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Sugar-Based Water Retention Agents in Meat Products: Enhancing Water-Holding Capacity and Promoting Health Benefits

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ABSTRACT: For the purpose of satisfying high demands for taste, color, flavor, and storage of meat products, water retention agents (WRAs) play an important role. Phosphate has been widely used as an attractive functional material for water retention in current practical applications. However, excessive phosphate addition and long-term consumption may be harmful impacts on health and the environment. Therefore, it is vital to develop safe and efficient phosphate-free WRAs for further improving water-holding capacity (WHC) efficacy and edible safety, especially in meat products. In particular, sugar water retention agents (SWRAs) are increasingly popular because of their perfect safety, excellent WHC, and superior biological properties. This review discusses the inducements and mechanisms underlying water loss in meat products. In addition, we focused on the research progresses and related mechanisms of SWRAs in the WHC of meat products and its unique biological functions, as well as the extraction technology. Finally, the future application and development of SWRA were prospected.

Keywords: sugar water retention agents; phosphate-free; meat products; water-holding capacity; biological function

1. Introduction

As the "soul" of modern food manufacturing, food additives have contributed to the rapid growth of the food industry [1]. Water retention agent (WRA) is added to food during the processing to maintain the internal moisture content, which plays a considerable role in food additives, can control water activity, extend shelf life and ensure food quality [2,3], especially in the quality of meat products. According to projection, there will be a 452 million ton increase in global meat consumption between 1980 and 2050 [4], which makes it crucial to maintain the quality of the final meat product. Thus, it is not only important to control the moisture content of meat products, but also closely related to the quality of the product, including color, juiciness, and tenderness [5,6]. Therefore, controlling the moisture and how it exists is key to ensuring the quality of meat products, which is why the selection of WRAs is so crucial. Most of the WRAs commonly used in markets for

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meat products are phosphates framed by legislation that can improve water-holding capacity (WHC), reduce freezing and melting loss, change texture, produce better color and reduce cooking loss during the processing [7,8]. A compound phosphate or phosphate-containing compound food WRA can reduce water loss and increase water content to effectively improve WHC, simplify food processing technology, and reduce the total amount of additives through the synergistic effect of several substances, thereby reducing the production costs of food processing enterprises and essentially replacing single phosphates [9,10].

Despite its wide use in meat products due to its good WHC, phosphate also has many side effects in practical application (Fig. 1): (I) Products treated with more than 0.5% phosphate will affect the color and cause unpleasant metallic astringency and soapy taste. As a result of precipitation, meat products will display "snowflakes" and "crystals" during storage [11]; (II) Overphosphorylated cooked or cured cooked pork may contain *Clostridium perfringens spores* [12], which may also cause abdominal pain and indigestion if ingested in large quantities in a short period of time [13]; (III) Long-term phosphate intake could produce hormonal changes equivalent to mild hyperparathyroidism, reduce 1, 25 (OH) 2D levels, disrupt calcium homeostasis, and impair calcium absorption, increasing the risk of bone diseases such as rickets and osteoporosis [14,15]; (IV) A high serum phosphorus level increases the burden on the kidney, causes endothelial dysfunction and vascular calcification, increases the risk of cardiovascular diseases (such as hypertension and atherosclerosis), and even speeds up the progression of lung and prostate cancers [16–21]; (V) While phosphate in room temperature and above condition can be used to maintain moisture and yield well, it also increases the difficulty of corrosion protection, resulting in an increase in the overall cost rather than a decrease [22]; (VI) Despite the low level of phosphate consumption in food, waste and abuse are still prevalent in the production process, causing phosphate to enter the ecosystem and may cause eutrophication in rivers [23]. The current situation of achieving "carbon neutral" and a "carbon peak" calls for food processing to revert to green, low-carbon, and energy-saving processes [24]. Therefore, phosphorous-free WRA that is both safe, efficient, and low-cost is an economically and socially significant technology.

Phosphorus-free WRAs mainly include sugars, proteins and phosphorus-free salts [25,26]. Using phosphate-free WRA can solve the major problems of import and export trade frustration caused by excessive phosphate addition, such as product quality decline and cost increase, that are currently facing the meat processing and food production industry. It benefits the food industry economically and has wide applications. Especially, sugar-based water retention agents (SWRAs) is widely applied in practice due to its low-cost, excellent stability, and unique biological function. In addition to obtain excellent WHC by forming hydrogen bonds, stabilizing and expanding the spatial structure, chelating synthesis of three-dimensional network, increasing the water indication tension, increasing the glass transition temperature to lock the water in meat products, they can deliver powerful health benefits such as regulating oxidative stress levels, blood lipids and blood sugar, modulating immune response and gut microbiome, and others [27–30]. This review describes the ways and mechanisms of water loss in meat products and focuses on the progress of SWRAs. The types and

mechanisms for meat products excellent WHC of action of SWRA were systematically reviewed, as well as the biological function and extraction technology. Finally, prospects for developing SWRA were outlined.

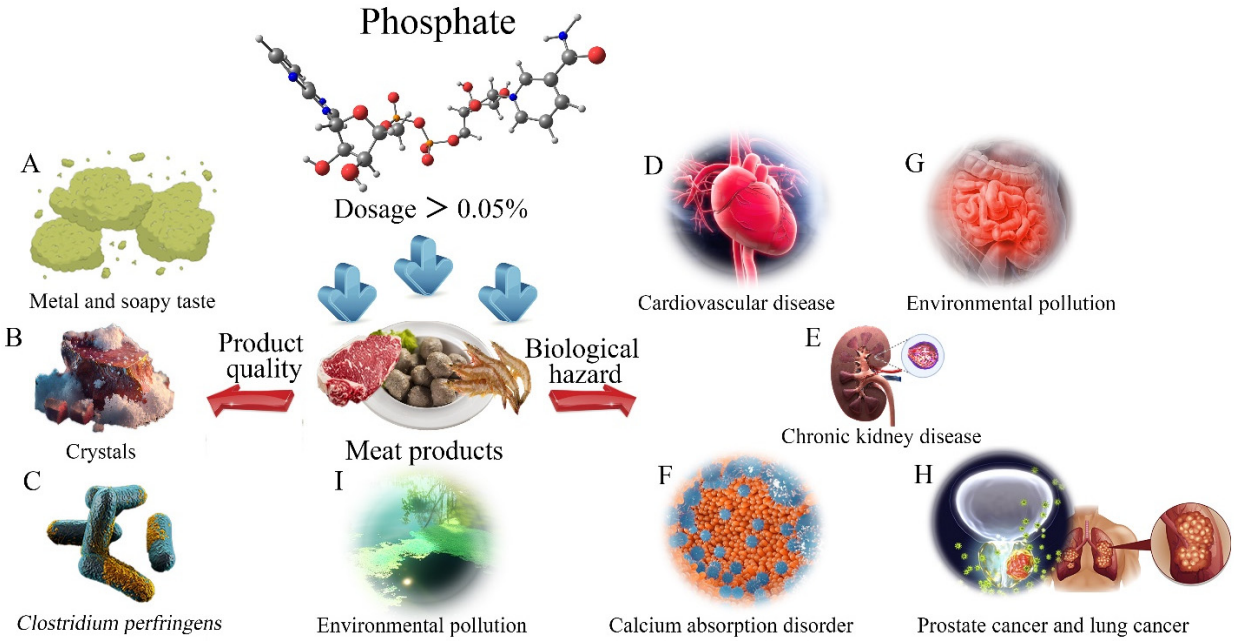

Figure 1. The disadvantages of phosphate WRA. A. The astringency of metal and soapy taste; B. Formation of crystals. C. Induce the development of *Clostridium perfringens* spores in cooked pork; D. Cardiovascular disease (e.g., atherosclerosis); E. Aggravation of chronic kidney disease; F. Calcium absorption disorder; G. Abdominal pain and diarrhea; H. Prostate cancer and lung cancer; I. Environmental pollution.

