frontiers | Frontiers in Food Science and Technology

TYPE Mini Review
PUBLISHED 14 December 2023
DOI 10.3389/frfst.2023.1331245

EDITED BY
Fanbin Kong,
University of Georgia, United States

REVIEWED BY
Daniso Beswa,
University of Johannesburg, South Africa

*CORRESPONDENCE
Aberham Hailu Feyissa,
✉ abhfe@food.dtu.dk

RECEIVED 31 October 2023
ACCEPTED 01 December 2023
PUBLISHED 14 December 2023

CITATION
Aabel LS, Jensen SN, Hakme E and Feyissa AH (2023), Review on physical properties and acrylamide formation in seaweed bread.
Front. Food. Sci. Technol. 3:1331245.
doi: 10.3389/frfst.2023.1331245

Review on physical properties and acrylamide formation in seaweed bread

Lukas Salvó Aabel[1], Sarah Normann Jensen[1,2], Elena Hakme[2] and Aberham Hailu Feyissa[1]*

[1]Food Production Engineering, DTU Food, Technical University of Denmark, Lyngby, Denmark, [2]Analytical Food Chemistry, DTU Food, Technical University of Denmark, Lyngby, Denmark

Bread, a dietary staple worldwide, owes its diverse physical properties to a complex interplay of composition and processing. This review focuses on recent developments in understanding the physical attributes of bread. It particularly emphasises the effects of ingredient substitution with seaweed, processing parameters, and acrylamide formation. It also encompasses aspects, such as kinetic studies. Special attention is given to the integration of seaweed in bread production. Additionally, it addresses the challenges faced in this field and offers prospects for future research.

KEYWORDS

bread texture, seaweed, process contaminants, food safety, food quality

1 Introduction

Gaining insight into bread, a staple food worldwide, requires a comprehensive understanding of its physicochemical composition, processing methods, and potential for contaminant formation. It is essential to understand how various ingredients influence these aspects, as well as their impact on physical attributes like texture, volume, color, crust thickness, and crumb structure. Such knowledge is crucial when exploring new formulations and refining processing parameters (Yildiz et al., 2012; Ferrero, 2017; Král et al., 2018). There is a considerable body of research dedicated to the advancement of bread production, ingredient substitution, investigation of consumer preferences, enhancement of nutritional values, creation of innovative products, and meeting sustainability goals (Nova et al., 2020; Cappelli et al., 2021; Elena et al., 2021; Wang and Jian, 2022). Recent studies explored the impact of different seaweed concentrations on the bread's texture, dough rheology, and consumer acceptability. Besides, the process of bread-making can result in the formation of thermally induced process contaminants. The probable human carcinogen acrylamide is formed in starch-rich foods, including bread and bakery products, at temperatures above 120°C (Streekstra and Livingston, 2020). Recent research aims to reduce acrylamide formation through process conditions, adjusting the amount of precursors, post-process intervention, and applying kinetic modeling (Abedi et al., 2023; Şen and Gökmen, 2023). This review begins with an examination of the key components in bread dough: the role of starch, damaged starch, proteins (specifically glutenin and gliadin), lipids, and yeast. Following this, the paper investigates the incorporation of seaweed into bread, evaluating how it affects the bread's physical and sensory properties. This paper also addresses food safety by examining the formation of acrylamide in seaweed bread.

2 Composition and physical properties of bread

Understanding ingredients' impact on bread requires knowledge of the dough's basic components. Below is a detailed overview.

2.1 Flour

Starch constitutes 75%–80% of the flour's dry weight (DW) and is vital for dough formation and yeast growth. Starch granules, influenced by milling, are categorized into larger A-type (20–35 μm) oval-shaped and smaller B-type (2–8 μm) spherical granules (Zhou et al., 2014; Guan et al., 2020). These granules contain around 25% amylose and 75% amylopectin (Chen et al., 2016). Amylose is a linear sequence of α-1,4-glycosidic bonded glucose units, whereas amylopectin is made up of glucose units with branches occurring every 20–25 residues due to α-1,6-bonds. This forms a large branched structure. The branches form clusters which create double helices and become crystalline lamellae. Branched points, termed amorphous lamellae, are unordered and likely house amylose. These alternating layers make up the semicrystalline starch granule matrix (Seung, 2020). In flour, around 5%–13% is Damaged Starch (DS). DS granules have a higher water absorption due to easier access to the amorphous regions, and it is easier for amylase enzymes to break DS down into simple sugars. The amount of DS in flour has a significant influence on dough rheology (Guan et al., 2020).

Approximately 2%–3% of the flour is non-starch polysaccharides, predominantly arabinoxylan (Garófalo et al., 2011). Arabinoxylans are water-extractable, which stabilizes dough gas retention, and water-unextractable, which can adversely affect the dough by retaining water (Garófalo et al., 2011).

