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The role of water alternatives in bread formulation and its quality; An emerging source of sustainable and cost-effective bakery improvers

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ABSTRACT

Bread as staple food worldwide has a fundamental role in our daily diet. Accordingly, its fortification with sustainable, cost-effective and clean-label bakery additives has received considerable attention. Recently, increasing efforts has been devoted to apply potential water alternatives (W_{AL}) in bread formulation for its enrichment. Water is one of the most important ingredients in bread formulation, which has undeniable effects on rheological behaviors of the manufactured dough, subsequent textural features and other quality characteristics of the final product. There are also some promising reports about potential W_{AL} in bread-making process. These W_{AL} can be categorized in three main groups including dairy-based, plant-based and fermented extracts that are reviewed in the present article. These ingredients have crucial effects on the quality indices of the produced bread. Production of fortified functional bread with improved sensory attributes, enhanced nutritional values, extended shelf-life and modified texture are some of the emerging potentials of these W_{AL} in bakery industries. Protein content, nutritional profile, bioactive ingredients and antioxidant activity of these W_{AL} are also key parameters involved in their techno-functional capabilities of the produced bread.

1. Introduction

There are several promising opportunities to produce novel value-added functional foods using plant-based or dairy-based materials as non-fermented or fermented with proper starter cultures to enhance different aspects of the product quality. Production of functional bread as staple food has also several important criteria including product quality and shelf-life, as well as consumer health and nutrition. Accordingly, bread fortification with sustainable, cost-effective and clean-label ingredients has received considerable attention especially in developing countries to overcome complex malnutrition defects (Akhtar et al., 2011; Betoret and Rosell, 2020). Bread is a globally consumed food product that holds a significant position in the diets of many nations. Its popularity stems from its accessibility, ready-to-eat nature, low-cost, diverse varieties with different flavors, textures and nutritional benefits. Bread also serves as a source of essential nutrients, particularly carbohydrates, fiber, protein and certain minerals e.g., magnesium, phosphate and iron. According to reports, Russia, Iran and Turkey rank as the top bread-consuming countries globally, with per capita consumption of 118, 116 and 104 kg, respectively (Mastromatteo et al., 2014; Mesta-Corral et al., 2024).

Cereal flours and water are the main parts of bread ingredients along with baker's yeast or sourdough (SD). Considering the type of manufactured bread, there are several formulations and baking strategies that affect diversity of this staple food worldwide. Among ingredients used, water is a key component in bread formulation, playing a crucial role in yeast activity and dough temperature. It also aids in the development of the gluten network and enhances enzymatic activities that modify dough

Abbreviations: EPS, exopolysaccharides; FDA, food and drug administration; GRAS, generally recognized as safe; LAB, lactic acid bacteria; OA, overall acceptability; SD, sourdough; SEM, scanning electron microscopy; TPA, texture profile analysis; TPC, total phenol content; W_{AL}, water alternatives; WHO, world health organization.

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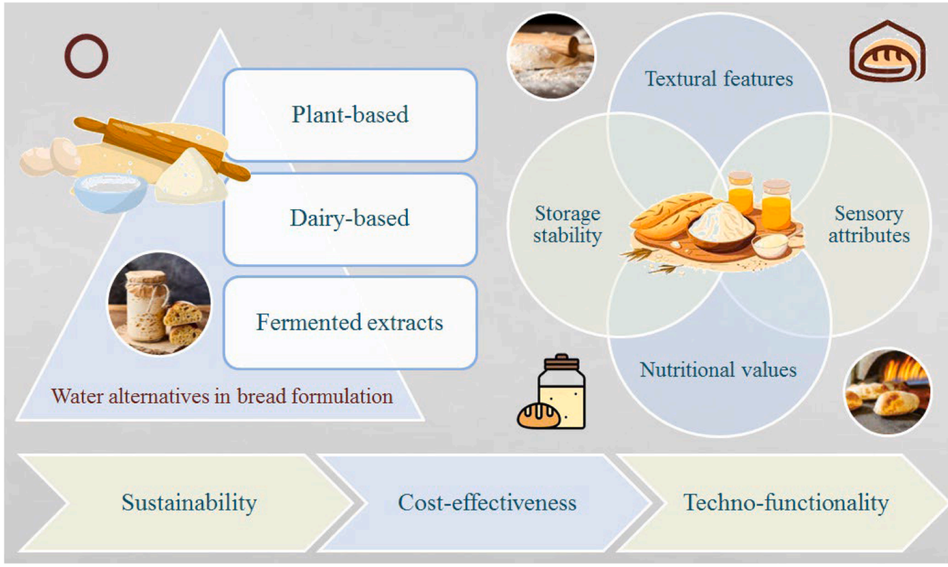

Fig. 1. The main water alternatives in bread formulation and their promising capabilities as functional bakery additives.

rheology and bread texture. A water alternative (W_{AL}) in bread-making process, depending on its type and composition, can also serve as an effective factor in improving nutritional profile, organoleptic properties and shelf-life of the product (Mollakhalili-Meybodi et al., 2023; Sadeghi et al., 2024). There are three main categories of W_{AL} in bread formulation including plant-based, dairy-based and fermented extracts (Fig. 1).