2. Water loss of meat products

The process of storing and processing meat products before consumption will affect the amount of moisture in the meat products as well as the taste and flavor (Fig. 2) [31,32].

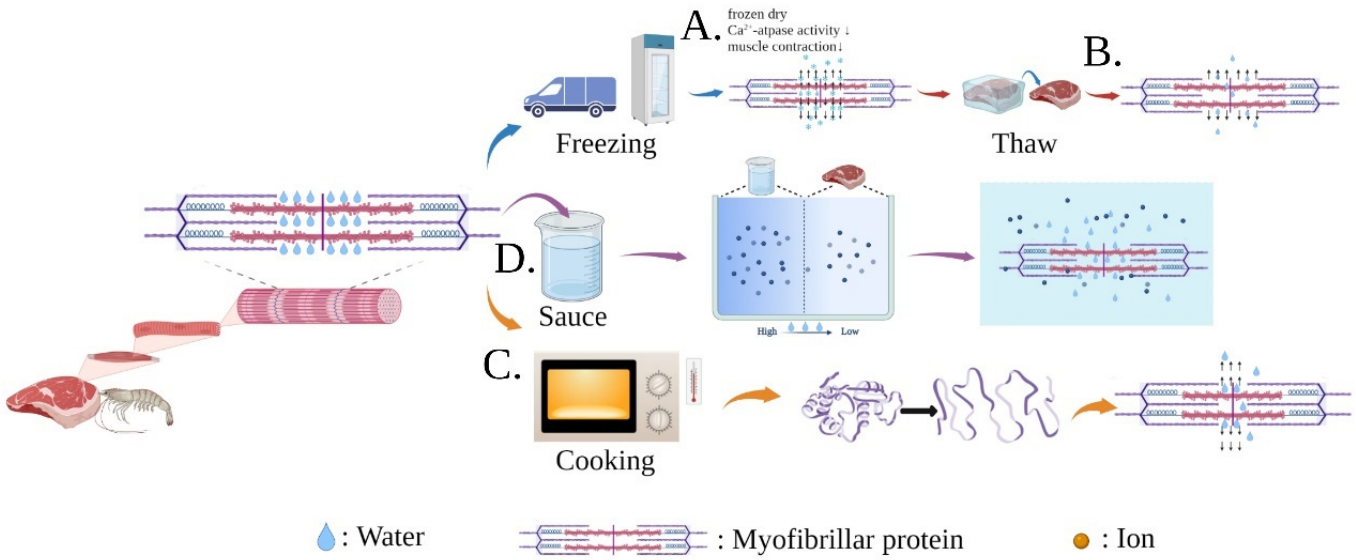

Figure 2. Water loss factors of meat products. A. Changes in temperature during frozen storage led to moisture sublimates, causing water to migrate to the surface and ice crystals to form, so that the meat becomes frozen dry, but more importantly, frozen causes Ca^{2+}-ATPase energy to be consumed, which reduces muscle contraction, water molecules to overflow, and internal ion strength to increase, resulting in an accelerated decomposition process; B. During thawing, Water remelts from ice crystals and cannot be fully absorbed by proteins to restore, resulting in drip loss; C. Thermal deformation occurs during cooking, resulting in severe muscle contraction and dehydration; D. Adding meat together with sauce causes the cells to contract and loss of water due to the high osmotic pressure.

2.1 Storage and transportation process

(1) Freezing: Meat products are typically frozen and stored to inhibit microbial growth and reduce autolyse activity, thereby extending shelf life [33,34]. In the process of frozen storage, however, protein denaturation may occur in meat products, causing damage to the electrostatic bond between water and protein, reducing WHC content and frozen dry [35]. During the freezing process, temperature changes cause water vapor pressure to differ and ice crystals to sublimate, resulting in surface drying and deterioration of the quality of meat products [36]. Further, the condensation of water into alters water migration rates and forms ice crystals in muscle tissue. In addition, myofibrillar protein (MP) undergoes freezing degeneration, which results in a decrease in Ca^{2+}-ATPase activity so that ATP-induced muscle fiber contraction is reduced. Subsequently, an increase in the movement of water molecules from inside the muscle fiber to the outside, and an excessive increase in intracellular ions after water migrates to the extracellular space leads to the degradation of myofibrils and intramuscular connective tissue during freezing [32,37–39]. All of these changes cause a continuous loss of water. The use of WRA before frozen dry is a common way to reduce consumption. The appropriate WRA can crosslink together to form a network structure, which increases the binding force of water molecules and effectively reduces water loss.

(2) Thaw: In the process of thawing, ice crystals melt into water, and the water cannot be absorbed fully by the protein in meat products, leading to water loss, usually called juice outflow, also known as drip loss, which adversely affects meat products' elasticity and tenderness [40,41].

2.2 Processing

(1) Cooking loss: Cooking causes protein thermal denaturation, resulting in muscle contractions and water loss, thus reducing weight and moisture content. For instance, water is the most abundant component in the fish’s body, and cooking will dehydrate the fish. Around 40 ℃ is generally the first stage of weight loss and 65 ℃ is the second. The water will be expelled and the WHC of muscle proteins will decrease after thermal contraction [42,43]. Meanwhile, beef has also been shown to have the most open structure in its network porosity at 60 ℃. The connective tissue network shrinks rapidly and permeability is extremely high, resulting in significant water loss. According to mass and heat transfer science, the pressure driven water loss is a substantially more important mechanism governing the water loss on frying of beef-burgers than the evaporation losses occurring at the surface crust [44].

(2) Osmotic pressure loss: After cooking, curing, and other processes, some meat products are put into sauces and packaged together for the market, but high osmotic pressure will force water to spread out between and within cells, inducing cell contraction [45]. This will reduce the net solid weight of the product and alter the original flavor [46].

