbic acid content (4.3 mg/100 g) by the eleventh day, alongside a decrease in total phenolic content (TPC) by 11.53% and antioxidant activity by 48%. In a subsequent investigation, Rizzo et al. (2018) explored the impact of SV cooking (121°C for 30 min) with the addition of 0.5% rosemary essential oil (REO) on the quality of fresh-cut potatoes over storage. This study observed a significant reduction in ascorbic acid levels by 77% on the eleventh day compared to the initial values, with total phenolics and antioxidant activity experiencing around a 35% decline. The research attributed these effects to the presence of monoterpenic hydrocarbons, oxygenated monoterpenes, and sesquiterpene hydrocarbons in REO, known for their antioxidant and antimicrobial properties, thereby aiding in the maintenance of quality during storage.

Rosemary essential oil's application in tilapia has demonstrated efficacy in both preserving and extending the shelf life of the fillets, as evidenced by Zavadlav et al. (2020). This dual benefit of preservation and flavor enhancement is particularly valuable for seafood, making rosemary oil a distinctive choice for food preservation. Moreover, the utilization of REO in SV fish preparation can offer significant advantages to the seafood industry, serving as a natural and flavor-enhancing method to prolong shelf life and maintain quality. In addition to its use in tilapia, rosemary's broad-spectrum antimicrobial effects, especially against *L. monocytogenes*, have been substantiated in beef processed through SV cook-chill (SVCC) technology. Gouveia et al. (2017) noted that

rosemary essential oil, at its minimum inhibitory concentration, achieved a notable additional 2-log10 reduction in *L. monocytogenes* populations over 14 days at both 2°C and 8°C, compared to controls. This highlights rosemary's potential as a natural preservative, emphasizing the importance of adequate chilling storage to mitigate consumer risk.

The implications of incorporating rosemary essential oil in SV fish preparation extend considerably within the food industry. Its application is not only advantageous for seafood but also shows promise in enhancing food safety and shelf life across various segments of the food industry, given its efficacy against pathogens like *L. monocytogenes*. The findings from the study by Gouveia et al. (2017) further support the potential of rosemary essential oil as a formidable antimicrobial agent, indicating its broad applicability in improving food safety and shelf life. The ability of rosemary oil to significantly diminish pathogen populations while concurrently enhancing flavor offers a dual advantage, positioning rosemary essential oil as a valuable asset in the food processing and preservation toolkit of the seafood industry.

Further emphasizing the utility of essential oils in SV processing, Gal et al. (2023) demonstrated that incorporating 0.5% (*w*/*v*) REO into fresh-cut sliced potatoes significantly curbed the proliferation of mesophilic bacteria and *Enterobacteriaceae*. This addition not only improved sensory attributes, such as sour and floury tastes, but also stabilized the hue value over 12 days of storage, effectively preventing browning and preserving visual appeal (Luo et al., 2019).

The application of ***oregano essential oil*** (OEO) has been identified as an effective measure to control bacterial growth in minimally processed potatoes prepared via SV, highlighting its efficacy in enhancing food safety and flavor (Zavadlav et al., 2020).

The broader application of OEO in SV cooking merges food safety with sensory enhancement, showcasing its natural antibacterial properties and aromatic profile to elevate the appeal and quality of SV vegetables. This integration aligns with increasing consumer preference for clean, safe, and flavorful food options, marking essential oils as key contributors to the advancement of SV culinary practices.

Coriander essential oil's (CEO) application to ground lamb showcased its efficacy in curbing *Listeria innocua*, as revealed by da by Omidi-Mirzaei et al. (2021), underscoring its potential as a potent natural antimicrobial agent suitable for SV cooking. The study conducted delved into the preservative effects of CEO on ground lamb mutton. This investigation highlighted that CEO significantly impacts pH levels, moisture content, colour indices, and sensory attributes of lamb mutton inoculated with *Listeria innocua* over an 8-day storage period across different temperatures. Remarkably, the essential oil maintained the meat's quality attributes, particularly at lower temperatures, demonstrating enhanced pH stability, moisture retention, colour preservation, and sensory appeal compared to control samples. These outcomes indicate CEO's capability as an efficient natural preservative, capable of extending the shelf life and preserving the quality of lamb mutton under suitable storage conditions, thereby affirming its value in the food industry for improving the safety and quality of meat products through natural methodologies.