Flour's protein content ranges from 7% to 15% (DW), depending on the wheat variety. Glutenin and gliadin compromise 75%–85% of total protein content and are crucial for dough's viscosity and plasticity, forming the gluten network. Upon hydration, glutenin and gliadin begin forming bonds, creating the viscoelastic network. Protease enzymes present in the flour cleave peptide bonds in the proteins, which help the protein chains in the gluten structure form bonds. Multiple bonds are formed between the amino acid side chains. Weaker bonds constantly reconfigure, while stronger disulfide bonds stabilize the protein matrix, making kneaded dough tougher (Sivam et al., 2010; Žilić et al., 2011). Glutenin ensures dough's strength and elasticity, while gliadin provides viscosity and extensibility. While no single gluten structure model is universally accepted, several are widely recognized (Belton, 1999; Shewry et al., 2002; Wieser, 2007; Shewry and Lafiandra, 2022).

Glutenin polymers are made up of high-molecular-weight (HMW) subunits ranging from 60 to 90 kDa and low-molecular-weight (LMW) subunits ranging from 10 to 70 kDa. These are interconnected by disulfide bonds between the cysteine residues. HMW subunits contribute significantly to dough elasticity, accounting for 45%–70% of dough variation despite making up only for 7%–15% of gluten and 1%–1.7% of flour (Wang et al., 2018). The middle domain of HMW subunits is rich in glutamine and forms a spring-like β-spiral structure vital for elasticity. LMW subunits, comprising 19%–25% of the gluten, add to the polymer backbone and affect dough resistance (Wieser and Kieffer, 2001).

Gliadins have a globular structure and act as a plasticizer within the gluten matrix where the critical deformation of the long glutenin polymers takes place. Gliadins contribute to the extensibility of the dough and its ability to stretch without ripping. The gliadins are thought to interact with glutenin via non-covalent forces (Shewry and Lafiandra, 2022).

Wheat flour has 2%–2.5% lipids, where 65% are bound, 35% free, and 9% are free polar lipids which enhance loaf volume and texture (Pareyt et al., 2011). Lipids act as surfactants and lubricants in dough, affecting gluten structure and elasticity. They interact with gluten proteins through hydrophobic and polar forces, with non-polar lipids trapped in the gluten matrix and polar lipids bonding to HMW-GS and LMW-GS, enhancing gas retention (McCann et al., 2009).

2.2 Leavening agents and gas production

The primary yeast used in breadmaking is *Saccharomyces cerevisiae*. When yeast is added to dough, it metabolizes sugars, generating CO_2 that gets trapped in the dough, causing it to rise. Initially, in aerobic conditions, yeast uses oxygen and produces CO_2. Once the oxygen is depleted, yeast switches from aerobic to anaerobic fermentation, producing both CO_2 and ethanol, which contributes to the oven spring. Yeast activity and fermentation are influenced by dough composition, temperature, and sugar availability. Amylase enzymes are responsible for breaking down starches into fermentable sugars. While salt inhibits yeast, amino acids and minerals like Mg^{2+} and Ca^{2+} enhance fermentation (Peña et al., 2015; Struyf et al., 2017).

2.3 Ingredient substitution—Seaweed

Seaweed is considered an environmentally sustainable component, finding growing applications in various food products, notably bread (Polat et al., 2021). While traditionally limited, the incorporation of seaweed in bread has seen a notable increase recently, with numerous studies contributing to this field. A comprehensive summary of these research findings can be found in Table 1.

Mamat et al. (2023) studied the effect on texture by incorporating 1%–9% red seaweed (*K. alvarezii*) powder into wheat flour in Chinese steamed buns. Specifically, the addition of the seaweed powder increased the hardness and chewiness of the buns, while cohesiveness, volume, and springiness decreased as the seaweed powder concentration increased. Sensory evaluations (9-scale hedonic test) showed that buns with up to 6% seaweed powder were acceptable (Mamat et al., 2023).

Sasue et al. (2023) investigated the addition of *K. alvarezii* powder into baked buns. As the addition of powder increased from 3% to 12% in the buns, there was a significant increase in hardness (N/mm), ranging from 62.4% to 160.8%. The researchers attributed this increased hardness to the high dietary fiber content in the seaweed, which also diminished yeast activity, thereby producing buns with a more rigid texture and reduced internal pore sizes (Sasue et al., 2023).

TABLE 1 Overview of articles concerning seaweed introduction to wheat bread production.

Ingredient	Textural effect	Source
Seaweed powder to bread	Increased hardness with increasing seaweed content	Sasue et al. (2023)
Seaweed powder to steamed buns	Higher seaweed percentages (1.5%–9%) increased hardness and decreased springiness	Mamat et al. (2023)
Seaweed powder to bread	Higher seaweed percentages (2%–8%) reduced bread sensory acceptability	Lamont and McSweeney (2021)
Seaweed powder to bread	Decreased the physical characteristics, e.g., volume, density, and firmness	Mamat et al. (2021)
Seaweed powder to bread	Retains dough shape but reduces porosity and expansion	Arufe et al. (2018)
Seaweed powder to muffins	Increased seaweed decreases height, volume, springiness, and acceptability	Mamat et al. (2018)
Seaweed powder to bread	Increases water absorption and decreases volume	Mamat et al. (2013)

A study by Lamont and McSweeney (2021) investigated the sensory acceptability of bread with varying concentrations of seaweed (*A. nodosum* and *C. crispus*). A consumer panel rated bread samples with incrementally higher seaweed concentrations. As the proportion of seaweed in the bread formulation increased, a consistent decline in the overall acceptability ratings was observed. Breads containing A. nodosum and C. crispus were deemed acceptable when incorporated at concentrations of 4% and 2%, respectively (Lamont and McSweeney, 2021).