Importantly, bread can act as a carrier for bioactive compounds, enhancing its nutritional value and potential health benefits. These compounds can be incorporated through various methods, including the use of specific flours, plant/dairy-based extracts/by-products, or even nanotechnology to entrap and deliver these beneficial substances. Considering the high amounts of food by-products, recycling of these potential value-added substrates has received considerable attentions as a sustainable solution for economic losses and climate change problems in the near future. SD biotechnology is also an emerging approach to revalorize agro/food by-products to manufacture enriched bread containing these value-added bioactive compounds. Most of the W_{AL} are also plant/dairy-based by-products that are cost-effective materials for bread-making compared to the common bakery additives. Interestingly, application of food by-products as efficient substrates for SD fermentation has been reviewed by Pontonio et al. (2024) focusing on their techno-functional capabilities. Bread fortification with plant/dairy-based by-products offers a sustainable way to enhance nutritional value and potentially improve the sensory attributes of the product. Food by-products can be incorporated into bread formulations, increasing bioactive compounds, fiber content and mineral levels. These by-products can also improve the nutritional profile and rheological behaviors of the produced dough. There are several mechanisms to enhance nutritional value of bread fortified with food by-products like incorporating nutrient-rich by-products into the dough, which directly increases the bread's nutrient content. Additionally, these by-products can improve the bread's shelf-life and sensory properties, making it more appealing and practical. Furthermore, emerging techniques like microencapsulation can be used to protect and deliver sensitive nutrients, ensuring their stability and effectiveness during processing, storage period and gastrointestinal transit (Sadeghi et al., 2023; Pontonio et al., 2024).

Plant-based materials include fruit and vegetable juices or extracts obtained from various parts of plants, which due to their fiber and phenolic compounds (phenolics), can also positively impact different quality indices of the produced bread. Dairy-based resources, such as milk, whey and buttermilk, are also highly nutritious, and due to their moderate acidity, enhance the quality of the product. Recently, considering limitations associated with dairy-based beverages like their cholesterol content, lactose intolerance and potential allergenic activity of dairy proteins, plant-based beverages and juices as proper alternative delivery vehicles/media for nutraceuticals has received considerable attentions. Fermented functional beverages/juices/extracts are also emerging W_{AL} in bread. The common substrates used to produce functional extracts are including fruit-based, cereals, legumes, nuts and plant-based milks (Gavahian et al., 2020; Gupta et al., 2023).

There are several important factors to select a proper starter culture in fermented extract processing as complex plant/dairy-based matrices: (i) survivability/adaptability of the strain in the substrate with efficient population for proper acidification; (ii) effects of the strain on sensory attributes of the final product. High survival of lactic acid bacteria (LAB) in contrast to other Gram-positive bacteria in the present of phenolics is a crucial task to apply them in this type of alternatives as starter culture due to their detoxification capability. Recently, microbial diversity of traditional beverages as proper isolation source have been reviewed for adaptable microbial cultures, and potential beneficial cultures including bacteria and fungi for application in this category of functional products (Amoah et al., 2022; da Silva Vale et al., 2023).

Although application of powdered or microencapsulated extracts is common in bread processing compared to their liquid form, considering the logic of their application, minimally processed extracts have higher nutritional profile for efficient bread fortification. Moreover, lower cost and simplicity of the process is another benefit compared to the powdered or encapsulated ingredients (Rahaie et al., 2014; Rousta et al., 2021). Application of these W_{AL} in bread formulation is an emerging strategy to enhance different aspects of the product quality. Proteins of dairy-based materials and their interaction with gluten network, as well as acidic pH, fiber content and phenolics of plant-based materials are some important beneficial components that affect nutritional profile, organoleptic properties, textural features and storage stability of the supplemented product. Techno-functional capabilities of these value-added bakery improvers are also discussed in the following sections focusing on the main action mechanisms involved in their promising effects.

2. Promising effects of water alternatives on bread quality

2.1. Sensory attributes

Flavor, aroma, shape, color, chew ability and mouth feel are some of the most important sensory attributes of the produced bread that can be studied using validated instrumental analyses or trained panelists' evaluation. These organoleptic properties of bread have also strong correlation with its consumer acceptability. There are interesting reports about effects of W_{AL} on overall acceptability (OA) of the manufactured bread. For example, Pokuah et al. (2024) produced bread by fully substituting water with soymilk as optimized formulation, which received significantly higher scores for aroma, taste and OA compared to the control commercial sample. These researchers suggested that the improved OA of the bread could be attributed to the increased Maillard reaction in the soymilk added bread. Raczyk et al. (2022) used tomato, carrot and beetroot juices to produce bread; the results showed that tomato juice had no significant effect on sensory attributes, while carrot juice and beetroot juice were influential. The highest score was achieved in bread containing 50 % beetroot juice. Moreover, using 15 % carrot juice as W_{AL} had an adverse effect on the bread's porosity, flavor and color. When the replacement level was increased to 50 %, it had a positive effect on taste and porosity, while negatively affecting the flavor and color of the crust, resulting in lower scores for the produced samples compared to the control bread. These researchers identified aromatic compounds, flavoring substances and acidity as factors affecting the taste of bread and its OA.