The effectiveness of CEO in combating *L. monocytogenes* emphasizes the critical role of essential oils in bolstering the microbiological safety of SV products, especially pertinent for fish, where pathogen control is imperative. The findings from Omidi-Mirzaei et al. (2021) lend further support to the viability of CEO as a formidable antimicrobial agent, notably against *L. monocytogenes*, in SV cook-chill beef products. This suggests that the antimicrobial efficacy of CEO transcends fish, extending to other SV processed foods, indicating its widespread applicability in enhancing food safety and shelf life. The capability of CEO to significantly reduce pathogen populations while also enhancing flavor presents a dual advantage, positioning CEO as a valuable asset in the food industry's arsenal for processing and preservation.

The utilization of ***laurel essential oil*** (LEO) in rainbow trout has demonstrated promising antimicrobial properties against *L. monocytogenes*, showcasing its potential as a natural inhibitor for enhancing both safety and

flavor in SV cooking methods. The study conducted by da Silva et al. (2017) effectively highlights LEO's efficacy in vitro, positioning it as a valuable natural antimicrobial agent. This finding is complemented by the work of Abouel-Yazeedv et al. (2015), which explores the use of natural preservatives, including LEO, in extending the shelf-life of sea bass during cooled storage, underscoring the potential for natural preservatives in seafood preservation.

Bolat et al. (2019) investigated the effects of LEO on microbiological, chemical, and sensory changes in vacuum-packed SV European sea bass under chilled conditions. Their findings further validate the efficacy of LEO as a natural preservative, highlighting its ability to mitigate microbial growth and enhance the sensory attributes of SV seafood.

These studies collectively underscore the significance of LEO in the culinary and safety aspects of SV cooking, offering a natural solution to food safety concerns. By integrating LEO, the food industry can address modern consumer preferences for natural ingredients and traditional culinary techniques, enhancing the microbiological safety and overall quality of SV products, particularly in seafood, where pathogen control is paramount.

Sage essential oil's (SEO) application to beef tenderloin, as explored by Gal et al. (2023), has shown significant promise in reducing the survival of *L. monocytogenes*, highlighting its potential as a natural additive for enhancing meat safety through SV cooking. This aligns with further research by Çetinkaya (2020), which demonstrated sage's (*Salvia officinalis*, Linnaeus 1753) application to SV-cooked fish fillets, revealing significant antioxidant effects without compromising the nutritional and sensory properties of the fish. Sage essential oil not only maintained the fillets' quality by mitigating spoilage and lipid oxidation but also extended their shelf life and sensory acceptability by at least five days. These observations underscore sage's role as an effective natural antioxidant in SV-processed foods, providing a beneficial approach for food preservation that safeguards both sensory and nutritional values.

Moreover, the effectiveness of sage essential oil in combating *Salmonella enterica* during beef SV storage (Gál et al., 2023) and the impact of thyme essential oil in improving the quality and microbial safety of fresh-cut potatoes (Sarengaowa et al., 2023) underscore the wide-ranging benefits of essential oils in ensuring food safety while enriching sensory experiences in SV cooking.

Drawing upon the research by Gál et al. (2023), a case study highlights the use of sage essential oil as a natural inhibitor during the SV cooking of beef tenderloin. The study demonstrated sage essential oil's capacity to reduce the survival of *L. monocytogenes*, thereby enhancing meat safety. Furthermore, the addition of sage not only contributed to microbial safety but also improved the oxidative stability and sensory properties of the beef tenderloin, indicating an increase in shelf life and consumer appeal. This example illustrates the dual benefits of using natural inhibitors in SV cooking: ensuring food safety and enriching sensory quality, making it an attractive option for the meat industry.