2.3 Factors affecting WHC of meat products

Water in meat products is mainly preserved in the structure of muscle and muscle cells and can be divided into bound water (about 10%), retained water and free water [5,47]. Under freezing conditions, bound water has little mobility and is tightly bound to proteins. WHC is primarily maintained by steric hindrance and the

attraction of bound water. Free water has weak surface forces and flows unhindered in and out of tissues. As a result, WRAs aim to maintain the retained water [5]. As shown in Fig. 3, temperature, pH value, ionic strength, actomyosin dissociation, degree of proteolysis and spatial effect are some of the main factors that influence the WHC of meat products [7,48,49]. Temperature affects the chemical/physical state and distribution of water in muscle. The net charge effect of protein molecules is mainly affected by the PH value. As muscle is converted into meat, lactic acid accumulates and the pH value decreases. At the isoelectric point, a protein's electrostatic strength is 0 and its fixation force to water decreases. The gap between myosin fibers and actin fibers shrinks due to charge repulsion. Moreover, weak ionic strength will reduce the dissolution of MP; actomyosin that is not dissociated into actin and myosin is difficult to swell; degradation of proteins may result in reduced cytoskeletal protein levels and myoglobin oxidation; crossbridges forming between thick and thin myofilaments, sarcomeres shortening and the size of muscle cells decreasing will reduce the space available for water. Consequently, the water retention space will decrease rapidly under the comprehensive action, and water will leak into the sarcoplasm from the MP and further into space outside the myocytes, resulting in a substantial reduction of hydraulic power in the meat product system [5,50–53].

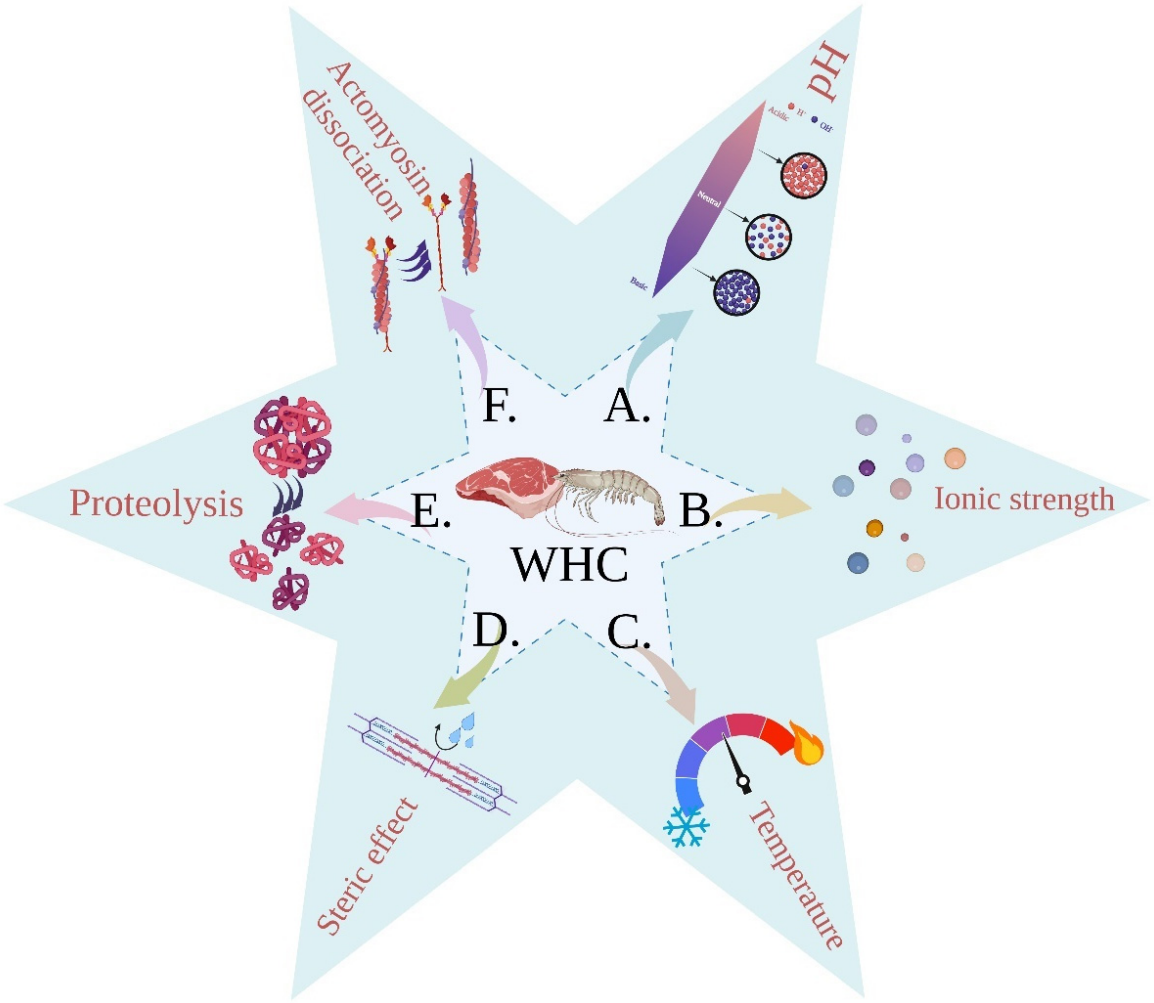

Figure 3. Factors of WHC in meat products A. PH affects the net charge effect of protein molecules; B. Weak ionic strength will reduce the dissolution of MP; C. Temperature affects the chemical/physical state and distribution of water in muscle; D. Crossbridges forming between thick and thin myofilaments, sarcomeres shortening and the size of muscle cells decreasing will reduce the space available for water; E. Proteolysis leads to changes in cytoskeleton configuration, formation of channels and water loss; F. Actomyosin that is not dissociated into actin and myosin is difficult to swell.

3. SWRA for excellent WHC

Saccharides can be classified into monosaccharides with one sugar molecule, disaccharides with two sugar molecules, oligosaccharides with three to ten monosaccharides, and polysaccharides with numerous sugar molecule chains [54,55]. The main ones that can be used as SWRA among them in meat products are: disaccharides: trehalose (TR); oligosaccharides: xylooligosaccharides, inulin, sorbitol, and xylitol; polysaccharides: chitosan (CS) and its derivatives, pectin, aminated low-methyl pectin seaweed gum, xanthan gum (XG), carrageenan, etc. The majority of them are decomposed by enzymes after entering the body [56], so they are considered safe biologically.

The factors of SWRA having excellent WHC are illustrated in Fig. 4: (I) The majority of SWRAs include hydroxyl and carbonyl groups, and some also contain amino, imino, acyl, and other hydrophilic groups. These hydrophilic groups can form hydrogen bonds with water molecules, which support the excellent WHC of SWRA; (II) On the surface of meat products, polysaccharides combine with calcium or magnesium ions to form a protective film, which protects the original spatial structure of actomyosin and stabilizes the moisture inside the meat [57]; (III) Polysaccharides of different molecular weight can penetrate into meat products muscle by capillary force and other actions, and interact with proteins to expand the space between muscle fibers [2], for example, with a positive charge group of polysaccharides, such as CS can combine with proteins to increase the space between myofibril, myofibrils and lessen water-soluble protein loss [25]; (IV) They could create a strong three-dimensional network with calcium/magnesium chelating to capture the water [58]; (V) Polysaccharides with different molecular weights can also serve as antifreeze agents in the freezing of meat products to prevent the denaturation of muscle proteins, which is due to their ability to increase the apparent tension of water [32,59]; (VI) A few SWRAs, such as TR, can increase the vitrification temperature of a system, causing the cell components to enter a vitrification state, forming a continuous phase, inhibiting the movement of water molecules, and preventing ice crystal growth [60]. Thus, the application of SWRA for excellent WHC of meat products has been paid more and more attention. In addition, maximum level of use of different SWRAs in meat products are described at the beginning of each subsection in accordance with the Food and Drug Administration (FDA) and the China National Standard (GB) 2760-2014 National Food Safety for food additives relevant standards (unlabeled dose indicates that this substance is generally recognized as safe when used in accordance with good manufacturing practice.) [61,62].

