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The influence of processing technologies on the biological activity of carbohydrates in food

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ABSTRACT

Food processing transforms raw materials into different food forms using physical or chemical techniques. Recently, carbohydrates have gained attention for their diverse biological activities like antioxidant, anticancer, and antimutagenic effects. Selecting suitable processing methods is crucial to preserve the beneficial properties of carbohydrates. This review discusses the impact of non-thermal and thermal processing on the physicochemical and biological traits of carbohydrates, highlighting the need for understanding the mechanisms underlying these changes. Future research will focus on enhancing and safeguarding the biological and functional aspects of carbohydrates through improved processing techniques. The goal is to optimize methods that maintain the beneficial properties of carbohydrates, maximizing their health benefits for consumers.

1. Introduction

Carbohydrates include monose, oligosaccharides, polysaccharides, and complex carbohydrates combined with protein or lipids (Li et al., 2023). It widely exists in plants, microorganisms, and animals (Fig. 1). In recent years, carbohydrates have garnered significant attention from researchers in food and biomedicine, with investigations into its potential antitumor, immunomodulatory, antioxidative, and anti-inflammatory effects (Zhao et al., 2019). Researchers extracted water-soluble polysaccharide from the dried pericarp of *Zanthoxylum bungeanum*, resulting in WZBP-A-III being identified as a pectic polysaccharide with a "smooth region" structure and fewer side chains, demonstrating the most potent antioxidation activity. Moreover, it was observed that WZBP-A-III extended the lifespan of *Drosophila melanogaster* and enhanced the activity of antioxidant enzymes (Liu, Deng, et al., 2024). Algal polysaccharides are also a huge natural polysaccharide biological resource, *Ulva lactuca* polysaccharide alleviates type 2 diabetes by enhancing insulin tolerance and increasing SOD and CAT activities, leading to reduced blood glucose levels (Ruan et al., 2023). The antitumor and immunomodulatory effects of fungal polysaccharides are particularly prominent, the water-soluble polysaccharides AcF1 and AcF3 from *Inonotus obliquus* have a strong potential for cancer immunotherapy by triggering multiple PRRs and by inducing potent anticancer activity of macrophages (Wold et al., 2024). These main bioactive compounds have high anticancer and antioxidant activities *in vitro* and *in vivo*, and play an essential role in preventing many chronic diseases (Fig. 2).

Food processing is the transformation of raw food materials into food or other forms of food by physical or chemical means, which can be used to preserve and improve food nutrition and sensory characteristics (Benchamas et al., 2020). Food processing can enhance food safety by inactivating food-borne pathogens, natural toxins, or other harmful components. Following processing, the material's digestibility, bioavailability, functional properties, and nutritional value are

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enhanced, while its texture and flavor become more appealing (Huang, Ai, et al., 2022; Wang & Li, 2024). On the other hand, food processing will also bring some adverse consequences, such as losing some nutrients, forming toxic compounds (acrylamide or acrolein), and produce compounds that harm taste perception, texture, or color (Zhao et al., 2019).

Food processing often alters the physical and chemical properties of various nutrients in food, which in turn influence their biological activities. Hence, selecting appropriate processing methods and conditions is paramount depending on the intended processing objectives. While many researchers investigate the physiological functions of carbohydrates, there remains a need to systematically analyze and study changes in the physicochemical properties and biological activity of carbohydrate compounds before and after processing. This paper aims to review the alterations in carbohydrate content and biological activity during food processing.

2. Thermal and non-thermal processing on carbohydrates

Food processing methods can be roughly divided into heat treatment and non-thermal processing depending on whether the food is heat-treated (Gomez-Lopez et al., 2022). Thermal processing methods for food include baking, frying, blanching, extrusion, *etc.* Cooking is food processing from the perspective of diet, the food can obtain better color, fragrance, and taste of food, making it easier for the body to absorb nutrients (Fernandez et al., 2024). Theories of heat transfer and thermodynamics support the non-thermal processing technology, which revolves around the research and development of new microwave, infrared, and radiation science technologies, including ultra-high pressure processing, ultrasound technology, pulse technology, ultraviolet radiation technology, and others (Liu, Ye, et al., 2024). These technologies are mainly used for food sterilization and enzyme inactivation. Compared with heat sterilization, non-thermal processing has an excellent protective effect on the color, aroma, taste, functionality, and nutritional components of food, especially heat-sensitive nutrition. It can ensure the original freshness and quality (Pandiselvam et al., 2023). For example, extrusion processing can increase the level of resistant starch and the amount of soluble non-starch polysaccharide in cereals (Boukid & Castellari, 2022; Huang, Liu, et al., 2022). Extracting alginate from brown algae through extrusion yields alginate of higher purity compared to the traditional batch extraction process (Sugiono et al., 2019). The viscosity of pectin increases under high pressure, possibly due to pressure altering the intermolecular interactions of pectin. Boiling carrots and green beans leads to the degradation of pectin (Broxterman et al., 2017). During the cooking of kidney beans, polysaccharide will dissolve, resulting in a decrease in total fiber content (Khrisanapant et al., 2021). However, the increase in fiber content during boiling may be attributed to the formation of complexes between polysaccharide and other food compounds, such as proteins (Khrisanapant et al., 2021). The processing of *Brassica* in home food preparation or industrial processing may have a significant impact on the content of glucosinolates; the heat treatment of cooking, microwaving, and frying has no significant effect on the yield of glucosinolates. In contrast, boiling reduces the content of glucosinolates by about 90% more effectively (Barba et al., 2016).

Understanding the impact of food processing technologies on the structure and activity of bioactive carbohydrates aids in the rational selection of processing technologies and conditions and facilitates the optimal utilization of food raw materials.