The broader implications of SEO's effectiveness in reducing pathogen survival, particularly in beef tenderloin, point towards a promising avenue for natural food safety solutions within meat processing. Especially relevant for SV cooking, where the equilibrium between flavor and safety is crucial, SEO offers a natural method to address food safety concerns. This is particularly pertinent given the findings of Ismail et al. (2019), which suggest sage essential oil's potential in not only safeguarding against pathogens like *L. monocytogenes* but also in enhancing the overall quality of meat products through its antioxidant properties. Consequently, SEO emerges as a valuable asset for the food industry, advocating for its integration into meat processing and preservation strategies to achieve a balance of flavor, safety, and nutritional integrity.

In SV cooking, the strategic use of natural inhibitors and essential oils such as grape seed extract, oregano, rosemary, coriander, laurel, and sage essential oils, as well as citric acid, demonstrates significant synergistic effects. These combinations not only enhance the sensory qualities of foods like ground beef, potatoes, tilapia, and rainbow trout but also markedly improve food safety and extend shelf life. Studies by Cosansu et al. (2019), Zavadlav

et al. (2020), da Silva et al. (2017), Ismail et al. (2019), and Russo et al. (2023) highlight these effects, showcasing how these inhibitors work in tandem to reduce bacterial resistance, control microbial growth, and impart nuanced flavours. The interplay between these natural additives and the food matrices creates products that are not only safe and longer-lasting but also more enjoyable in terms of taste, aligning with contemporary culinary trends towards natural, clean-label ingredients.

Organic acids

Russo et al. (2023) conducted an insightful study on the SV cooking of Mediterranean mussels (*Mytilus galloprovincialis*), where citric acid was used as a natural inhibitor. This approach not only aimed at ensuring food safety but also at assessing the quality of the mussels post-cooking. The findings revealed that incorporating citric acid into the SV cooking process significantly reduced spoilage and lipid oxidation, thereby enhancing the microbiological quality of the mussels. This case exemplifies how SV cooking, when coupled with citric acid, can serve as a powerful tool to maintain and even improve the quality of seafood, promoting a healthier and safer consumption experience.

Building on the innovative work of Russo et al. (2023), the study by Hong et al. (2016) further explores the realm of natural food preservation techniques, specifically focusing on the SV cooking of chicken. In this study, lime juice and citric acid were evaluated for their effectiveness in preventing pink discoloration and inhibiting bacterial growth in SV-cooked chicken breasts. The results demonstrated that both lime juice and citric acid effectively reduced pH levels, pink discoloration, lipid oxidation, and expressible drip while also enhancing microbiological safety without negatively impacting sensory qualities. These findings underscore the potential of natural additives like lime juice and citric acid in improving food safety and quality, aligning with consumer preferences for natural ingredients.

The convergence of findings from Russo et al. (2023) and Hong et al. (2016) illustrates a broader trend towards leveraging natural inhibitors to address food quality and safety challenges in different culinary contexts. This body of research validates the notion that natural additives can be successfully integrated into modern cooking techniques like SV cooking to deliver enhanced food quality, extend shelf life, and ensure safety, without compromising sensory characteristics. Thus, these studies collectively contribute valuable insights into the development of healthier, safer, and more sustainable food processing methods, emphasizing the importance of natural preservatives in the culinary and food science fields.

Generally, the experiments involved the use of only one natural inhibitor, and big source for exploration is given by the use of inhibitors'mixture. A ground-breaking study by Abouel-Yazeed et al. (2015) explored the effectiveness of using natural preservatives such as laurel and other botanical extracts to control the shelf-life of sea bass (*Dicentrarchus labrax*) during refrigerated storage. This investigation highlighted the synergistic potential of combining SV cooking with natural preservatives to not only extend the shelf life of seafood but also to enhance its flavor profile. By incorporating laurel essential oil in the SV packaging, the sea bass demonstrated significant improvements in microbiological stability and sensory attributes, including taste and aroma. This case study underscores the commercial viability of integrating natural preservatives in SV cooking processes, offering a sustainable method to preserve seafood with added flavor benefits.