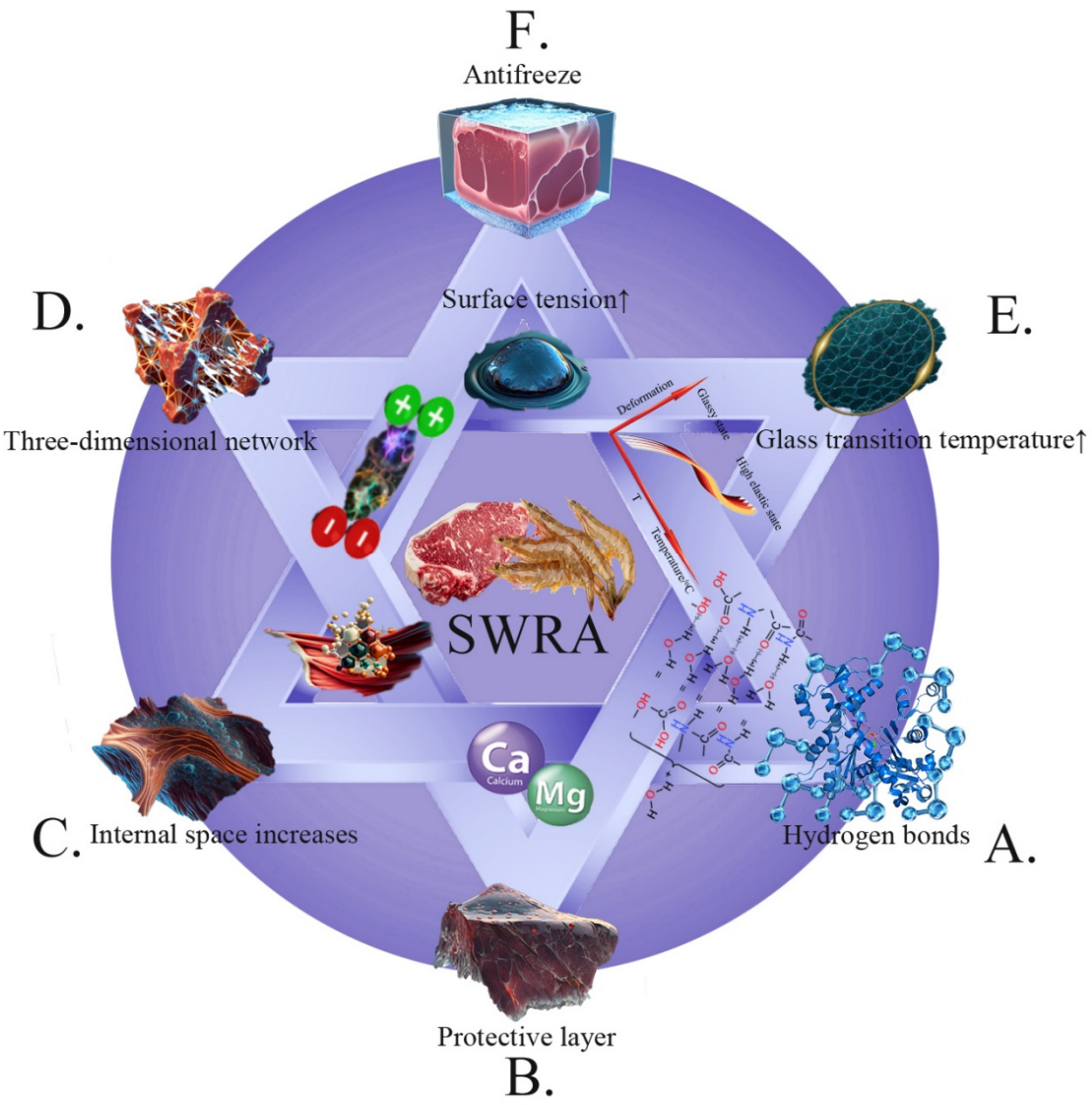

Figure 4. The reasons of keeping excellent WHC with SWRA. A. Hydrophilic groups, such as hydroxyl, carbonyl, and amino, can form hydrogen bonds with water to provide excellent WHC; B. Polysaccharide forms a protective layer on the surface of meat products when it combines with calcium ions; C. Increase the space between muscle fibers by infiltrating into protein through capillary force; D. Establish a powerful in muscle by chelating calcium and magnesium ions; E. Reduce freezing denaturation by increasing the surface tension of water; F. As the vitrification transition temperature in the system was increased, the cell components entered the vitrification state, hindering the movement of water molecules and preventing ice crystal growth.

3.1 Trehalose (TR) and the derivatives

TR was initially isolated from ergot of rye by Wiggers et al. in 1882 and has been found in plants, bacteria and invertebrates, particularly in yeasts, molds and other fungi with a content of more than 20% of the dry weight of organisms, hence the name yeast sugar [63]. A TR molecule is formed by the condensation of two glucose molecules *via* the hemiacetal hydroxyl group. It is a non-reducing disaccharide since it contains no free aldehyde groups. The molecular formula is $C_{12}H_{22}O_{11}\cdot 2H_2O$, and the molecular weight is 378.33 [64]. The glycosidic bond connecting two hexose rings in TR has very low energy (1 kcal·mol^{-1}), while the glycosidic bond energy of non-reducing sucrose is much higher (27 kcal·mol^{-1}). In other words, TR is only 45% as sweet as granulated sugar [65,66].

Among the reasons TR can be applied as a WRA is that it alters the glass transition temperature, causes the cell components to enter a glass state, forms a new continuous phase subsequently, hinders molecule

mobility, prevents the growth of ice crystals, and improves WHC [60]. In addition to increasing salt solubility and Ca^{2+}-ATPase activity of MP, it can also appropriately concentrate water molecules near the membrane and protein surface to reduce mechanical damage caused by ice crystals to muscle structure, as well as inhibit protein denaturation, which is beneficial to WHC [67–69]. TR and alginate oligosaccharides (AOS) treated prawn muscle extracellular space were significantly smaller than control samples, and the muscle fibers were more closely arranged, similar to the results after phosphate compounds treatment (Fig. 7A, B, C, D and E) [69]. A large number of biological enzymes suitable for TR biosynthesis have been developed as a result of great efforts in the field of enzymology, so that the production cost has been greatly reduced [70]. According to Tee et al., frozen Spanish mackerel (*Scomberomorus guttatus*) fish balls with TR had the lowest drip loss when frozen at -20 ℃ for one day as compared to the group with sorbitol added to a sucrose mixture and inulin [71]. Furthermore, Chen et al. [72] found that TR and AOS could effectively inhibit the increase of total sulfhydryl, active sulfhydryl and carbonyl groups in MP, thereby significantly reducing the oxidation rate and structural changes of MP, thus significantly improve the storage stability of shrimp (*Litopenaeus vannamei*) muscle and prolong its shelf life. At the same time, B. Zhang et al. [73–75] further investigated the effects of TR, alginate and AOS on the quality of frozen shrimp (*Litopenaeus vannamei*). The water loss rate for shrimp pretreated with TR and AOS (6.02%, 8.14% and 5.99%, 8.19%, respectively) was significantly lower than fresh water treatment (9.75% and 15.09%) after 9 weeks storage, as well as the cooking loss rate, and the moisture retention mechanism was speculated to be TR and AOS interacting closely with myosin through electrostatic interaction and hydrogen bonds, thereby stabilizing the structure of frozen storage in absence of water, significantly slowing down the degradation of MP and reducing mechanical damage to shrimp muscles. Meanwhile, as a result of cooking the shrimp with TR and AOS, large ice crystals were prevented from forming, fibers were arranged more closely, and smaller extracellular space and higher moisture content were obtained upon 6 weeks of frozen storage [76]. In addition, the composite formula could further enhance WHC. As an example, the alkaline TR solution prepared from TR and sodium bicarbonate is capable of maintaining the integrity of tissues and cells weever (*Micropterus salmoides*) and prevent water loss, color deterioration, protein denaturation and degradation during repeated freeze-thawed cycles [77].