Mamat et al. (2021) found that incorporating seaweed powder (*K. alvarezii*) into bread influenced its physical and sensory properties. A farinograph analysis showed increased water absorption, development time, and mixing tolerance, but decreased stability time with increasing seaweed addition. Texturally, the buns' volume, bulk density, and firmness were affected negatively with increasing seaweed powder concentration. Interestingly, sensory assessments showed a decrease in consumer preference as the seaweed content increased (Mamat et al., 2021).

Arufe et al. (2018) showed the addition of seaweed powder (*F. vesiculosus*) to wheat dough strengthens the dough's ability to hold its shape early in the proofing process, but eventually decreased the dough's final porosity. The authors speculate that the increased viscosity hinders bubble growth, limiting dough expansion. This can result in denser bread with a firmer crumb. When more than 4% seaweed powder was added, the bread became denser with a green hue to the crust (Arufe et al., 2018).

Mamat et al. (2018) investigated the effects of incorporating seaweed powder (*K. alvarezii*) into muffin formulations. With an increase in seaweed powder content, the muffin's moisture content rose (which is a characteristic of hydrocolloids), while the muffins showed a reduction in height and volume. Texturally, the muffins became harder and less springy with increasing seaweed concentration. Sensory evaluations (7-point hedonic scale) showed that the addition of up to 6% seaweed powder did not significantly change the muffins' sensory attributes. However, once again, testing consumer preference showed that muffins without seaweed powder were preferred (Mamat et al., 2018).

Mamat et al. (2013) showed that increasing concentrations of seaweed (K. alvarezii) in dough reduced its stickiness and disrupted the development of the gluten network. This was attributed to the hydrocolloids in the seaweed, which enhance water absorption. As a result, the dough's volume decreased with higher seaweed content, and there was a notable increase in batter density. This denser batter hindered the formation of bubble nuclei and the dough's ability to rise, impacting the bread's texture. However, the results showed that it was possible to add up to 8% seaweed powder to the dough without compromising quality (Mamat et al., 2013).

3 Undesired chemical formation: Acrylamide

3.1 Mechanism of acrylamide formation

Acrylamide is formed during thermal processing (>120°C) as a part of Maillard reactions between reducing sugars (e.g., fructose and glucose) and asparagine. It is typically formed in low moisture and starch-rich food, e.g., bread and potato chips (EFSA, 2015; Lemos et al., 2023). Acrylamide formation is unavoidable in thermally processed food products due to the intertwining with simultaneous Maillard reactions underlining browning, aroma, and flavor development underlining product palatability. However, acrylamide is a probable human carcinogen (IARC, 2022). Specific criteria have been established by the Commission Regulation (EU) 2017/2158 to minimize the acrylamide content present in food, including a benchmark level of 50 μg/kg in wheat bread. EFSA reports a mean value of 42 μg/kg for soft bread, making bread the second largest contributor (up to 31% across age groups) to daily acrylamide intake (EFSA, 2015; Raffan and Halford, 2019).

The research aims to unravel the intricate mechanisms underlying acrylamide formation during high-temperature baking, shedding light on mitigation strategies. Known impacting factors on acrylamide formation include amino acids, reducing sugars, temperature, water activity (a_W), moisture content, and pH (Streekstra and Livingston, 2020). In the simplest picture, asparagine is considered the limiting factor for acrylamide formation in bread (Streekstra and Livingston, 2020). However, interfering formation pathways and competition for available amino acids constitute a complicating factor in complex food matrix relying on specific ingredients and processing conditions.

For yeast-leaved bread, it was demonstrated that the addition of fructose did not significantly affect the acrylamide level. In contrast, non-yeast-leaved bakery products were reported to contain significantly higher acrylamide levels with added reducing sugars (Surdyk et al., 2004; Hamlet et al., 2007). Moisture, a_W, and local temperature are essential for acrylamide formation in bread, with 99%

of the acrylamide content in the crust (Streekstra and Livingston, 2020). There is a strong dependence between temperature and moisture, limiting the temperature from exceeding the formation threshold of 120°C in the crumb. The a_W directly impacts the acrylamide formation, exhibiting a maximum impact when a_W is at or below 0.4 (Streekstra and Livingston, 2020).

The pH is known to impact acrylamide formation, with a maximal formation at a pH of 7–9 (Rydberg et al., 2003; De Vleeschouwer et al., 2006). Meanwhile, experiments indicate that acrylamide levels can be pH-independent, and the type of acidic compounds present is crucial (Muzhingi et al., 2018; Mildner-Szkudlarz et al., 2019). The typical pH of dough and bread ranges from 5 to 6 (Muzhingi et al., 2018; Mildner-Szkudlarz et al., 2019).