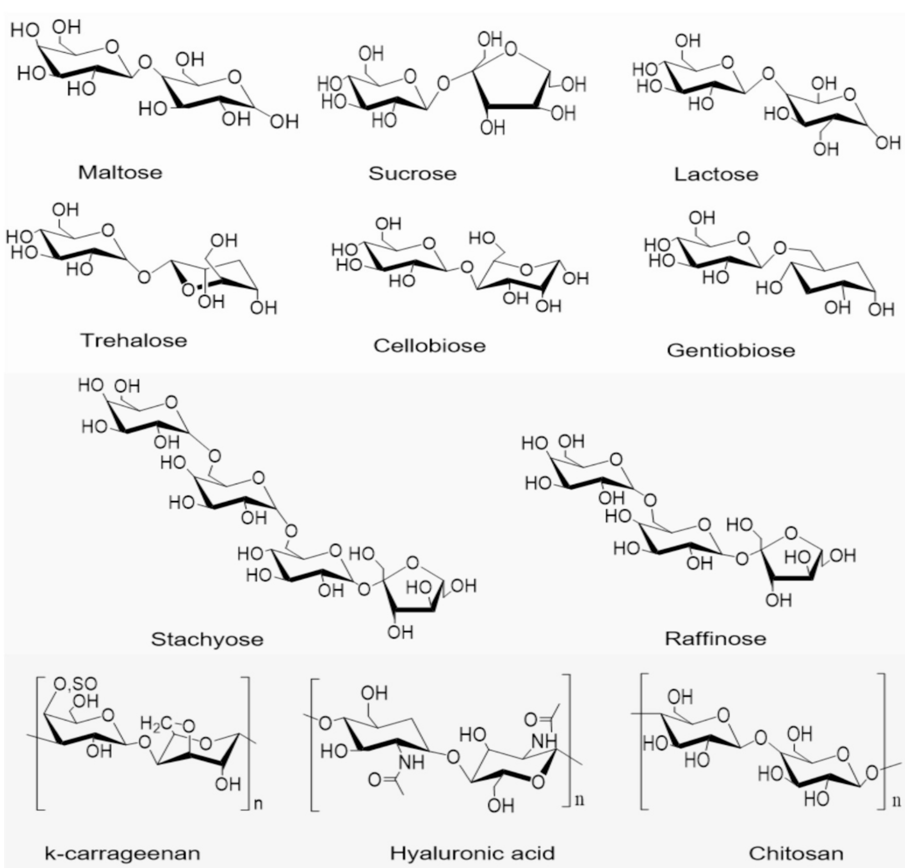

Fig. 1. Chemical structure of common carbohydrates.

3. Thermal processing

Thermal processing is the most widely employed process technology in the food industry, ensuring the microbiological safety of products (Ali et al., 2023). These methods primarily involve generating heat external to the product, achieved through combustion of fuels or *via* an electric resistive heater, and transferring it into the product through conduction and convection mechanisms (Lin & Xiao, 2024).

3.1. The baking, frying and other daily cooking techniques

Baking, and frying, are indispensable steps in the production of bread and cake products, such as starch gelatinization and protein denaturation after baking, frying the bread and cake reach maturity. Besides providing the flavor of food, the daily cooking techniques can kill microorganisms and reduce the moisture content to play a role in preserving (Lin & Xiao, 2024). The starch is the main ingredient in many foods and the main polysaccharide in the human diet. Starch granules are mainly composed of two main polysaccharides, amylose and amylopectin. Both polysaccharides consist of α-(1,4)-linked D-glucose residues that are linked to each other by α-(1,6)-glycosidic bonds to form branches in the polymer (Cui et al., 2022). The non-starch polysaccharides can be divided into the major groups: cellulose, non-cellulose polymers, pectin. Arabinoxylan, mixed linked β-glucan, mannan, and xyloglucan are examples of non-cellulose polymers, while polygalacturonic acids replaced by arabinan, galactan, and arabinogalactan belong to the pectin category (Ciudad-Mulero et al., 2019; He et al., 2022). In the cooking process, resistant starch increased while amylose decreased. The granular structure of glutinous rice starch is significantly compromised by frying, leading to a transformation from a regular, complete, and smooth appearance to an irregular, rough texture. Scanning Electron Microscopy micrographs demonstrate the fracture of disk-shaped starch grains during frying, resulting in the formation of a continuous and dense gel structure. Moreover, an increase in frying temperature is associated with a decrease in starch molecular weight. X-ray Diffraction and Fourier Transform Infrared data indicate the formation of starch-lipid complexes during frying. *In vitro* digestion analysis reveals a decrease in starch digestibility and an increase in resistant starch content following frying. Additionally, the shear stability of fried starch improves, while swelling and solubility