Despite TR is an effective liposomal lysis protector according to the main mechanisms of water replacement and vitrification, its osmolar dehydration effect cannot be ignored [78]. The application of liposomes as carriers of soy phosphatidylcholine in food products can improve the nutritional composition, however, they tend to form vesicular aggregates, thereby reducing yields. To address this issue, Marín-Peñalver et al. [78] added TR as a protective agent for soybean phosphatidylcholine liposomes to salt-ground hake (*M. merluccius*) muscle to evaluate the hydration and other characteristics. As a result, Freeze-thawed liposomes and freeze-dried containing TR (FT-T and FD-T) significantly increased the WHC (90.27 ± 1.86 and 85.88 ± 1.73 respectively) and decreased the thermal gelation capacity of salt-ground hake muscle compared with liposomes alone (57.26 ± 2.44).

3.2 Chitosan (CS) and the derivatives

(0.6%). A chemical or enzyme process can convert chitin into CS, which is the most important derivative of chitin. The chemical conversion method, however, is preferred due to its low cost and suitability for mass production [79]. CS is a random copolymer formed from D-glucosamine and N-acetyl-D-glucosamine units, linked by β-1,4 glycosidic linkages [80] and deacetylation is determined by the ratio between the two units. It is possible to convert CS into a water-soluble acid medium when the chemical deacetylation degree reaches approximately 50%. The amino group in the chain is protonated and the polymer becomes cationic as CS is dissolved in an acidic environment, which allows it to interact with different types of molecules, thus turning CS into the only cationic marine polysaccharide whose positive charge can interact with the negatively charged cell membrane of microorganisms for anti-microbial purposes [80].

As a SWRA, the mechanism of CS is that producing a special insulating layer after freeze-thawing, which reduces the water loss and drip loss, as well as enhances the WHC of meat products. Numerous studies have demonstrated that adding CS to frozen salmon, minced meat, vacuum packaged beef, emulsified fish sausage and many others could improve their protein and lipid oxidation as well as the WHC [81–85]. As an example, Boruzi et al. [86] demonstrated that CS-based coating incorporating walnut leaves and cherry stem extracts is also effective in preventing lipid oxidation and reducing water loss. In addition, Zhao et al. [87] indicated that the addition of clove emulsion made the CS coating have stronger shading property and lower water vapor permeability (WVP). CS alone, however, often fails gradually over time and adversely affects other properties of the product, such as viscosity, hardness, shear force, etc. [88]. The current solution is to combine CS with other WRAs to improve its application. For example, A. chouljenko et al. [89] treated frozen shrimp with CS and CS-sodium tripolyphosphate solution significantly reduced weight loss within 30 days compared with untreated or treated with acetic acid and sodium tripolyphosphate solution frozen shrimp. Furthermore, Karsli et al. [90] coated meat products with CS, especially the data of the 3%w/v CS in 3%w/v aspartic acid (CHAS) group showed that CS coating treatment could effectively inhibit the growth of microorganisms, delay lipid oxidation, reduce cooking loss, and retain color and texture.

However, CS is insoluble in water, has a high viscosity, and tends to coagulate with proteins at higher pH values, resulting in a decrease in the texture, flavor, and quality of meat, which limits its use in the food industry. Hence, water-soluble chitosan (WSC) can be prepared from acidic -CH polymer chains or enzymatic degradation to produce low molecular weight -CH with greater solubility, such as carboxymethyl chitosan (CMCS). Enzymatic processes are preferable to chemical reactions since the former can be more easily controlled than the latter which occur at a faster rate [91]. Bonilla et al. [91] examined the effect of CS and WSC obtained by chitosanase treatment of *Streptomyces* sp. N174 on the quality of refrigerated catfish fillets, which showed a 70% reduction in fat oxidation and great antibacterial activity after 20 days of refrigerated storage still below spoilage limits, while at this time WSC again showed advantages, maintaining better hardness and viscosity compared to acetic acid-treated CS. Meanwhile, Diao et al. [92]

showed that the water in the WS group (RTE Spiced Chicken Meat soaked in sterile distilled water for 90 s) had moved in an unstable direction and AS group (adding garlic aqueous extracts after ultrasonic treatment of the CMCS solution) for 8 d of storage. The change in water distribution could be due to the influence of microorganisms and enzymes, which resulted in the deterioration of the meat and a drastic reduction in WHC. In contrast, the water distribution in the AS group was closest to that of fresh chicken, indicating that the garlic extract-CMCS ultrasonic coating film contributed to the WHC of the RTE Spiced Chicken Meat. In recent years, water-based nano-CS has gained popularity. P. Chantarasataporn et al. [93] indicated that the weight gain rate and cooking rate of Pacific white shrimp (*Litopenaeus vannamei*) can be as high as 14% and 18% respectively by mixing 0.25% (w/w) CS whisker (CSWK) with 2.5% NaCl and 1% $NaHCO_3$ at pH 8 at 4 ºC, even reaching the result of mixed phosphate treatment. CSWK expands the gap between myofibrils in shrimp meat and produces a layer structure similar to that of fresh shrimp, so it can maintain shrimp quality, especially its color and texture, for 48 hours. Meanwhile, CSWK-treated prawn containing $NaHCO_3$ showed more extensive myofibril swelling and more sarcomere swelling, with less attachment on the Z-line compared with mixed phosphate compounds (MPC) in the longitudinal structure of uncooked prawn myofibril observed by SEM (Fig. 7F, G and H). It was confirmed that CSWK retained myofibril units and was superior to MPC treatment. Additionally, Chouljenko et al. [89] and others have shown that vacuum tumbling CS or CS-sodium tripolyphosphate can effectively reduce aerobic plate counts and lipid oxidation of cryogenically frozen shrimp during frozen storage maintaining desired physico-chemical properties. In addition, with a casting method and NaOH solution modification, Chang et al. [94] prepared CS films whose mechanical property increase as well as swelling property, WVP, and oxygen permeability reduce with increasing NaOH concentration and neutralization time. Simultaneously, CS film prevents lipid oxidation and microbial growth more effectively than unpackaged blank samples over a period of ten days of storage. Drip loss, thiobarbituric acid reactant, aerobic plate number, pH value and total volatile basic nitrogen are lower. Furthermore, Li et al. [25] studied the synergistic effect of different concentrations of TR, potassium bicarbonate and CS on the WHC of tilapia fillets, and studied the tilapia fillets after frozen storage for 3 months. With the increase of TR concentration, the thawing loss rate decreased significantly from 9.18% to 6.60% and $KHCO_3$ 1.0% increased the weight of fish fillets by 3.41%. Gradually, the weight gain rate of fish fillets decreased with increasing CS concentration. In contrast to other experimental groups, tilapia fillets treated with 0.5% CS grew at a weight gain rate of 1.66%. After performing combined optimization, they found that tilapia fillets vacuum thawed with 4% TR + 12% $KHCO_3$ + 2% CS had a good texture, a good chewing sensation, and the best WHC. To sum up, CS, as SWRA, plays an important role in maintaining WHC in meat products, and its adverse effects on color, flavor and texture can also be improved by modification or combined with other WRA strategies. Therefore, it is not difficult to conclude that CS has great potential in future applications.