Tsanasidou et al. (2021) produced bread using untreated cheese whey, which initially showed no significant difference in taste and odor compared to the control sample on day zero. Meanwhile, after four days of storage at room temperature, the sample containing 240 mL whey in 400 g wheat flour showed a significant change in taste. The manufactured bread also showed a decrease in odor during the four-day storage. According to Izzo et al. (2020), 100 % of water was replaced with freeze-dried and liquid goat whey fermented with *Lactiplantibacillus plantarum* (CECT 220, 221, 223, 748), to produce pita bread. Sensory attributes showed no significant difference between the control sample and other breads. The highest score (7.1) was given to the control sample, while the lowest score (3.6) was observed in bread containing liquid fermented whey. In the same vein, no significant differences were observed in sensory attributes by Kakan et al. (2016), where paneer whey (25–100 % as W_{AL}) was used in bread production. Iuga et al. (2020) replaced 12.5 % of the water with acid whey in bread production and found the lowest scores in appearance, color, aroma, taste, flavor and texture. However, in terms of OA, the sample containing 12.5 % acid whey received higher scores compared to the sample with 25 % acid whey. When milk was used as W_{AL} at 25 % and 12.5 %, no significant differences were observed between the produced samples.

In the study of Bilgin et al. (2006), the wheat bread containing 100 % whey achieved higher OA compared to the buttermilk. It seems that whey with a pH around 5–6, which is not very acidic, does not significantly affect sensory attributes. However, more acidic whey with a lower pH influencing the fermentation time and baker's yeast activity, improves sensory attributes of the product during the first days of storage. Nonetheless, over time, it produces the sour taste which negatively affects sensory attributes. Another emerging application of W_{AL} in bread processing is modification of the OA in SD added products. Sour taste is one of the most important sensory attributes of the SD breads, which is not usually accepted by all consumers. Accordingly, herbal extracts can be used in SD or SD bread formulation as W_{AL} to improve this criterion (Sadeghi et al., 2023). In this regard, Ziaee rizi et al. (2024) and Safari et al. (2025) verified the positive effect of ginger and garlic extracts, respectively on quality indices of the produced SD bread. Production of wheat bread with controlled fermented sprouted mung bean containing ginger extract not only increased mold-free shelf-life of the product after 7 days storage in a challenge test, but also improved its textural features (reduced crumb hardness and increased loaf specific volume) in the study of Ziaee Rizi et al. (2024). Moreover, there was no significant difference between control bread and the aforementioned sample in terms of OA. Meanwhile, this sample showed the highest chew-ability and aroma among the studied sensory attributes compared to the produced breads. Accordingly, application of W_{AL} has direct and/or indirect effects on OA of the produced bread considering their natures, components and interactions with flour ingredients during fermentation and baking processes.

2.2. Nutritional values

Protein fortification, particularly in terms of essential amino acids, fiber and vitamin enrichment, as well as enhancing total phenolic content (TPC) or antioxidant activity are some of the most important roles of W_{AL} on nutritional values of the produced breads. It should be mentioned that, high temperatures during baking, storage conditions, and consumption over a few days are key factors that affect the nutritional values of the product. Therefore, it is essential to consider all of these factors when producing bread with a new formulation. Also, adding W_{AL}, depending on the type of additive and its components, can enhance health-promoting effects on consumers. For instance, adding W_{AL} rich in protein, antioxidant compounds, vitamins and fiber can produce bread with higher nutritional value. In this regard, application of fermented and non-fermented plant-based extracts, fruit juices and/or other herbal extracts as W_{AL} in SD bread enables us to produce phenolic-rich breads with enhanced health-promoting and techno-functional features. These herbal extracts are rich in antioxidants and other bioactive compounds with approved potential effects on safety of food supply chain and consumers health (Nionelli et al., 2018).