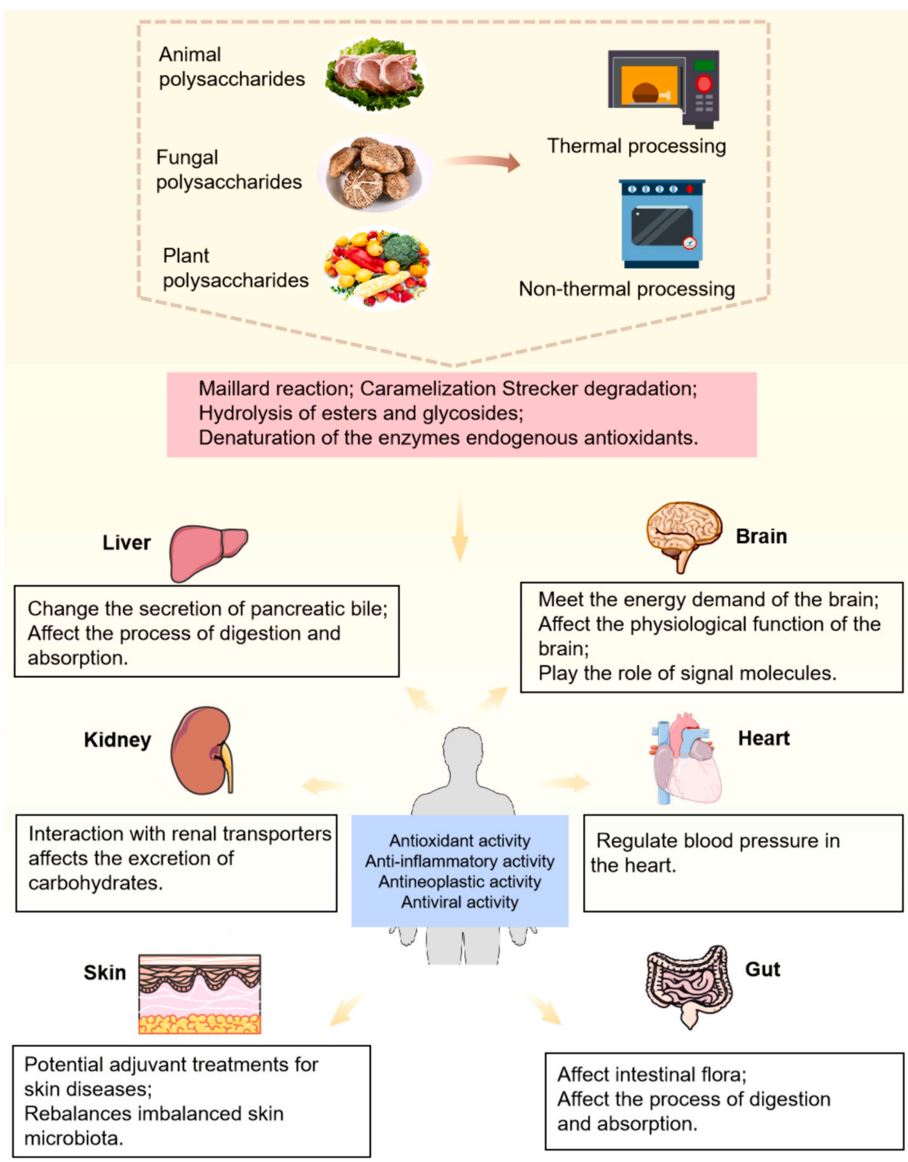

Fig. 2. Absorption and disposal of polysaccharides after food processing by human beings, polysaccharide seems to increase antioxidant capacity and inhibit oxidative stress and inflammation.

decrease (Ciudad-Mulero et al., 2022). Also, non-cellulose polymers and pectin polysaccharide decreased during the daily cooking process (Yang et al., 2020). Thaler (1979) reported that polysaccharides are degraded after light baking, while this proportion increases to 35%–40% after deep baking (200–230 °C,15–20 min). Arabinogalactans are more easily degraded than mannan or cellulose; degraded mannans may interact with Maillard products during roasting to produce molecular complexes. The depolymerization could be attributed to a loss of side-chain arabinose and fission of the galactose backbone.

Saccharides in daily cooking undergo degradation under Maillard and gelatinization conditions. For starch grains, high temperature or specific humidity leads to gelatinization, causing water molecules to enter the amorphous part of the starch grains and break the hydrogen bonds. With increasing temperature, the hydrogen bond in the crystallization zone of starch grains is disrupted, leading to the irreversible and rapid transformation of starch into a highly viscous starch paste (Fig. 3). In this process, the morphology of starch particles is destroyed, resulting in the severe degradation of amylopectin and the formation of starch - lipid complex. Therefore, in daily cooking, whether the functional activity of bioactive polysaccharide is still effective after processing and how to make its structure suitable for Maillard reaction and gelatinization is still a challenge to be studied.

3.2. Blanching

The blanching process can purify the specific enzymes in the food, reduce the nutrient content of the microorganisms, and eliminate some microorganisms, particularly those remaining on the product's surface (Lee et al., 2023). Blanching effectively removes air between the cells of fruits or vegetables and obtain storage stability. Besides extending the shelf life, blanching can also enhance the color of most fruits and vegetables (Lee et al., 2023). According to report, blanching apple slices resulted in a lower browning index and a higher antioxidant capacity (Wang et al., 2022). Wang et al. (2018) utilized atomic force microscopy, low-field nuclear magnetic resonance and magnetic resonance imaging to determine the nanostructure, water state and distribution of pectin in the cell wall of the samples, and observed that the berry tissues were obviously softened by bleaching, while the water-soluble pectin increased, the polysaccharide nanostructures of grapes cell wall showed obvious depolymerization and degradation.

After high humidity hot air impact blanching increased the content of water-soluble pectin, transmission electron microscopy showed that blanching destroyed the cell wall structure and the integrity of the interlayer (Deng et al., 2018). Blanching may affect carbohydrates by inactivating enzymes, demethylating pectin, and the structural changes of cell wall induced by bleaching are mainly due to the β- elimination degradation of pectin (Sila et al., 2009) (Fig. 4**)**. During the processing of *Pueraria lobata* root, polyphenol oxidase can be inactivated by pre-cooking or blanching to inhibit browning. The blanching treatment specifically protects the integrity of *Pueraria lobata* whole powder cells, which may be that blanching makes the cell wall pectin undergo a demethylation reaction and strengthens the cell wall, and reduces the release of starch, it is manifested as a decrease in the blue iodine value (Liu et al., 2021). Highly methylated pectin is not readily soluble in water, leading to the outflow of intracellular solution from fruits and vegetables, thus affecting the release of sugars, With an increase in blanching time, the effects of hot water and steam treatments on peach quality are similar, resulting in more collapsed surface microstructure. This treatment leads to the passivation and deactivation of phenol oxidase and peroxidase, texture decline, weakened browning degree, decreased VC content, and increased total phenol content and antioxidant capacity (Fan et al., 2019). Nonetheless, blanching can affect texture and nutrient content, reduced total starch and carbohydrate content. Future research could explore optimized blanching methods to balance preservation and nutritional quality in various food processing contexts.