Minimizing acrylamide formation relies on a detailed understanding of the impacting factors outlined and how these factors interplay with thermal processing and kinetic behavior. Kinetic modeling can help pin down the driving factors in acrylamide formation to improve chemical reaction understanding and minimize contamination.

3.2 Mitigation strategies

Innovative strategies to reduce acrylamide levels in bread, encompassing ingredient modifications, process optimization, and enzymatic treatments, are at the forefront of research in ensuring the safety of bread products. The mitigation strategies can be divided into three separate categories: i) production conditions, ii) ingredients, and iii) process control conditions. The production conditions include early production steps that can have a decisive effect on the final acrylamide concentration, e.g., the cereal's growth conditions (Streekstra and Livingston, 2020). Sulfur-derived soil, growing season, location, and local weather affect the cereal's level of free asparagine. In addition, the level of asparagine is also found to vary, depending on cereal species, with levels ranging from 116 to 965 μg/kg (Streekstra and Livingston, 2020).

Some food supplements and ingredients affect the final acrylamide level in bread, e.g., enzymes, antioxidants, amino acids, and acidic polysaccharides. Enzymatic mitigation can be achieved by acrylamide precursor depletion from asparaginase and glucose oxidase, while amylase and protease increase amino acids and reducing sugar content (Abedi et al., 2023). Antioxidant addition showed a diverse impact on the acrylamide formation. Examples of lowering effects include adding bamboo leaves or Green Tea to breadsticks, which showed 82.9% and 72.5% reductions, respectively. Adding rosemary (dry, oil, or leaves) to wheat buns decreased the acrylamide level from 57% to 67%. Adding black cumin and fennel seeds to biscuits reduced acrylamide levels by 61% and 78% (Streekstra and Livingston, 2020). Meanwhile, adding curcumin to asparagine-fructose model systems significantly enhanced acrylamide levels (Jin et al., 2013). Complex ingredients, e.g., seaweed, contains antioxidants such as C vitamins, with an average content of 0.773 mg/g DW across green, brown, and red seaweeds (Nielsen et al., 2021). However, seaweed also contains asparagine and other amino acids that potentially impact acrylamide formation (Sharma et al., 2018).

Different settings in the breadmaking process, including baking time and temperature, can impact acrylamide contamination. Thermal processing strategies, hereby, provide a direct way to modify the acrylamide formation. Combining a lower baking temperature and longer baking time can minimize acrylamide formation while achieving regular crust browning. Another strategy to maintain the crust browning includes applying time-dependent temperature reduction during baking. Additional process factors include the humidity during baking or coating of the bread crust (Ahrné et al., 2007; Liu et al., 2018).

In addition, fermentation time also impacts acrylamide levels. Prolonging yeast fermentation from 30 to 360 min resulted in an 87% lower acrylamide content in whole-grain wheat bread (Fredriksson et al., 2004). However, extending the fermentation (from 70 to 150 min) and baking time (from 20 to 30 min) increased acrylamide concentration by up to a factor of 2 in white bread (Lemos et al., 2023).

4 Processing and kinetic studies

Food quality, process optimization, and safety are governed by chemical, biochemical, microbial, and physical changes over time, making kinetics an essential aspect of food science (Van Boekel, 2008; Rabeler and Feyissa, 2018). Kinetic studies, underpinned by advanced modeling techniques, provide dynamic insights into the time-dependent changes in bread characteristics during baking.

Examples include process-dependent a_w measuring the water available to participate in reactions (including microbial growth, chemical, and enzymatic reactions) and influencing shelf-life, surface browning, which is directly correlated with acrylamide levels, and chemical reaction kinetics (Surdyk et al., 2004; Wedzicha et al., 2005; Van Boekel, 2008; Mauer and Bradley, 2017).

Kinetic profiling of food quality and chemical contaminants requires a large number of time-consuming and costly analytical experiments. Consequently, experiments often focus on idealized model systems where derived parameters can be interpreted directly (Claeys et al., 2005; De Vleeschouwer et al., 2006; Hedegaard et al., 2008; Pastoriza et al., 2012). An important aspect is the learning between the kinetic behavior in well-defined ideal model systems and real food products. While mechanistic ideas can be pinpointed in model systems, insights should be tested in complex real-food tests for quantitative applications (Van Boekel, 2008). Another aspect is the application of design of experiment methods to statistically evaluate the impact of process and product changes on physical quality, e.g., color and texture (Rabeler and Feyissa, 2018). These methods minimize the number of measurements while optimizing the product quality and hold potential for new ingredients implementation in bread.