In the study by Pokuah et al. (2024), replacing water with soymilk in bread production resulted in a 1.2-fold increase in crude protein content. Considering the lack of essential amino acids and weakness of cereals in terms of nutritional profile, fortification of bread with protein-rich ingredients like soybean and its derivatives is a crucial part of bread-making process in the near future. Replacing water with 125 g frozen acerola (fruit native to tropical regions of the America) pulp along with 125 g crystalline sugar in bread production (in 500 g wheat flour) also resulted in an increase in vitamin C (from 0 to 33.67 mg/100 g) and TPC (from 50.65 to 239.35 mg/100 g) (Boas et al., 2024). It is worth mentioning that vitamin C can be used to prevent the irreversible oxidation of phenolics. Moreover, the world health organization (WHO) recommends a daily intake of at least 45 mg vitamin C for a healthy adult. Therefore, using breads enriched with vitamin C could contribute to meeting part of the daily vitamin C requirement.

Cunha et al. (2023) produced bread using 35 % pequi (a fruit native to Brazil) pulp as W_{AL}, resulting in bread with a higher fiber content compared to the control sample. The crude fiber content of the control bread was equal to 0.45 g/100 g, while the bread containing 35 % pequi pulp had 0.59 g fiber/100 g, showing a significant increase in fiber content. Dietary fiber is an important component in food and plant edible parts, resistant to digestion and absorption in the small intestine, and is partially or fully fermented in the large intestine. Given the proven beneficial properties of dietary fiber in food, the food and drug administration (FDA) of USA recommends a daily intake of 28 g. As a result, the use of pequi pulp produces bread with higher nutritional value. Kaya and Asir (2022) reported that addition of black and green kombucha teas (100 % replacement) to bread improved TPC especially in crust compared to the crumb, which could be due to the Maillard reaction during baking and the breakdown of high-molecular-weight phenolics into smaller ingredients under the acidic conditions of kombucha fermentation and or under baking process (Antolak et al., 2021). There are also some reports indicated that the baking process did not degrade phenolics, and the increase in TPC can be partly due to the release of these ingredients into the bread matrix (Raczyk et al., 2022). Interestingly, W_{AL} in bread-making can influence the levels of anti-nutritional compounds, primarily through their impact on enzyme activity, dough hydration and overall processing conditions. The type of W_{AL} and the specific processing method can affect the extent of anti-nutrient reduction. Water-salt soluble extract obtained from controlled SD fermentation has also potential application to reduce phytic acid content of the product due to its acidic pH and probably present of the microbial phytases produced during fermentation. These W_{AL} affect indigenous phytase activity through modification of the pH (Sadeghi et al., 2023).

There is also limited research on dairy sources as W_{AL} in bread production in terms of nutritional value. Given that dairy products are rich in protein, using such ingredients can increase the protein content of bread, contributing to the production of a more nutritious product. In this regard, Luz et al. (2021) used fermented mozzarella whey as W_{AL} in bread production at 50 % and 100 %. TPC in the bread containing L. plantarum TR7 at both concentrations was higher than that of the control sample especially in 100 % whey added bread. Considering the inefficient nutritional components especially proteins in cereal flours, fortification of bread dough using cost-effective W_{AL} is a fundamental progress to develop functional breads and to enhance consumer's health in developing countries.

2.3. Antifungal activity

Generally, bread spoilage can occur through bacterial and fungal contaminations; meanwhile, moldiness is the most important obstacle in bread shelf-life due to its effects on consumer safety and huge economic losses. Importantly, fungal secondary metabolites such as mycotoxins are also amongst the high-risk hazardous factors for human. Chemical preservatives like propionic, sorbic and acetic acids, as well as their salts can eliminate the fungal spoilage in bread. Although these bakery additives are classified as generally recognized as safe (GRAS), their use causes consumer dissatisfaction due to development of some resistant fungal strains. There are some efficient clean-label strategies to extent mold-free shelf-life of the produced bread. Controlled SD fermentation using protective cultures and application of antifungal herbal extracts as alone or in combination with SD protective cultures are some examples of these effective approaches (Sadeghi et al., 2019; Ziaee rizi et al., 2024). In promising studies, combined application of SD fermentation and antifungal herbal extracts was also reported to extent mold-free shelf-life of the produced bread (Nionelli et al., 2018; Rasoulifar et al., 2024). Application of herbal extracts as SD formulation not only affects OA of the produced SD bread but also improves mold-free shelf-life of the product. Antimicrobial compounds of herbal extracts or inhibitory metabolites produced during fermentation by SD LAB are effective in this preservative activity.