3.3 Hydrocolloids and their derivatives

Hydrocolloids are macromolecular substances that can dissolve in water and can be hydrated into a

sticky, greasy solution or colloid under specific conditions. The unique composition and microstructure of this material result in excellent thickening, gelling, water retention, and cohesion properties, all of which can be manipulated during the thermal induction process to change the interactions between the hydrophilic and hydrophobic phases to enhance the product's water binding and WHC [27,95]. Additionally, it is capable of developing good hydrophilic and water-holding properties through the interaction between the hydroxyl group and water, which reduces the free water and improves the freeze-thaw stability of frozen food systems. In addition, it can establish a strong network with protein and starch to intercept water and increase WHC. There may be a correlation between the different WHC of Hydrocolloids and their optimal pH and ionic strength, the temperature of the water available for hydration and cooking of meat products, emulsion stability, molecule size, shape, and their different gel-forming abilities based on their interactions with other macromolecules present in the system [58]. For instance, Carrageenan is able to obtain superior WHC by adjusting pH and ionic strength, changing emulsion stability, forming hydrogen bonds through hydroxyl groups interacting with water, and establishing strong gel networks with proteins and starches [58,96,97]. Fig. 5 is a summary of saccharide hydrocolloids applied to WHC of meat products.

Figure 5. Source and structural formula of SWRA that are hydrocolloids.

3.3.1 Pectin and aminated low methoxy pectin (ALMP)

A natural high molecular polysaccharide polymer with an anionic polysaccharide backbone of α-1,4-linked D-galacturonic acids in common, pectin refers to a group of polysaccharide substances closely arranged between the primary cell wall and adjacent cells of higher plants, as well as a group of complex

colloidal polymers derived from plant cells [98]. Studies have pointed out that pectin as an antifreeze [99] can also improve the moisture content and texture properties of meat emulsions [100], and delay the fat oxidation of chicken nuggets during cold storage [101]. Kim et al. [100] studied the effects of soy hull pectin and insoluble fiber on the properties of fresh frozen/thawed beef patties. 1% dietary fiber (soy hull pectin and insoluble fiber) increased the moisture content of fresh and frozen/thawed beef patties, in addition to eliminating differences in cooking yield and firmness between fresh and frozen/thawed beef patties, soy hull pectin can also prevent differences in color and fat oxidation between fresh and frozen/thawed beef patties. Moreover, Nawaz et al. [102] examined the effects of four kinds of pectins with different molecular weights and structural features containing 1.5% w/w of wheat flour on the functional, structural and water binding properties of sugar snap cookies partially substituted with fish meat. Pectin (CU-201 and CU-601) had a greater hydrodynamics radius and average side chain length, which controlled biscuit expansion excessively and had a high bound moisture content for the cookies. The addition of 15% inulin and pectin (inulin: pectin = 1:1) to Frankfurt sausage meat batters (an emulsified meat product) has been shown to enhance water retention and stability during emulsification [103,104]. Similarly, the results of Han et al. [85] also reported that cellulose, hydroxymethylcellulose, CS and pectin all helped to reduce the cooking loss of model meat products.

Low methoxyl pectins (LMP) can be extracted from sunflower plates or potatoes, or obtained by deesterifying high methoxyl pectin. ALMP is an example of LMP obtained by ammonia deesterification. Amination replaces methoxy (hydrophobic) with amide groups (hydrophilic). As a result of the amidation of LMP, the polysaccharide can have a greater affinity for the MP. Accordingly, a greater degree of amidation may be associated with better mechanical properties [105]. The treatment of aquatic products with ALMP, such as Mexican flounder (*Cyclopsetta chittendeni*) healthy recombined minced meat products (1% ALMP) [106], striped mullet (*Mugil cephalus*) (1%-5% ALMP) [105] and Jumbo squid (*Dosidicus Gias*) (0.5%-3.0% ALMP) [107], can significantly increase the WHC and mechanical properties of the products, as well as a little effect on the color, which may be due to the fact that amidation appears to alter the hydrophilicity of pectin molecules, obtaining a more compatible hydrophilic colloid suitable for processing high-fat foods. Adding 0.2% calcium chloride to Surimi products can significantly further improve their shear stress, hardness, and WHC [108].

3.3.2 Xanthan gum (XG)

Xanthomonas campestris produces XG, an extracellular polyanionic heteropolysaccharide based on carbohydrates; XG comprises of D-glucosyl, D-mannosyl, and D-glucuronyl acid residues in a 2:2:1 molar ratio with varying proportions of O-acetyl and pyruvyl residues. Its molecular weight is approximately 2 million g/mol [109–112].

The high viscosity, salt resistance, thermal stability, and food compatibility of XG have contributed to its commercial success [113]. Torti et al. [2] found that 0.5% XG solution could significantly reduce the drip loss and cooking loss of Atlantic white shrimp (*Litopenaeus setiferus*) as well as brown shrimp. As well,

Hasanpour also used soybean protein concentrate and XG as gels, finding that the mixture had a better WHC for Silver carp (*Hypophthalmichthys molitrix*) surimi than the commercial mixture that contained sorbitol and sucrose [114]. In addition, Perez-Santaescolastica et al. demonstrated something about a model lean meat product that the 0.5% XG treatment group (drip loss = 0.4%) showed superior WHC compared with the control group (drip loss = 30.8%), and there was almost no drip loss in 1% XG treatment group (0.12%). However, the WHC of the i-carrageenan group (1%), the potato starch group (3%) and the soluble citrus fiber group (3%) was relatively low (drip losses of 4.27%, 6.93%, and 1.95%, respectively). The addition of XG will alter the rheological parameters and thicken the sample in practice [115]. Rather et al. [116] added XG as a fat replacer in goshtaba-a traditional meat product of India by utilizing this property. According to the results of scanning electron microscopy, XG forms a complex gel network with more water and no significant difference was observed in cohesion, stickiness, and chewiness between the product containing 0.5% XG and the control substance containing 20% fat. Chattong et al. pointed out that adding locust bean gum (LBG) to ostrich-meat emulsions could significantly enhance the structural elasticity of meat emulsions, while adding carboxymethyl celluloses (CMCs) and XG had antagonistic effect. This may be due to the fact that CMCs and XG (-COO-) cross-linked with positively charged amino acid side chains in meat proteins, preventing the protein matrix from directly interacting with water, thus reducing the WHC of the corresponding ostrich meat emulsions. In contrast, XG can form more complex networks with other WRAs, such as guar gum [113]. Additionally, the addition of both XG and whey protein to low-fat sausages during hot processing can increase the glass transition temperature, thereby reducing the water that escapes during heat treatment [26].