3.3. Extrusion

Food extrusion processing technology is a high and new technology that integrates mixing, stirring, crushing, heating, cooking, sterilization, puffing, and molding, due to its minimal nutrient loss, negligible nutrient depletion, high speed, and other reasons, it has developed rapidly in the food processing industry (Flores et al., 2024). The formation of gel in the extrusion process is related to amylose, and the viscosity of the material is related to amylopectin. The high shear force in the extrusion process can convert starch into glucose to the greatest extent and reduce the relative molecular weight of starch (Ge et al., 2024). The study of Wang et al. (2016) found that the soluble fiber content of mixed flour after extrusion was significantly higher than that of mixed flour before extrusion (MFBE). The increase in soluble fiber (SF) may be attributed to the high temperature and high pressure during the extrusion process. The lipid and amylose content of MFBE is significantly lower which may be attributed to the interaction between

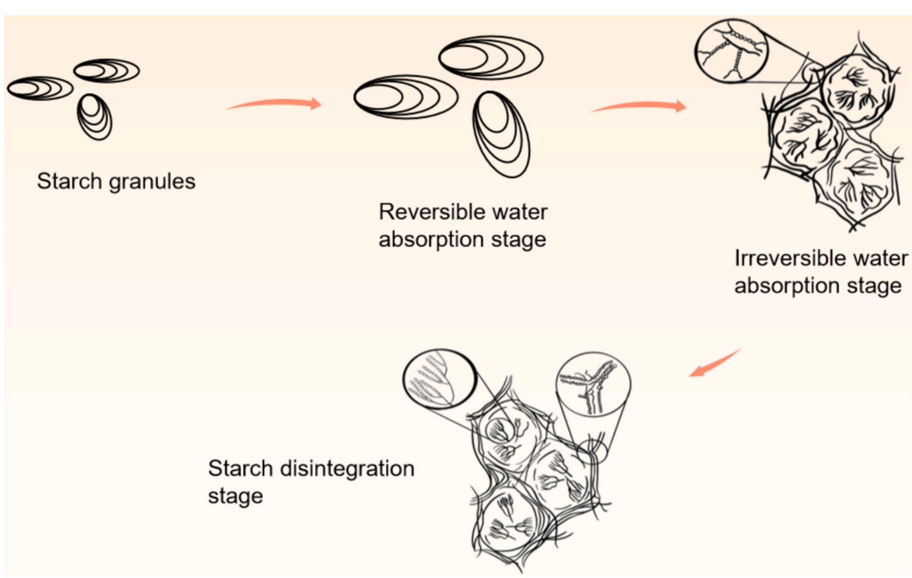

Fig. 3. Diagram of how starch-water mixture changes during daily cooking.

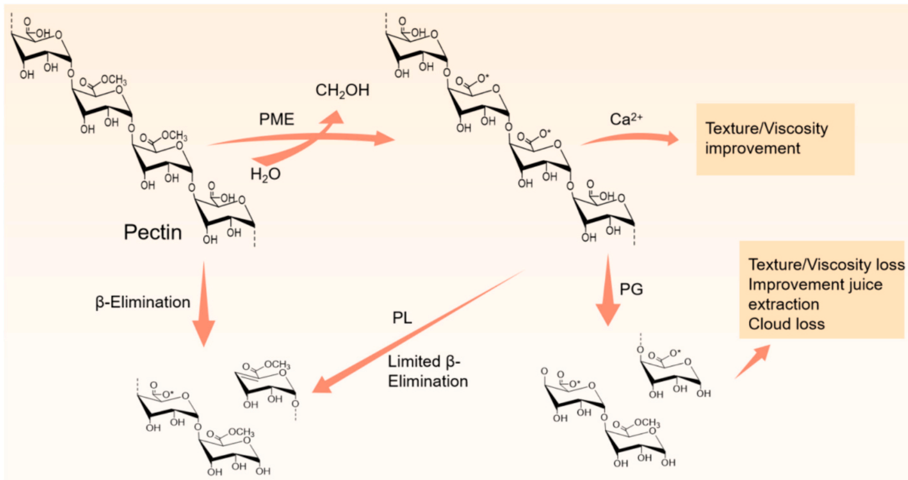

Fig. 4. Schematic diagram illustrating the improvement of juice extraction. PME: pectin methylesterase, Ca^{+2}: calcium crosslinking, PG: polygalacturonase, PL: pectin lyase, and T: temperature.

lipid and amylose during extrusion. Using of single-screw extruders to extrude different kinds of barley, When the extrusion temperature is 130 °C, the water content is 20%, the rotation speed is 220 r/min, the content of β-glucan and soluble dietary fiber is significantly increased, while the content of insoluble dietary fiber is significantly reduced, the extrusion process caused changes in dietary fiber content and affected the molecular weight of dietary fiber (Honcu et al., 2016). Also, after barley is extruded, the average molecular weight of arabinoxylan and β-glucan is reduced, thereby improving the extractability of the two carbohydrates , the reason may be due to the extrusion of barley. The speed of the screw reaches 400 r/min, which makes the shearing force on the material more extensive, which leads to the break of the chemical bond (Vasanthan et al., 2002).

Extrusion degrades amylopectin and increases the proportion of amylose. A more significant shearing force will cause chemical bonds to break, which will change the relative molecular mass of carbohydrate compounds. In addition, research data shows that when the temperature of the barrel reaches about 180 °C, the loss rate of sucrose is 15%–20%. The analysis of this process is mainly due to the occurrence of Maillard between reducing sugars and proteins. The reaction led to this result (Fig. 5A).