Many studies have shown that plant-based extracts contain various bioactive components that can control the growth of fungi. For example, Nionelli et al. (2018) used hop extract in SD bread production, which delayed fungal growth for up to 14 days. These researchers observed that the addition of 0.3 % (w/v) calcium propionate or 25 % (v/v) hop extract significantly reduced the germination of Penicillium roqueforti. Hop extract, due to its bitter acids and essential oils, interferes with ion transport and alters proton ion concentrations across cell membranes, leading to intracellular accumulation, reduced pH, and ultimately, microbial cell death. The phenolics in hop extract also prevent microorganism replication by accumulating inside the cell or penetrating the phospholipid membrane. Moreover, correlation between antioxidant activity and in situ antifungal effect of these ingredients has been reported in some studies. It is hypothesized that the degradation of phenolics of the herbal extract to effective ingredients during fermentation is also very important in this inhibitory effect (Karabín et al., 2016; Purabdolah et al., 2020). Mikulec et al. (2020) added cistus (a medicinal herb that grows in Mediterranean regions) extract at 2.5, 5 and 7.5 % as W_{AL} in bread, and evaluated the shelf-life of the product 1 to 5 days after baking. The results showed that the total bacterial count, total aerobic amylolytic bacterial count, and total spores of amylolytic bacteria were lower in the bread containing extract. On the third day, Aspergillus niger growth was visible in the control bread, and changes in the bread crumb (crumb becoming soft, sticky and viscous) indicated the growth of Bacillus bacteria. Meanwhile, in samples containing 2.5 and 5 % extract, changes appeared in the crumb by day three, suggesting the growth of Bacillus, but no mold growth was observed until day five. In the bread containing 7.5 % extract, no mold growth was observed, and bacterial activity-induced changes were minimal.

Algboory et al. (2021) utilized the aqueous extract of *Cyperus rotundus* rhizome as W_{AL} (10 % and 20 %) in wheat bread, demonstrating the potential of plant extracts for enhancing the shelf-life of bread. The aqueous extract exhibited significant antimicrobial activity, inhibiting the growth of A. niger (78 %), Penicillium spp. (89 %), Bacillus cereus (90 %) and Bacillus subtilis (95 %). Fungal growth in bread containing the extract was also delayed until the 11th day of storage at 30 °C, compared to the control sample, where growth appeared after just 4 days. Accordingly, the significant effect of the extract on fungal growth was verified. The researchers attributed the antimicrobial properties of the extract to the presence of phenolics such as coumarins, tannins and flavonoids. It is now known that phenolics, by forming soluble high-molecular-weight complexes and binding to proteins, can interact with the surface receptors of microbial cells and disrupt their activities. In another study, completely replacing water with sweet whey from goat's milk fermented with L. plantarum, in pita bread, showed stronger antifungal effect compared to freeze-dried whey on Penicillium brevicompactum and Penicillium expansum (Izzo et al., 2020). Moreover, L. plantarum 220, 223 and 221 strains exhibited stronger antifungal effects than L. plantarum 748. In samples where sweet fermented whey was used as W_{AL}, a 100 % reduction in the growth of P. expansum and a 98 % reduction in P. brevicompactum growth were also observed. The results showed that after storing pita bread at room temperature for 10–20 days, the pH decreased (pH ranged from 4.63 to 5.08, while the pH of the control sample was 6.11). The researchers stated that the antifungal effect was likely due to the organic acids produced (e.g., lactic and acetic acids) during fermentation, and the pH reduction after fermentation.

Luz et al. (2021) explained the antimicrobial effect of organic acids as being due to the creation of unfavorable acidic conditions for the growth of harmful microorganisms, interference with maintaining the cell membrane potential, reduction of intracellular pH, and inhibition of active transport. Although in the study by Izzo et al. (2020), the complete replacement of water with fermented whey also affected the reduction of water activity. As a result, the aforementioned researchers identified the reduction of water activity and pH as key factors contributing to the increased shelf-life of pita bread. According to the obtained data, combined application of controlled fermentation and herbal extract as a complex hurdle affect mold growth and sporulation in bread and bread dough environments that extended mold-free shelf-life of the product.

2.4. Textural features and staling rate

Crumb hardness, chewiness, cohesiveness, springiness and other parameters of texture profile analysis (TPA), along with specific volume, porosity and weight loss are some of the most important textural features of the produced bread. Fresh, high-quality bread is soft and flexible in terms of texture. When chewed, it does not have a doughy texture and does not stick to the teeth. Textural features of the baked goods are important quality characteristics not only in terms of consumer acceptance and storage stability of the product but also from its digestibility viewpoint. These parameters have crucial effects on acceptability and shelf-life of the product (especially due to negative correlation between crumb hardness during storage period and staling rate of the product). There are also some reports about effects of W_{AL} on textural features of the manufactured bread focusing on the involved action modes.