3.3.3 Alginate

(1%). Alginate is a by-product of iodine and mannitol extracted from kelp or sargassum of brown algae. The main commercial form is sodium alginate (SAL), calcium and magnesium salts, and it is an unbranched anionic polysaccharide composed of β-D-manuronic acid (M) and α-L-gulonic acid (G), connected by glycosidic bonds, and is primarily used in food [117–119].

A large part of the reason for the high WVP of SAL is its high hydrophilicity. It is possible to form an insoluble polymer film by cross-linking with calcium to reduce oxygen and vapor permeability. Furthermore, meat products can retain their sensory qualities when fat and alginate gel are combined by heat induction. At present, alginate has been used in pork patties, steaks and other meat products, which not only play the role of dehydration, color retention, decrease drip loss and preserving flavor, but also significantly reduces cholesterol and fat calories [120]. Specifically, the addition of SAL can significantly improve the emulsion stability and WHC of the meat emulsions. The low-fat meat emulsion CCL shows higher pH value, cooking yield and Warner-Bratzler (W-B) shear force, thus obtaining higher flavor and texture scores, while the score of color, appearance and juiciness increased slightly, so the overall palatability score was the highest [121,122]. Further, when combined with essential oils, enzymes, CS, organic acids, metal nanoparticles, and chelating agents in meat products, SAL may be able to effectively retain moisture and prevent volume

shrinkage, as well as improve the mechanical and barrier properties of meat products as well as reduce cooking loss. It can also reduce the degradation of color and texture, inhibit microbial reproduction, and delay oxidation, so as to enhance the sensory acceptance of meat products. To illustrate, the combined use of α-tocopherol and resveratrol can prevent water loss and fat oxidation to improve the quality in vacuum-packed refrigerated bream and smoked cod products [57,123]. Further, meat batters prepared with SAL containing olive oil had the lowest cooking loss compared with meat batters prepared with pork backfat, and some fat and water were embedded in these substrates, so less was released during cooking [124].

Yao et al. [49] applied 0.1%-0.5% (w/w) SAL (molecular weight is 2660, 3890 and 4640 kDa, respectively) in chicken breast myosin gel to investigate WHC of different molecular weights and alginate addition amounts (Fig. 7I, J, K and L). Using 0.1%-0.5% SAL with relative molecular weight enhanced the WHC of the myosin-SAL gel, and the higher the concentration of SAL, the better the WHC. Electrostatic interaction and hydrogen bonding contribute to the intermolecular aggregation of the myosin-SAL molecule system, and the SAL of larger molecules can easily overcome the steric hindrance effect to enhance the intermolecular interaction. This aggregation results in increased turbidity, higher transition temperatures, reduced surface hydrophobicity of the myosin SAL solution, and the formation of a heterogeneous network with large holes to encase the water. It's important to point out that there will be a decrease in the sensory qualities and rigidity of the meat products due to the high concentration of alginate in the product [125].

Alginate, on the other hand, can be combined with other antioxidants or antibacterial substances to prolong the shelf life of meat. A good example is that compound WRAs including calcium alginate/artemisia fragrance essential oil [126], SAL/glycerol/tea polyphenols, alginate/thyme and garlic essential oils [127], alginate/rosemary and oregano essential oils [128,129] not only have excellent WHC, but also make meat products have better antioxidant activity and shelf life. Moreover, the probiotic capsule prepared using cactus pear peel flour or apple marc flour combined with alginate and pectin can effectively promote the reproduction of lactic acid bacteria and inhibit pathogenic bacteria such as coliform bacteria, and has positive WHC, which provides a favorable scheme for the addition of non-dairy matrix probiotics [130]. At the same time, alginate produces additional carboxyl groups through succinic anhydride modification, bringing the antioxidant center of the molecule close to the interface, increasing its anti-free radical and metal-chelating properties and protecting the lipids from oxidation [131]. On the other hand, combining potassium alginate with ultrasonic treatment can enhance the tenderization reaction. After co-treatment, MP undergoes structural changes that lead to stronger electrostatic repulsion between β-sheet structures and PA molecules, which reduces the size of the complex condensate of extracting MP, and forms a complex gel network that keeps more moisture [132].

3.3.4 Carrageenan

Carrageenan comes from red marine giant algae, which is alternately connected by 1, 3-β-D-galactose and 1, 4-β-D-galactose as the basic skeleton. Generally, its products are white or yellowish powders with no smell or taste, although some have a slight seaweed flavor [133,134].

Carrageenan, a WRA in meat products, may bind with protein to create micelles, improving the stability of the product during storage and heat processing, as well as boosting yields [135–138]. κ-carrageenan (KCG) is also utilized alone or in conjunction with other additives in high-protein meat products as grass carp because it can effectively regulate the water mobility in protein molecules as well as enhance the viscoelasticity of MP gel [139–141]. When soy protein isolate (SPI)-carrageenan is added, it alters some of the internal chemical bonds of salt-soluble meat protein (SSMP), such as disulfide bonds and hydrophobic interactions, which may cause the SSMP to expand and change its conformation as well as produce some embedded mercaptans or other functional groups, such as acidic side chains and hydrophobic groups. New intermolecular disulfide bonds are created by activating the peptides NH and CO. Thus a stable and orderly protein gel network is formed in the protein system [142]. When olive leaf extract was added to mutton during storage, it decreased WVP, increased the elongation at break, decreased the tensile strength and decreased the WVP, and inhibited the initial count of aerobic mesophiles [143]. In the meantime, a total polyphenol extract-carrageenan reduced the WVP and the growth rate of psychrophiles in lamb meat preservation [144]. There is also a strong interaction in yellow konjac flour-KCG that results in a strong elastic gel. Recombinant meat products can benefit from the mixed gels significantly in terms of hardness and WHC [145]. Moreover, the addition of oat flour-carrageenan significantly reduced the fat content of Meatkofta, increased the moisture content, made the product softer and more juicy, and was still acceptable when stored at 4°C for 6 weeks in a nitrogen sealed bag [146]. A combination of SPI and carrageenan reduced the cooking loss of ground pork patties to a higher extent than either SPI or carrageenan alone, and the hardness and chewiness of the samples were also improved. Smoother, the structure was continuous, and the protein matrix was more compact [147]. Besides, the combination of LBG and KCG increased the cooking yield, and the presence of other ions (K^+, Na^+, Ca^{2+}) could enhance the function of KCG and its synergism with LBG, improve the texture and WHC, and had only a slight effect on the color of meat products [148]. In reality, however, there is some concern that the addition of high levels (0.8% and 1.5%) of carrageenan may adversely affect the elasticity of turkey meat sausages [96].