3.4. Sterilization

Traditional sterilization technology involves thermal processing aimed at killing microorganisms in food, stabilizing food quality, effectively extending the shelf life of food, reducing the presence of harmful bacteria, and preventing human infection caused by the ingestion of live bacteria or bacterial toxins, which can lead to human poisonin (Wei et al., 2023). The heat sterilization technology in the food processing link mainly includes pasteurization and ultra-high temperature sterilization (Wada & Loennerdal, 2014). The Maillard reaction is a kind of non-enzymatic browning that widely exists in heat sterilization processing (Sun et al., 2023). Dairy products are rich in protein, peptides, amino acids, lactose, and galactose, making it challenging to avoid Maillard's reaction during the heat treatment of dairy products. For example, the glycosylation reaction of protein is a Maillard reaction, in which carbohydrates are linked to proteins of covalent bonds to form glycosylated proteins (Jiménez-Castaño et al., 2007). The content of Maillard reaction products (MRP) in differently heat-treated dairy products varies. The higher the heating temperature and the longer the heating time, the higher the MRP content (Wada & Loennerdal, 2015). Lactose not only participates in the Maillard reaction during the heat treatment but also decomposes above 100 °C. As the temperature

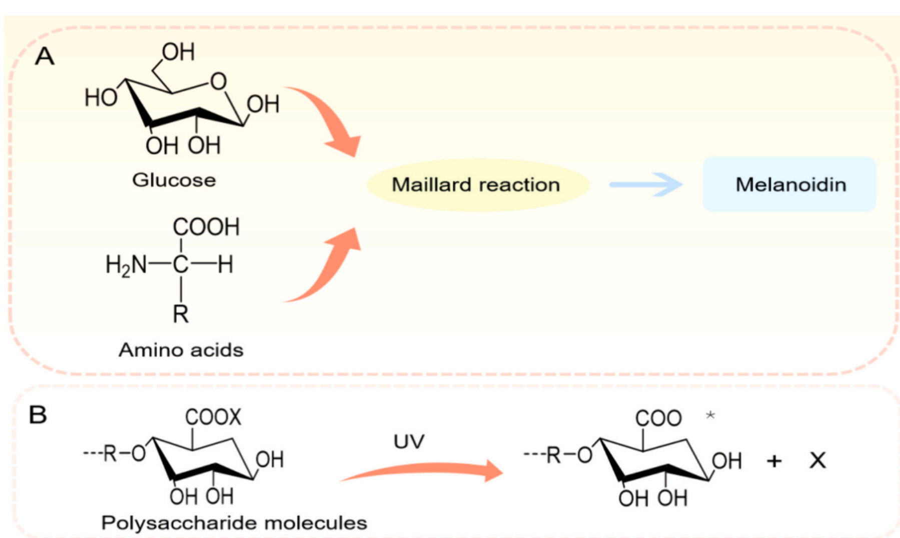

Fig. 5. Maillard reaction of glucose occurs (A); Uronic acid undergoes decarboxylation under UV (B).

increases, lactose will be severely browned due to caramelization (Singh et al., 2021).

4. Non-thermal processing

Food non-thermal processing is a new food processing technology, mainly used for sterilization and blunt enzymes, including ultra-high pressure, high pressure pulsed electric field, high pressure carbon dioxide, ionizing radiation, pulsed magnetic field and other technologies for food processing (Gomez-Lopez et al., 2022).

4.1. Ultra-high pressure processing (UHP)

Ultra-high pressure (UHP) processing technology has garnered increasing attention in the food industry as a non-thermal food processing method (Zhao et al., 2019). UHP acts on non-covalent bonds such as hydrogen bonds, ionic bonds, and hydrophobic bonds, leading to protein denaturation, enzyme inactivation, and sterilization, which will impact the food (Xu et al., 2023). UHP can make starch into a paste and protein into a gelatinous state, obtaining a different food flavor from the heat treatment (Xu et al., 2019). This disruption is caused by breaking hydrogen bonds and interrupting hydrophobic interactions between the molecules. Water molecules from the treatment replace the broken hydrogen bonds, causing extensive hydration. This results in a loss of ordered structure in amylose molecules and the transition of amylopectin from helices to random coils, losing their crystallinity (Carvalho et al., 2024). The extraction of polysaccharides from shier using UHP technology has been demonstrated to be feasible. However, the application of high pressure may result in the rupture, loosening, and shrinking of cell walls, bringing about structural alterations in the material (Zheng et al., 2024). While UHP can induce softening in beans, the degree of softening is lower compared to that achieved through heat treatment. This could be attributed to high pressure inducing conformational changes in the molecular structure and active enzyme centers, resulting in a loss of activity. Consequently, there is a decrease in the degradation of pectin in cell walls, and gel esterase is inactivated, thereby maintaining the structural integrity of the cells (Zhao, He, et al., 2023).

4.2. Ultrasound processing

Ultrasound treatment has beneficial changes in food quality and physical and chemical properties (Gencdag et al., 2021). Ultrasound treatment can represent a viable non-thermal technology for inactivating microorganisms in a mixture of fresh orange and celery juice while improving its stability and maintaining its freshness and quality (Ruiz-De Anda et al., 2019). Ultrasound reduced the particle size, turbidity, and gel properties of hawthorn pectin and decreased the molecular weight and distribution, and enhanced the antioxidant activity of pectin (Chen et al., 2019). In addition, long-term treatment reduces the total phenol content and *in vitro* antioxidant activity of sweet potato powder, which is mainly due to pyrolysis caused by cavitation and the release of hydroxyl free radicals (Cui & Zhu, 2020). These changes depend on the time, degradation, and modification of the chemical components of flour (such as starch and polyphenols). However, ultrasound can also induce adverse effects on food quality, for example, the appearance of off-flavors and degradation of compounds related to nutritional attributes, such as vitamins, polyphenols, omega-3 fatty acids, protein, carotenoids, and fiber (Schiano et al., 2019).