In this regard, adding 35 % silver fir (*Abies alba* Mill.) needles extract

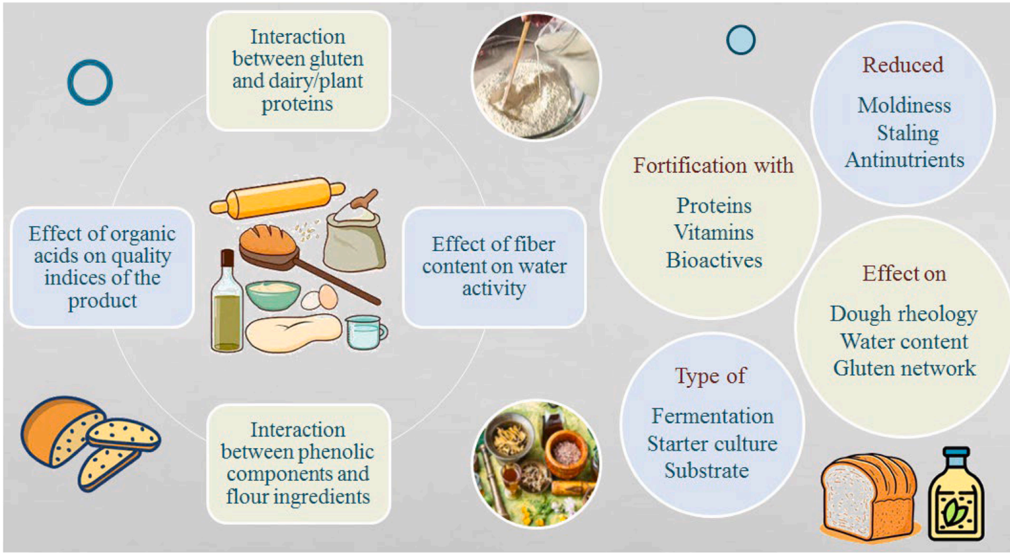

Fig. 2. Action modes involved in techno-functional capabilities of water alternatives in bread-making process.

increased the crumb hardness by 37 %, springiness by 21 % and chewiness by 41 % (Parenti et al., 2022). However, no significant differences in texture indices were observed between the samples containing 100 % W_{AL} and the control. The interactions between flour and antioxidant compounds of the extract may explain the observed changes. These researchers suggested that the quantity, type and chemical structure of the antioxidant compounds cause it to act similarly to vitamin C, thereby increasing dough strength and volume. It is reported that vitamin C increases dough viscosity by forming disulfide bonds with gluten proteins, which consequently enhances the specific volume of the bread (Beghin et al., 2021). Application of acerola pulp as W_{AL} in bread resulted in higher crumb firmness and chewiness. However, no significant difference in springiness was observed by Boas et al. (2024). The lower pH of acerola pulp (3.16) and its phenolics were introduced as effective parameters in this activity. Phenolics enhanced the interaction between enzymes and reduced yeast activity, thus increasing the hardness of the bread. Under acidic conditions, gluten swells and starch undergo partial hydrolysis, which increases the hardness of the final product. The positive impact of phenolics on the quality of cereal products has also been reported. These compounds likely weaken the gluten network by disrupting disulfide bonds and due to their reducing properties, result in reduced hardness and cohesiveness. Additionally, by interacting with starch, they delay its retrogradation.

Generally, phenolics can have both negative and positive effects on crumb hardness. These compounds can delay staling and soften the crumb initially, but also increase hardness and chewiness during storage. Their impact depends on the amount and type of phenolics, as well as other factors like interactions of phenolics with other components, particularly proteins and starch during bread-making process. Phenolics interact with gluten primarily through hydrophobic interactions and hydrogen bonding, influencing the gluten properties and its network's structure. These interactions can lead to changes in protein aggregation, secondary structure and the formation of new bonds, ultimately affecting dough characteristics. Besides, phenolics interact with starch through both covalent and non-covalent bonds, with non-covalent interactions like hydrogen bonding being most prominent. These interactions can lead to the formation of non-inclusion complexes, affecting starch's properties, digestibility and structure, or inclusion complexes where phenolics fit into the helical structure of amylose. These interactions with gluten and starch have also undeniable effects on quality indices of the manufactured bread (Schefer et al., 2021; Zhu et al., 2008).

In another study, the bread containing 35 % pequi pulp showed higher fiber content compared to the control (Cunha et al., 2023). Most fiber compounds have a strong tendency to absorb water, which increases the water absorption capacity of the dough. Rosell et al. (2001) indicated that the hydroxyl groups present in fibers form hydrogen bonds with water, thus increasing the water-holding capacity of the dough. This tendency of fibers to bond with water prevents water loss during storage and, by potentially interacting with starch, delays its retrogradation (Gómez et al., 2003). Meanwhile, the presence of fiber in baked products, depending on the type of fiber added, its quantity, and the type of product, can show either a positive or negative effect on the texture. Dietary fibers significantly impact bread texture through various mechanisms related to their interaction with dough components, primarily starch and gluten. These interactions affect dough rheology and the final bread characteristics. Positively, fibers can increase water absorption, improve dough mixing tolerance or tenacity, and potentially slow down staling, while negatively, they can reduce crumb softness and loaf volume, and produce a more dense crumb that require adjustments to the baking process (Chareonthaikij et al., 2016). In the study by Graça et al. (2019), the addition of 30 g yogurt (in 96.6 g wheat flour) to bread and the analysis of the crumb structure using scanning electron microscopy (SEM) revealed that in the yogurt-containing sample, the cell structure was more complex, and there were more air bubbles between the starch granules and denatured gluten compared to the control sample. With an increase in the yogurt amount to 50 g (in 94.3 g wheat flour), a more laminated structure was observed in the bread. This phenomenon was attributed to higher interaction between casein and possibly the presence of exopolysaccharides (EPS), which interact with the gluten network. Addition of milk or acid whey at 12.5, 25 and 50 % to bread resulted in a significant increase in hardness, gumminess and chewiness (Iuga et al., 2020). The hardness of bread is influenced by the viscosity of the liquid phase. Therefore, the higher hardness in the samples containing milk or whey may be due to the higher viscosity, which leads to the formation of stronger structures. Thus, the interaction between dairy proteins and starch increased the viscosity of the liquid phase, resulting in crumb hardness. The increase in gumminess can be attributed to the weakening effect of whey and milk on the gluten network, which causes the dough to become denser. The calcium ions present in dairy products may also interact with the gluten network, reducing the water content in the dough, thereby resulting in a denser dough structure. Increasing of solid soluble components also reduce crumb specific volume due to the increasing of crumb weight and lower water migration from crumb into the crust (Codină et al., 2018; Graça et al., 2019).