Modeling enables faster optimization and improved understanding and predictions. One target is limiting contaminant formation in food products, e.g., minimizing acrylamide in bread. Modeling of process-induced acrylamide formation has, so far, primarily focused on french fries, potato-based products, cereals, and other low-moisture food products (Wedzicha et al., 2005; Parker et al., 2012; Şen and Gökmen, 2023). Models are developed at different levels, including empirical models (Corradini and Peleg, 2006; Jensen et al., 2008; Knol, 2008; Mariotti et al., 2015), multiresponse kinetic modeling defining formation pathways through mathematical models of reaction networks (Stadler et al., 2004; Wedzicha et al., 2005; Parker et al., 2012; Şen and Gökmen, 2023), and datacentric multi-regression models including machine-learning approaches (Arora et al., 2021; Smeesters et al., 2021; Wang et al., 2022). Importantly, there is a need for model enhancements to account for the introduction of new ingredients, e.g., seaweed, into food products.

5 Conclusion

This study provides an examination of bread composition, emphasizing the main components that contribute significantly to the variations of the bread as well as introducing seaweed as a novel ingredient in bread making and acrylamide formation. Knowing the specific interactions between gluten proteins, starch, lipids, and yeast in dough is essential for optimizing bread's desired texture and how new ingredients might affect the bread. Research has shown that incorporating seaweed into bread introduces new challenges and complexities. Seaweed can significantly alter the textural properties, sensory acceptability, and overall quality of the bread. This necessitates a careful balance and precise formulation to ensure the bread maintains its desirable characteristics. Acrylamide formation relies strongly on the production, ingredients, and process. The known limiting factors in bread include asparagine and reducing sugars, which in part can be minimized through process-related or food supplementary mitigation strategies. The mechanisms linking intermediate compound formation during Millard reactions and acrylamide formation still need a better understanding. This missing link is even more critical when possible intermediary compounds increase, and product development includes new alternative substitutional ingredients, e.g., seaweed, with an unknown impact on the food matrix and chemical contaminants.

Author contributions

LA: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing–original draft. SJ: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing–original draft. EH: Conceptualization, Project administration, Resources, Supervision, Writing–review and editing. AF: Conceptualization, Methodology, Project administration, Resources, Supervision, Visualization, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abedi, E., Hashemi, S. M. B., and Ghiasi, F. (2023). Effective mitigation in the amount of acrylamide through enzymatic approaches. *Food Res. Int.* 172, 113177. doi:10.1016/j.foodres.2023.113177

Ahrné, L., Andersson, C., Floberg, P., Rosén, J., and Lingnert, H. (2007). Effect of crust temperature and water content on acrylamide formation during baking of white bread: Steam and falling temperature baking. *LWT- Food Sci. Technol.* 40 (10), 1708–1715. doi:10.1016/j.lwt.2007.01.010

Arora, M., Mangipudi, P., and Dutta, M. K. (2021). Deep learning neural networks for acrylamide identification in potato chips using transfer learning approach. *J. Ambient Intell. Humaniz. Comput.* 12 (12), 10601–10614. doi:10.1007/s12652-020-02867-2

Arufe, S., Della Valle, G., Chiron, H., Chenlo, F., Sineiro, J., and Moreira, R. (2018). Effect of brown seaweed powder on physical and textural properties of wheat bread. *Eur. Food Res. Technol.* 244 (1), 1–10. doi:10.1007/s00217-017-2929-8

Belton, P. S. (1999). Mini review: on the elasticity of wheat gluten. *J. Cereal Sci.* 29 (2), 103–107. doi:10.1006/jcrs.1998.0227

Cappelli, A., Cini, E., Nunes, C., and Rocha, D. (2021). Challenges and Opportunities in wheat flour, Pasta, bread, and bakery product production chains: a systematic review of innovations and improvement strategies to increase sustainability, productivity, and product quality. *Sustainability.* 13 (5), 2608. doi:10.3390/su13052608

Chen, G.-X., Zhou, J.-W., Liu, Y.-L., Lu, X.-B., Han, C.-X., Zhang, W.-Y., et al. (2016). Biosynthesis and regulation of wheat amylose and amylopectin from proteomic and phosphoproteomic characterization of granule-binding proteins. *Sci. Rep.* 6 (1), 33111. doi:10.1038/srep33111

Claeys, W., De Vleeschouwer, K., and Hendrickx, M. (2005). Effect of amino acids on acrylamide formation and elimination kinetics. *Biotechnol. Prog.* 21 (5), 1525–1530. doi:10.1021/bp050194s

Corradini, M. G., and Peleg, M. (2006). Linear and non-linear kinetics in the Synthesis and degradation of acrylamide in foods and model systems. *Crit. Rev. Food Sci. Nutr.* 46 (6), 489–517. doi:10.1080/10408390600758280

De Vleeschouwer, K., Van Der Plancken, I., Van Loey, A., and Hendrickx, M. (2006). Impact of PH on the kinetics of Acrylamide Formation/Elimination reactions in model systems. *J. Agric. Food Chem.* 54 (20), 7847–7855. doi:10.1021/jf0611264

EFSA. (2015). Scientific Opinion on acrylamide in food. *Eur. Food Saf. Auth. (EFSA) J.* 13 (6). doi:10.2903/J.EFSA.2015.4104

Elena, P. M., Loredana, U. E., Carmen, M. A., Elena, P. E., and Alexandra, J. (2021). Consumer preferences and expectations. *Trends Wheat Bread Mak.*, 431–458. doi:10.1016/B978-0-12-821048-2.00015-5