4.3. Pulse processing

The types of pulse processing mainly include pulsed light (PL), pulsed electric field (PEF), and intense pulsed light (IPL). PL is a new non-thermal sterilization technology characterized by its lack of radiation, absence of chemical residue, low energy consumption, and high efficiency (Braga et al., 2019). It effectively eliminates harmful microorganisms such as viruses, fungi and bacteria through photothermal and photochemical effects, thereby achieves sterilization effect, with minimal impact on the nutritional value and quality of food (John & Ramaswamy, 2018). PL irradiation induces changes in the crystalline regions in the polysaccharide structure, leading to the formation of larger polysaccharide molecules. From the original kinetic simulation, it is concluded that the value of W0 to W80 increases with the increase of times, and the high energy barrier of W80 can be obtained, which is not conducive to the dehydration of polysaccharides, so the polysaccharides are better preserved (Tsai et al., 2017).

PEF treatment technology is a new technology, and its ability to improve biological activity has attracted more and more attention (Cholet et al., 2014). More researchers are employing PEF treatment for polysaccharide extraction, with its primary mechanism involving the disruption of cell membranes (Xu et al., 2024). Under high electric field intensity, the potential difference inside and outside the cell membrane becomes larger, which leads to the appearance of pores on the cell membrane, so that more solvents can enter the cells, and more polysaccharides can easily permeate the cell membrane. Therefore, the higher the yield of polysaccharide. PEF treatment accelerated the extraction speed and improved the extraction rate of corn silk polysaccharide (Thikham et al., 2024). Using PEF technology to extract polysaccharides from *Rana Temporaria chensinensis* David, which found that the total sugar content was 26.34% higher than that of compound extraction method, with fewer impurities in the extracted materials (Yin et al., 2006).

IPL, as a non-heat treatment method, can reduce enzyme activity by altering enzyme structure, thereby mitigating adverse reactions caused by the browning reaction during processing (Alhendi, 2021). IPL treatment has been shown to reduce non-enzymatic browning during drying, effectively retaining sodium glutamate, reducing sugars, and total phenols, while increasing the content of dried lentinan and reducing sugars, and reducing the generation of 5-hydroxymethylfurfural (Zhang et al., 2021). Therefore, pulse treatment technology can effectively inprove the polysaccharide content.

4.4. Ultraviolet radiation processing

Ultraviolet light (UV) is an electromagnetic wave with a wavelength lies between visible light and X-ray, and its sterilization effect is most effective at a wavelength of 254 nm (Tinello & Lante, 2018). The primary sterilization mechanism of ultraviolet rays is the damage to microbial nucleic acid. When exposed to ultraviolet rays, microorganisms undergo photochemical damage, leading to the formation of photoproducts, which in turn inhibit DNA replication and transcription, ultimately resulting in microbial death (Salazar et al., 2022). UVA-LED treatment could effectively inhibit the browning of fresh-cut apples and pears. Some studies have shown that polysaccharides such as dextran, pectin and cellulose will degrade under ultraviolet irradiation, and the main performance of degradation is the decrease of viscosity (Lante et al., 2016). Uronic acid could directly absorb ultraviolet energy, form free radicals, depolymerize and decarboxylate polysaccharides (Fig. 5B). Understanding the role of uronic acid in absorbing UV energy to facilitate the depolymerization and decarboxylation of polysaccharide opens new possibilities for innovative applications in food processing.

In the future of UV processing, polysaccharides present significant potential for enhancing sterilization efficacy and food preservation. By harnessing UV technology to optimize the degradation of polysaccharides like dextran, pectin, and cellulose, notable improve their viscosity reduction properties. This advancement has the potential to transform food processing methods, offering more efficient and environmentally friendly approaches to sterilization and preservation. With continued research and innovation, UV processing holds promise for enhancing the safety and shelf life of food products, meeting the evolving needs of consumers and the food industry.

5. Effect of process on bioactivities of carbohydrates

5.1. Antioxidant activity

The polysaccharides' antioxidant activity is influenced by molecular weight, monosaccharide composition, sulfate position, and many other factors (Fernandes & Coimbra, 2023). People have paid more and more attention to antioxidant products through studying cell models and experimental animal models, which observed that carbohydrate compounds mainly realize antioxidants by regulating antioxidant defense system and signal pathways related to oxidative stress (Fig. 6). The fucoidan appears to exert anti-dyslipidemic and anti-atherosclerotic effects by inducing lipoprotein lipase activity and inhibiting inflammation and oxidative stres (Du et al., 2022; Yokota et al., 2016). Five different types of polysaccharides from different varieties of a*uricularia auricula* by alkali method and then deproteinized them, the antioxidant mechanism of *Auricularia auricula* polysaccharides might be related to its ability to up-regulate the activity of antioxidant enzymes *in vivo* (Xu et al., 2016). The chemical composition of *Pleurotus ostreatus* polysaccharides changed significantly in each processing process. The antioxidant activity decreased by approximately 26% after blanching and by 12% after boiling. Furthermore, the antioxidant activity of samples subjected to blanching and fermentation decreased by up to about 52%, which was attributed to the reduction in protein and phenolic compounds (Radzki et al., 2016). The freeze-dried form of *Angelica Sinensis* polysaccharide (ASP-FD) exhibited the highest antioxidant capacity, potentially attributed to variations in monosaccharide ratios, elevated GalA content, and the relatively low molecular weight and loose internal structure of the polysaccharides (Wang et al., 2019).

The change in antioxidant activity may be in many ways, two hypotheses have been proposed to explain this phenomenon. First of all, the Maillard reaction, caramelization, and hydrolysis of esters and glycosides occur during the healing process, resulting in new antioxidants, reducing the antioxidant activity of polysaccharides (Eliodório et al., 2023). Secondly, endogenous enzymes are denatured due to heat, thus degrading antioxidants (Losada-Barreiro et al., 2022). Therefore, the antioxidant activity of polysaccharides is also affected during cooking.