Table 1
Water alternatives and their effects on bread quality indices focusing on the involved action modes.

Water alternative	The most important effect	Mechanism of action	Ref.
Textural features			
Camel milk (30, 60 and 90 %)	Reduction of hardness (from 10.11 to 8.73) and chewiness (from 8.88 to 6.99), and increasing of cohesiveness (from 0.69 to 0.77) in gluten-free rice and buckwheat-based bread in control and supplemented sample with 90 % camel milk	Enhanced water absorption capacity and peak viscosity, with reduced dough stability and the temperature at peak viscosity	Abid et al. (2025)
Silver fir needles extract (35 and 100 %)	Increasing of crumb hardness (37 %) and chewiness (41 %) in supplemented sample with 35 % extract compared to the control, Anti-staling activity	Redistribution of moisture, starch-gluten interactions, and starch modification	Parenti et al. (2022)
Hydroalcoholic Corinthian grape extract (30 %)	Increasing of crumb hardness (0.32 N in control and 0.51 N in supplemented sample)	Creation of an azeotropic mixture, leading to a loss of available water and evaporation during baking	Nikolaou et al. (2022)
Kombucha; green tea and black tea (100 %)	Increased crust formation time, and hardness (4586 g in control and 6404–6871 g in supplemented samples)	Activity of phenolic compounds and the lower moisture content	Kaya and Asir (2022)
Cistus extract (2.5, 5 and 7.5 %)	Delayed staling and reduced crumb hardness (72.89 % increase in control and 29.03 increase in supplemented sample after 5 days storage)	Alterations in starch properties, gluten dilution, and increasing of fiber content	Mikulec et al. (2020)
Ultra-filtrated milk permeate and cheese whey (50 and 100 %)	Slight increase in ratio of solution absorption during dough preparation (farinograph) of Egyptian Baladi bread	Increase in ash, total solids, minerals carbohydrate and protein contents, as well as significant effect on dough mixing properties	Mahdy and Abo El-Naga (2018)
Fermented skim milk, acid cheese whey and buttermilk (25, 50, 75 and 100 %)	Retardation of staling rate with a softer texture	Increased stability time, water absorption, development time and decreased extensibility, maximum resistance to extension and energy	Hassan et al. (2013)
Sensory attributes			
Aqueous extract of *Cyperus rotundus* rhizome (10 and 20 %)	Adverse effect on sensory attributes of wheat bread (reduced flavor and aroma scores from 8.0 to 7.57 to 6.36–7.71 and 6.88–7.04 in supplemented samples, respectively)	Decrease in the aroma and taste scores due to the reduction in pH of the extract-containing bread	Algboory et al. (2021)

Table 1 (*continued*)

Water alternative	The most important effect	Mechanism of action	Ref.
Stinging nettle leaves and extracts (2.5 and 5 %)	Application of extract enhanced sensory properties of the product compared to leaves (The highest content of proteins was observed in the samples containing 5 % of extract and 2.5 % of both leaves and extract)	Improved bread's composition in phenolic acids, micro and macro elements with verified biological activity	Đurović et al. (2020)
Nutritional value			
Carrot juice, beetroot juice, and tomato juice (15, 30 and 50 %)	Increased antioxidant activity (DPPH radical scavenging activity of 108 μmol Trol/100 g in control and 1383 and 432 μmol Trol/100 g in supplemented samples with 50 % beetroot and carrot juices, respectively)	Production of bioactive compounds alongside total phenolic content (TPC)	Raczyk et al. (2022)
Camel milk (30, 50, 70 and 100 %)	Improved nutritional value (11.95 vs 14.01 %, 19.1 vs 20.9 % and 1.17 vs 1.65 % protein, linoleic acid and α-linolenic acid contents respectively in control compared to the supplemented sample with 100 % camel milk)	Progressive increase in the content of α-linolenic acid and linoleic acid as two essential fatty acids	Almoraie and Shatwan (2021)
Aqueous garlic extract (3, 6 and 9 mL/250 g flour)	Increased antioxidant activity	Improved phytochemical profile of bread in terms of flavonols, TPC, β-carotene and flavonoids	Suleria et al. (2015)
Shelf-life			
Buffalo whey fermented with L. plantarum TR7 and Lactobacillus ghanensis TR2 (50 and 100 %)	Extension of bread shelf-life up to 19 days post-baking	Production of volatile compounds during fermentation	Luz et al. (2021)
Kefir (10 and 20 %)	Longer 4–5 days shelf-life in sourdough bread containing kefir	Production of organic acids, higher acidity and greater formation of antimicrobial metabolites	Plessas et al. (2011)