Ferrero, C. (2017). Hydrocolloids in wheat breadmaking: a concise review. *Food Hydrocoll.* 68, 15–22. doi:10.1016/j.foodhyd.2016.11.044

Fredriksson, H., Tallving, J., Rosén, J., and Åman, P. (2004). Fermentation reduces free asparagine in dough and acrylamide content in bread. *Cereal Chem.* 81 (5), 650–653. doi:10.1094/cchem.2004.81.5.650

Garófalo, L., Vazquez, D., Ferreira, F., and Soule, S. (2011). Wheat flour non-starch polysaccharides and their effect on dough rheological properties. *Industrial Crops Prod.* 34 (2), 1327–1331. doi:10.1016/j.indcrop.2010.12.003

Guan, E., Yang, Y., Pang, J., Zhang, T., Li, M., and Bian, K. (2020). Ultrafine grinding of wheat flour: effect of flour/starch granule profiles and particle size distribution on falling number and pasting properties. *Food Sci. Nutr.* 8 (6), 2581–2587. doi:10.1002/fsn3.1431

Hamlet, C. G., Sadd, P. A., Liang, L., Jayaratne, S. M., and Skingle, M. (2007). Exploiting processing conditions to reduce acrylamide in cereal-based foods. Available at: https://www.researchgate.net/publication/228603991.

Hedegaard, R. V., Frandsen, H., and Skibsted, L. H. (2008). Kinetics of formation of acrylamide and Schiff base intermediates from asparagine and glucose. *Food Chem.* 108 (2008), 917–925. doi:10.1016/j.foodchem.2007.11.073

IARC. (2022). List of classifications – IARC (international agency for research on cancer) monographs on the identification of carcinogenic hazards to humans. Available at: https://monographs.iarc.who.int/list-of-classifications.

Jensen, B. B. B., Lennox, M., Granby, K., and Adler-Nissen, J. (2008). Robust modelling of heat-induced reactions in an industrial food production process exemplified by acrylamide generation in breakfast cereals. *Food Bioprod. Process.* 86 (3), 154–162. doi:10.1016/j.fbp.2007.10.014

Jin, C., Wu, X., and Zhang, Y. (2013). Relationship between antioxidants and acrylamide formation: a review. *Food Res. Int.* 51 (2), 611–620. doi:10.1016/j.foodres.2012.12.047

Knol, J. J. (2008). *Kinetic modeling of acrylamide formation in aqueous reaction systems and potato crisps*. The Netherlands: Wageningen University.

Král, M., Pospiech, M., Běhalová, H., Dordevic, D., Ošťádalová, M., Tremlová, B., et al. (2018). Substitution of sodium chloride by salt microspheres in dough: effect on dough rheological properties. *J. Texture Stud.* 49 (4), 456–463. doi:10.1111/jtxs.12337

Lamont, T., and McSweeney, M. (2021). Consumer acceptability and chemical composition of whole-wheat breads incorporated with brown seaweed (*Ascophyllum nodosum*) or red seaweed (*Chondrus crispus*). *J. Sci. Food Agric.* 101 (4), 1507–1514. doi:10.1002/jsfa.10765

Lemos, A. C., Borba de, V. S., de Medeiros Burkert, J. F., Scaglioni, P. T., and Badiale-Furlong, E. (2023). Role of white bread matrix components and processing parameters on 5-hydroxymethylfurfural (HMF) and acrylamide formation. *Food control.* 145, 109407. doi:10.1016/j.foodcont.2022.109407

Liu, J., Liu, X., Man, Y., and Liu, Y. (2018). Reduction of acrylamide content in bread crust by starch coating. *J. Sci. Food Agric.* 98 (1), 336–345. doi:10.1002/jsfa.8476

Mamat, H., Akanda, J., Zainol, M. K., and Ling, Y. A. (2018). The influence of seaweed composite flour on the physicochemical properties of muffin. *J. Aquatic Food Prod. Technol.* 27 (5), 635–642. doi:10.1080/10498850.2018.1468841

Mamat, H., Ling, Y. Y., Abdul Aziz, A. H., Wahab, N. A. B., Mohd Rosli, R. G., Sarjadi, M. S., et al. (2023). Utilization of seaweed composite flour (Kappaphycus alvarezii) in the development of steamed bun. *J. Appl. Phycol.* 35 (4), 1911–1919. doi:10.1007/s10811-023-02989-y

Mamat, H., Matanjun, P., Ibrahim, S., Amin, S., Abdul Hamid, M., and Rameli, A. (2013). The effect of seaweed composite flour on the textural properties of dough and bread. *J. Appl. Phycol.* 26, 1057–1062. doi:10.1007/s10811-013-0082-8

Mamat, H. B., Wan Chen, Y., Abdul Hamid, M., Md Haque Akanda, J., Pusiran, A. K., and Zainol, M. K. (2021). Assessment of dough rheological characteristics and soft bread roll quality of wheat flour incorporated with seaweed powder. *Br. Food J.* 123 (12), 3888–3901. doi:10.1108/bfj-08-2020-0676

Mariotti, M., Cortés, P., Fromberg, A., Bysted, A., Pedreschi, F., and Granby, K. (2015). Heat toxicant contaminant mitigation in potato chips. *LWT - Food Sci. Technol.* 60 (2), 860–866. doi:10.1016/j.lwt.2014.09.023

Mauer, L. J., and Bradley, R. L. (2017). Moisture and total Solids analysis. in *Food science Text Series*. Editor S. S. Nielsen (Cham: Springer). Food Analysis.