Future research directions

The search for new natural inhibitors that can be integrated into SV cooking processes remains a promising area of research. With an ever-growing database of plant-based compounds exhibiting antimicrobial and antioxidant properties, future studies should focus on evaluating the efficacy of less common herbs, spices, and plant extracts. Research akin to the studies by Kačániová et al. (2021) and Gál et al. (2023) could expand to explore the potential of underutilized botanicals in enhancing food safety, sensory qualities, and nutritional value of SV-cooked foods.

Given the diversity of food types and their unique characteristics, there's a significant need to optimize SV cooking parameters (e.g.,

temperature, time, vacuum level) for different food matrices. Future research could build on the foundational work by Czarnowska-Kujawska et al. (2023) and Pongsetkul et al. (2023), investigating how varying SV conditions affect the interaction between food products and natural inhibitors, particularly focusing on the retention of nutritional and sensory attributes.

While the immediate benefits of SV cooking with natural inhibitors on food safety and quality are well documented, there's a gap in understanding the long-term health impacts of consuming such foods. Future studies should aim to assess the cumulative effects of regular consumption of SV-cooked foods with natural inhibitors on human health, similar to the perspective offered by Onyeaka et al. (2022). This research could provide critical insights into the dietary benefits or potential risks associated with these culinary practices.

Technological advancements in SV cooking equipment could further enhance the efficacy of natural inhibitors. Future research could explore the development of specialized SV devices that can better regulate the diffusion of natural inhibitors into the food matrix, ensuring uniform flavor and safety profiles. Studies focusing on equipment innovation, akin to the investigation of cooking conditions by Luo et al. (2019), could lead to more precise and efficient SV cooking methodologies.

The integration of natural inhibitors in SV cooking also presents an opportunity to investigate the economic and environmental sustainability of this culinary technique. Future research, building on the life cycle assessment model discussed by Avató et al. (2022), should explore the cost-effectiveness and ecological impact of sourcing and applying natural inhibitors in commercial SV cooking. This includes assessing the carbon footprint of producing these inhibitors and evaluating their role in reducing food waste through extended shelf life and improved safety.

Understanding consumer acceptance and market trends is crucial for the successful commercialization of SV cooking with natural inhibitors. Future studies should delve into consumer perceptions of SV-cooked foods enhanced with natural inhibitors, exploring preferences, willingness to pay, and perceived health benefits. This line of inquiry could follow the model of market landscape evaluations by Toon (2018), focusing specifically on how natural inhibitors influence consumer choices and acceptance in different culinary cultures.

The outlined future research directions aim to address the gaps in current knowledge and explore new horizons in the field of SV cooking with natural inhibitors. By focusing on these areas, researchers can contribute to the development of innovative culinary practices that prioritize health, sustainability, and sensory enjoyment. Collaboration between food scientists, chefs, and industry stakeholders will be key in advancing this field, ensuring that SV cooking with natural inhibitors remains at the forefront of culinary innovation and consumer preferences.

CONCLUSIONS

The integration of (SV) cooking with natural inhibitors represents a forward-looking approach that marries culinary innovation with food safety, nutritional enhancement, and sensory quality. This review has emphasized the transformative potential of SV cooking in leveraging natural inhibitors like essential oils and grape seed extract, not only to elevate the gastronomic experience but also to address contemporary consumer demands for healthful, sustainable, and flavorful food options. Future research directions, including the exploration of new natural inhibitors, optimization of SV parameters for diverse food matrices, and assessment of long-term health impacts, underscore the dynamic potential for growth and innovation within this field. As this culinary technique continues to evolve, it holds promise for revolutionizing food preparation, consumption, and appreciation, heralding a new era in the gastronomic landscape that prioritizes health, sustainability, and culinary excellence

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