TPC: total phenolic content.

The protein in bread flour forms a gluten network that provides structure and allows for gas retention during baking, contributing to an airy and well-risen loaf. When incorporating dairy/plant-based ingredients, the type and amount of substitution can affect the gluten network, potentially leading to variations in bread quality, especially when considering the type of bread flour used. Generally, strong bread flour, with its higher protein content, benefits from these additions by enhancing structure and loaf volume, while also influencing crust color and overall texture. However, excessive dairy/plan-based materials can negatively impact crumb hardness and specific volume. Moreover, heat treatment, both dry and hydrothermal, significantly affects the quality of bread made with dairy/plant-based materials by modifying the properties and structure of key ingredients like proteins and starch, and influencing their interactions. These changes impact the dough's rheology, moisture content, bread texture and overall sensory attributes. Specifically, heat affects starch retrogradation and gelatinization, causes protein aggregation and denaturation, and also alters moisture distribution within the loaf. Dry heat can increase crumb hardness and reduce rapidly digestible starch, while hydrothermal treatments can affect gluten network strength, protein solubility and starch properties. These changes can improve or impair bread quality depending on the specific treatment and type of ingredient. Excessive heat can also lead to undesirable changes like increased hardness and reduced digestibility.

In conclusion, the use of any type of W_{AL}, depending on its type and the components, creates different effects on the quality indices of the produced bread (Fig. 2). The presence of phenolics and fiber can show varying effects on the texture of the final product. Phenolics and peptide components of these W_{AL} in dough formulation affect disulfide bonds and subsequent gluten network structure. The pH and carbohydrate content of the extract are also involved in specific volume changes. Presence of organic acids affects protein and starch hydrolysis, which change dough intensity and its gas retention ability. Some reports about effects of W_{AL} on quality of the produced bread are illustrated in Table 1.

3. Conclusion

Fortification of bread as staple food has a key role in our daily diet. Bread is also a proper vehicle for functional components due to its low price and high worldwide acceptability. There are several approaches for bread fortification. Among them, application of plant-based, dairy-based and fermented extracts/juices as W_{AL} has received considerable attention. These sustainable, cost-effective and clean-label bakery additives have crucial effects on nutritional values and quality of the produced bread. Considering protein profile, fiber content and phenolics of these value-added ingredients, their effect on techno-functional capabilities of the product is undeniable. Moreover, acidic environment of the fermented dairy-based or plant-based materials along with microbial metabolites produced during fermentation affect textural features, sensory attributes, and also mold-free shelf-life of the supplemented bread. Accordingly, W_{AL} in bread-making process not only have fortification potential but also can improve quality properties of the product.

Despite the high production rates of enriched bread worldwide, bread waste remains a significant issue. Staling, moldiness and undesirable flavors caused by microbial activity are major contributors to bread waste. Application of W_{AL} not only can improve quality characteristics of the product but also can manage bread waste. Some of the main action modes involved in these promising effects has been discussed in the present article. Meanwhile, there are few reports about adverse effects of W_{AL} on sensory attributes or textural features of the product. Production of unwanted components like acrylamide in protein rich breads has also been reported that need to be addressed in the future. Accordingly, future trends in the field must be focused on novel W_{AL} with optimized formulation under controlled conditions for wider applications. Moreover, exact mechanisms underlying techno-functional features of these additives should be determined in molecular level using high-throughput instrumental analyses to expand our current knowledge about health-promoting potentials of these bakery additives.

Ethical statement

There are no studies with humans/animals in this work.

Data availability

No data was used for the research described in the article.

CRediT authorship contribution statement

Alireza Sadeghi: Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Zahra Kardooni:** Investigation, Writing – original draft. **Maryam Ebrahimi:** Data curation, Investigation, Methodology, Writing – original draft. **Elham Assadpour:** Methodology, Validation, Writing – review & editing. **Seid Mahdi Jafari:** Writing – review & editing, Validation, Methodology, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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