McCann, T. H., Small, D. M., Batey, I. L., Wrigley, C. W., and Day, L. (2009). Protein–lipid interactions in gluten elucidated using acetic acid fractionation. *Food Chem.* 115 (1), 105–112. doi:10.1016/j.foodchem.2008.11.070

Mildner-Szkudlarz, S., Różańska, M., Piechowska, P., Waśkiewicz, A., and Zawirska-Wojtasiak, R. (2019). Effects of polyphenols on volatile profile and acrylamide formation in a model wheat bread system. *Food Chem.* 297, 125008. doi:10.1016/j.foodchem.2019.125008

Muzhingi, T., Owade, J. O., Abong, G. O., Okoth, M. W., Heck, S., Low, J., et al. (2018). Sensory attributes of composite breads from shelf storable orange-fleshed Sweetpotato puree. *Open Agric.* 3 (1), 459–465. doi:10.1515/opag-2018-0051

Nielsen, C. W., Rustad, T., and Holdt, S. L. (2021). Vitamin C from seaweed: a review assessing seaweed as contributor to daily intake. *Foods* 10 (1), 198. doi:10.3390/foods10010198

Nova, P., Martins, A. P., Teixeira, C., Abreu, H., Silva, J. G., Silva, A. M., et al. (2020). Foods with microalgae and seaweeds fostering consumers health: a review on scientific and market innovations. *J. Appl. Phycol.* 32, 1789–1802. doi:10.1007/s10811-020-02129-w

Pareyt, B., Finnie, S. M., Putseys, J. A., and Delcour, J. A. (2011). Lipids in bread making: sources, interactions, and impact on bread quality. *J. Cereal Sci.* 54 (3), 266–279. doi:10.1016/j.jcs.2011.08.011

Parker, J. K., Balagiannis, D. P., Higley, J., Smith, G., Wedzicha, B. L., and Mottram, D. S. (2012). Kinetic model for the Formation of acrylamide during the finish-frying of commercial French fries. *J. Agric. Food Chem.* 60 (36), 9321–9331. doi:10.1021/jf302415n

Pastoriza, S., Rufián-Henares, J., and Morales, F. J. (2012). Reactivity of acrylamide with coffee melanoidins in model systems. *LWT - Food Sci. Technol.* 45 (2), 198–203. doi:10.1016/j.lwt.2011.08.004

Peña, A., Sánchez, N., Álvarez, H., Calahorra, M., and Ramírez-Salcedo, J. (2015). Effects of high medium pH on growth, metabolism and transport in *Saccharomyces cerevisiae*. *FEMS Yeast Res.* 15, fou005. doi:10.1093/femsyr/fou005

Polat, S., Trif, M., Rusu, A., Šimat, V., Čagalj, M., Alak, G., et al. (2021). Recent advances in industrial applications of seaweeds. *Crit. Rev. Food Sci. Nutr.* 0 (0), 4979–5008. doi:10.1080/10408398.2021.2010646

Rabeler, F., and Feyissa, A. H. (2018). Kinetic modeling of texture and color changes during thermal treatment of chicken breast meat. *Food Bioprocess Technol.* 11 (8), 1495–1504. doi:10.1007/s11947-018-2123-4

Raffan, S., and Halford, N. G. (2019). Acrylamide in food: Progress in and prospects for genetic and agronomic solutions. *Ann. Appl. Biol.* 175 (3), 259–281. doi:10.1111/aab.12536

Rydberg, P., Eriksson, S., Tareke, E., Karlsson, P., Ehrenberg, L., Törnqvist, M., et al. (2003). Investigations of factors that influence the acrylamide content of heated foodstuffs. *J. Agric. Food Chem.* 51, 7012–7018. doi:10.1021/jf034649

Sasue, A., Mohd Kasim, Z., and Zubairi, S. I. (2023). Evaluation of phytochemical, nutritional and sensory properties of high fibre bun developed by utilization of Kappaphycus alvarezii seaweed powder as a functional ingredient. *Arabian J. Chem.* 16 (8), 104953. doi:10.1016/j.arabjc.2023.104953

Şen, D., and Gökmen, V. (2023). Multiresponse kinetic modeling of Acrylamide Formation in low moisture food systems like Nuts and seeds during roasting. *ACS Food Sci. Technol.* 3 (9), 1606–1616. doi:10.1021/acsfoodscitech.3c00359

Seung, D. (2020). Amylose in starch: towards an understanding of biosynthesis, structure and function. *New Phytol.* 228 (5), 1490–1504. doi:10.1111/nph.16858