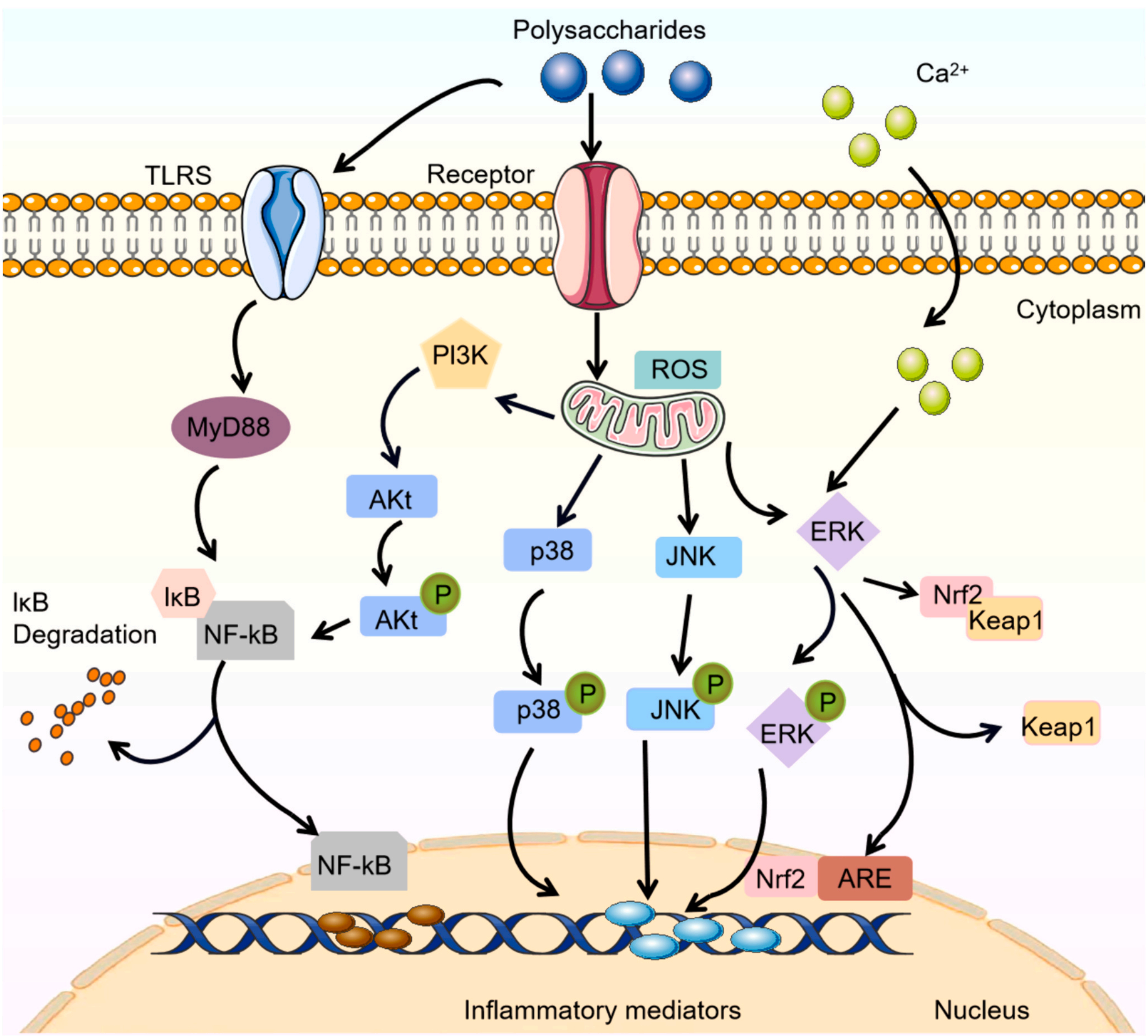

Fig. 6. Antioxidant reaction and cellular regulation of polysaccharides as antioxidants.

5.2. Antitumor activity

The chemical structure and physical properties of different polysaccharides exhibit significant variability in their anti-tumor properties (Zhao, Zhang, et al., 2023). These carbohydrate compounds demonstrate potent anti-tumor activity when combined with polypeptides, proteins, or other conjugates, or when linked with various side groups (Zhang et al., 2022). Their anti-tumor activity is demonstrated through direct inhibition of tumor cell growth, such as inducing tumor cell apoptosis, inhibiting tumor angiogenesis, and affecting tumor cell signal pathways (Su et al., 2024). Additionally, they exert an anti-tumor effect by enhancing immune function, including the activation of macrophages and lymphocytes (Chen & Huang, 2018) (Fig. 7). Chen et al. (2017) subjected it to high-temperature steam at 300 °C, resulting in the production of a special favorite black ginseng (FBG) with high concentrations of reducing sugar, rare saponin, and an aglycone. In the mouse model, the production of *TNF-α*, *IL-2*, and *IFN-γ* was significantly reduced when fed FBG, demonstrating that FBG could enhance immune function and induce apoptosis of tumor cells. The alteration in anti-tumor activity suggests that variations in the proportion of active ingredients under different processing conditions can influence anti-tumor efficacy (Prendeville & Lynch, 2022). Overall, understanding the relationship between molecular structure and anti-tumor activity can inform the development of more potent and targeted cancer therapies.

5.3. Anti-inflammatory activity

In recent years, the anti-inflammatory activity of polysaccharides has also attracted a lot of attention. The anti-inflammatory effect observed in the polysaccharide of *Morinda citrifolia Linn* (noni-PLS) is that it can block the action of inflammatory mediators and signal molecules and promote tissue dysfunction in several inflammatory diseases (Sousa et al., 2018). Wu et al. (2021) compared the structural differences between *Astragalus* polysaccharide homogeneous honey-processed *Astragalus* polysaccharides (HAPS3A) and *Astragalus* polysaccharides (APS3A) processed by homogeneous honey, and their effects on colitis in mice. The results indicated that the molar ratio of monosaccharides changed with honey processing, and HAPS3A exhibited superior anti-inflammatory effects compared to APS3A in terms of protecting intestinal mucosa and regulating cytokine expression. High-temperature processing led to the isomerization of polysaccharides, resulting in changes to the monosaccharide composition and their anti-inflammatory activity. *G. lucidum* fruiting body increased its polysaccharide yield after heat stress (HS) treatment at 42 °C. However, HS treatments at 37 °C and 45 °C did not significantly affect the polysaccharide yield. Additionally, the activity of polysaccharides also increased under the 42 °C HS treatment (Tan et al., 2018).