Sharma, S., Neves, L., Funderud, J., Mydland, L. T., Øverland, M., and Horn, S. J. (2018). Seasonal and depth variations in the chemical composition of cultivated Saccharina latissima. *Algal Res.* 32, 107–112. doi:10.1016/j.algal.2018.03.012

Shewry, P., Halford, N., Belton, P., and Tatham, A. (2002). The structure and properties of gluten: an elastic protein from wheat grain. *Philosophical Trans. R. Soc. Lond. Ser. B, Biol. Sci.* 357, 133–142. doi:10.1098/rstb.2001.1024

Shewry, P. R., and Lafiandra, D. (2022). Wheat glutenin polymers 1. Structure, assembly and properties. *J. Cereal Sci.* 106, 103486. doi:10.1016/j.jcs.2022.103486

Sivam, A. S., Sun-Waterhouse, D., Quek, S., and Perera, C. O. (2010). Properties of bread dough with added fiber polysaccharides and phenolic antioxidants: a review. *J. Food Sci.* 75 (8), R163–R174. doi:10.1111/j.1750-3841.2010.01815.x

Smeesters, L., Magnus, I., Virte, M., Thienpont, H., and Meulebroeck, W. (2021). Potato quality assessment by monitoring the acrylamide precursors using reflection spectroscopy and machine learning. *J. Food Eng.* 311, 110699. doi:10.1016/j.jfoodeng.2021.110699

Stadler, R. H., Robert, F., Riediker, S., Varga, N., Davidek, T., Phanie Devaud, S. Ä., et al. (2004). In-depth mechanistic study on the Formation of acrylamide and other vinylogous compounds by the maillard reaction. *J. Agric. Food Chem.* 52 (17), 5550–5558. doi:10.1021/jf0495486

Streekstra, H., and Livingston, A. (2020). Acrylamide in bread and baked products. *Elsevier Eb.*, 289–321. doi:10.1016/B978-0-08-102519-2.00010-4

Struyf, N., Van der Maelen, E., Hemdane, S., Verspreet, J., Verstrepen, K. J., and Courtin, C. M. (2017). Bread dough and baker's yeast: an uplifting synergy. *Compr. Rev. Food Sci. Food Saf.* 16 (5), 850–867. doi:10.1111/1541-4337.12282

Surdyk, N., Rosén, J., Andersson, R., and Åman, P. (2004). Effects of asparagine, fructose, and baking conditions on acrylamide content in Yeast-Leavened wheat bread. *J. Agric. Food Chem.* 52 (7), 2047–2051. doi:10.1021/jf034999w

Van Boekel, M. A. J. S. (2008). Kinetic modeling of food quality: a critical review. *Compr. Rev. Food Sci. Food Saf.* 7 (1), 144–158. doi:10.1111/j.1541-4337.2007.00036.x

Wang, D., Zhang, K., Dong, L., Dong, Z., Li, Y., Hussain, A., et al. (2018). Molecular genetic and genomic analysis of wheat milling and end-use traits in China: Progress and perspectives. *Crop J.* 6 (1), 68–81. doi:10.1016/j.cj.2017.10.001

Wang, L., Zhang, F., Wang, J., Wang, Q., Chen, X., Cheng, J., et al. (2022). Machine learning prediction of dual and dose-response effects of flavone carbon and oxygen glycosides on acrylamide formation. *Front. Nutr.* 9, 1042590. doi:10.3389/fnut.2022.1042590

Wang, Y., and Jian, C. (2022). Sustainable plant-based ingredients as wheat flour substitutes in bread making. *npj Sci. Food* 6, 49. doi:10.1038/s41538-022-00163-1

Wedzicha, B. L., Mottram, D. S., Elmore, J. S., Koutsidis, G., and Dodson, A. T. (2005). Kinetic models as a route to control acrylamide formation in food. *Adv. Exp. Med. Biol.* 561, 235–253. doi:10.1007/0-387-24980-X_18

Wieser, H. (2007). Chemistry of gluten proteins. *Food Microbiol.* 24 (2), 115–119. doi:10.1016/j.fm.2006.07.004

Wieser, H., and Kieffer, R. (2001). Correlations of the amount of gluten protein types to the technological properties of wheat flours determined on a micro-scale. *J. Cereal Sci.* 34 (1), 19–27. doi:10.1006/jcrs.2000.0385

Yildiz, O., Meral, R., and Dogan, I. S. (2012). Determination of stickiness values of different flour combinations. *Int. J. Food Eng.* 8 (3). doi:10.1515/1556-3758.2412

Zhou, W., Hui, Y. H., De Leyn, I., Pagani, M. A., Rosell, C. M., Selman, J. D., et al. (2014). *Bakery products science and technology*. John Wiley & Sons.

Žilić, S., Barać, M., Pešić, M., Dodig, D., and Ignjatović-Micić, D. (2011). Characterization of proteins from grain of different bread and durum wheat genotypes. *Int. J. Mol. Sci.* 12 (9), 5878–5894. doi:10.3390/ijms12095878