5.4. Antiviral activity

Polysaccharides possessing antiviral activity, as components with high efficiency and low toxicity, hold significant potential in medicine. Polysaccharides extracted from seaweed have demonstrated the ability to combat various viruses by interfering with different stages of viral infection (Anjali et al., 2022). Two kinds of homogeneous sulfated polysaccharides have been extracted from *Gymnogongurus griffithsiae* and *Cryptonemia crenulata*, both exhibiting remarkable anti-replication activity of dengue virus (Talarico et al., 2005). The principle underlying sulfated polysaccharides involves the addition of sulfate groups to the glycosyl units of polysaccharides, thereby altering their structure. This modification enhances the ability of polysaccharides to promote the phagocytosis of macrophages, stimulate the secretion of interleukins such as *IL-6* and *IL-1β* by macrophages, and improve antiviral immune activity (Chen et al., 2019). The antiviral mechanism of polysaccharides is that polysaccharides can directly enter cells to kill viruses. For example, carrageenan can directly kill viruses to not be infected, thus

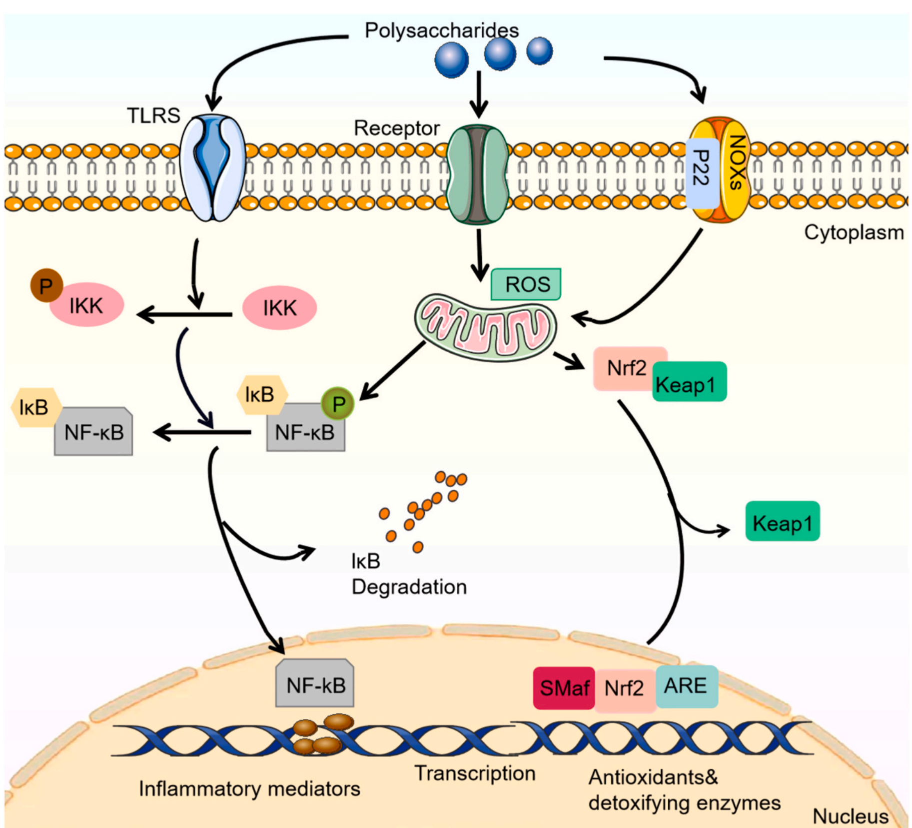

Fig. 7. Anti-tumor reaction and cellular regulation of polysaccharide.

effectively reducing the proliferation of viruses (Hu et al., 2019). The other is to inhibit virus adsorption, affect the steps of virus adsorption, including the expression of virus particles and proteins, and subsequently inhibiting virus invasion or replication. Additionally, polysaccharides can activate immune responses *in vivo* (Rao et al., 2020).

6. Conclusion

Various cooking methods induce significant chemical and physical alterations in food, impacting the biological activity and functional attributes of carbohydrates. Heat treatment, for instance, triggers the Maillard reaction in most carbohydrates, altering food flavor while reducing impurities in polysaccharides and modifying their structure and chemical composition. High-temperature processing causes polysaccharide isomerization, thereby changing monosaccharide composition and solubility. Glucosinolates degrade during heating, affecting polysaccharide biological activity. Extrusion degrades amylopectin, altering carbohydrate functionality. Non-thermal methods like ultrahigh pressure processing rupture cell walls, enhancing polysaccharide extraction efficiency, while ultraprocessing reduces molecular weight, improves antioxidant activity of pectin, and minimizes browning through pulse and ultraviolet technologies. Evaluating carbohydrate effects on physiology under various processing conditions is crucial for determining retention or elimination. Through an extensive examination of dietary carbohydrates in food processing, their functional characteristics have become a focal point of considerable interest. Future research endeavors are anticipated to delve into how carbohydrate activity evolves with diverse processing methods. For instance, there is a growing interest in understanding the effects of different heat treatments on the glycemic index of starchy foods.

CRediT authorship contribution statement

Peng Song: Writing – original draft. **Yajun Huang:** Writing – original draft. **Jingru Li:** Writing – original draft. **Shuo Shan:** Writing – review & editing. **Zhengsong Zhou:** Writing – review & editing. **Hui Cao:** Writing – review & editing, Investigation. **Chao Zhao:** Writing – review & editing, Investigation, Funding acquisition.

Declaration of competing 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.

Data availability

Data will be made available on request.

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