3.3.5 Konjac gum

The main component of konjac gum is konjac glucomannan (KGM), which is composed of β-1, 4-linked mannose and D-glucose residues with reported ratio of 1.4:1, or 1.6:1 [149]. KGM can form a thermally reversible gel when combined with other polysaccharides, such as XG [150]. Despite this, gel formation in an alkaline environment is a chemical process that involves deacetylation and is thermally irreversible. KGM also has good film-forming properties. Heating and dehydration in alkaline conditions will form a dural with high crystallinity, low water absorption and WVP, and has good stability in cold water, hot water, acidic solutions and even frying. The above films can reduce the loss of water in meat products [151–153]. In addition, KGM, as a fat substitute, can also retain the quality and flavor of the original meat products [154–156]. At the same time, the application of high hydrostatic pressure of 600 MPa enhanced the crystallinity of the gel network formed by the completely deacetylated glucomannan aqueous dispersion of 5

g/100 mL. In contrast, the pressure of 200 MPa is softer, more reflective and less cross-linked than the physical network produced in the control gel [157]. This provides a reference for recombinant fish products to obtain soft or hard texture.

3.3.6 Guar gum (GG)

(0.5%). The main chain of GG is a water-soluble non-ionic straight chain polysaccharide with randomly coupled 1, 6-linked galactose units (G) as side chains solubilize the linear backbone of 1, 4-linked d-mannose units (M) [158]. The large branches are believed to be responsible for their strong hydration properties and hydrogen bonding abilities [159]. As with KGM, GG can be used as a fat substitute to enhance emulsion stability and cooking yield of low fat meat emulsions and obtain sensory flavor characteristics similar to high-fat products [160], but with better WHC than carrageenan [161].

3.3.7 Locust bean gum (LBG)

(0.5%). The seeds of *Ceratonia siliqua* Linn, a leguminous plant native to the family Fabaceae, is used to make LBG, which mainly consists of a neutral galactomanan polymer made up of 1,4-linked d-mannopyronosyl units and every fourth of fifth chain is substituted on C6 with a d-galactopyranosyl unit [162]. LBG cannot form gel alone, but affected by its own structure, the exposed branched chain allows it to be mixed with other polysaccharides to form a gel structure [163,164]. For example, neutral water gel (LBG and GG) can improve the WHC of meatballs, but is dispersed in the whole matrix and does not interact with MP, only were located simply by inclusion [165,166]. Yao et al. [167] added LBG and red pitaya betacyanins to the polyvinyl alcohol substrate to obtain active/intelligent packaging films with layer-by-layer and spherical internal microstructure, which can well hinder the loss of internal water, and has excellent color retention and antioxidant properties so that the freshness of shrimp has a good response.

Additionally, the increasing amount presence of potassium ions and calcium ions can enhance the WHC of low salt sausage [168]. In addition, the high pressure environment can also make the polysaccharides expand better and increase the available binding sites, thus increasing the proportion of bound water and reducing water mobility, which in turn increases the strength of the gel. For example, (100 – 200) MPa can significantly increase the WHC (containing 3% sodium salt, 0.2% LBG, (0 − 0.8)% $CaCl_2$) of SSMP gel, while (300 – 400) MPa can reduce cooking loss, hardness and chewiness; 0.2% $CaCl_2$ can increase the hardness of LBG with 3% sodium-salt and 0.2% (SSMP-SL), but decrease its water-binding ability, elasticity and cohesion; 0.4% $CaCl_2$ and 300 MPa can reduce the thermal transition temperature of myosin head and myosin tail [169].

3.3.8 Flaxseed gum (FG)

(0.5%). FG is composed of neutral arabinoxylan with β-D- (1, 4) -xylan main chain and acidic pectic-like polysaccharides [170]. FG as food colloids is capable of forming thermally reversible gels and can replace most of the non-gel polysaccharides used in food and non-food applications. In meat processing, FG can emulsify fat, making fat in meat products more stable, as well as forming a good network structure

with proteins and starches, enhancing the WHC of meat products [171]. Sun et al. [172] induced a three-dimensional network in MP and retained water during heating and recooling. WHC reached a maximum (77.8%) after the addition of 0.4% FG, whereas that of the control group was only 46.6%. At the same time, the fluidity of water decreased as a whole, and FG may promote the expansion of MP before the orderly aggregation of myosin and actin chains, resulting in fine gel networks and more porous microstructure. Positively charged side chains of amino acids in proteins form these interactions between negatively charged carboxyl groups in FG molecules.

3.3.9 Modified starch (MDS)

(2.5%). In plants, starch is the most common storage form of carbohydrates, and it is commonly used in meat products since it can form gel and combine with water when heated, and improves the sensory and WHC characteristics of meat. However, starch shows poor rheological stability and low resistance to mechanical, thermal, and chemical reagents, so its application should be enhanced and expanded by altering the structure and hydrogen bond of amylose and amylopectin [173–176]. The water binding capacity of acid MDS, pregelatinized DMS and natural potato starch were 0.91 g/g, 1.05 g/g and 0.88 g/g, respectively [177]. In terms of freeze-thawed stability, compared with natural starch, 5% (w/w) acetate starch with lower inversion is more stable. Sausages containing acetate starch have the best tissue and pore size to retain moisture and show the highest WHC [178]. For example, the combination of natural cassava or corn starch and a MDS (MOD2) can reduce the fat content of meat products by at least 25%, the maximum moisture is 65%, the maximum starch content is 5% and the protein content is at least 12%. Adding 2.5% MDS to the formula has a better effect than the formula made of 5% natural cassava starch, indicating that the use of this type of starch is expected to develop high-quality low-fat meat products. In terms of various parameters evaluated, MDS showed better performance than natural starch, which is mainly in relation to reheating losses [179]. At the same time, the WHC and gel strength of myosin-resistant corn starch (RCS) gels of chicken breast meat was concentration-dependent on the addition of RCS (0.1%-0.6% w/w). A continuous, dense and uniform three-dimensional network will be formed between the myosin tail and RCS under the condition of heat induction, the increased transition temperature for the myosin tail (T_{peak2}) and heat-induced conformational transition from β-sheet to α-helix could also improve the WHC and gel strength [180].

The modified potato starch, on the other hand, possesses good anti-fat oxidation properties, which are capable of improving the color, texture, oxidation stability and physicochemical stability of rainbow trout (*Oncorhynchus mykiss*) fish burgers during storage [181]. Wu et al. [182] observed that the WHC of MP gel containing esterified potato starch (EPS) increased as gel temperature increased and was significantly higher than that of control group and MP-lard (MP-PO), which was obviously due to starch expansion and gelatinization during heating. The WHC of MP-PO-EPS gel formed at 70 ℃ reached 70%, which was slightly higher than that of MP-PO-EPS gel, but significantly higher than that of MP-EPS, MP-lard and MP-PO gel formed at the same temperature. It may be related to the synergistic effect of starch gelatinization and lipid emulsion on the immobilization of water. The expanded starch was coated on the oil

droplets and filled the pores in the gel network, thus significantly improving WHC. In addition, modified food starch can be combined with soybean protein concentrate [183] and KCG [184] to obtain better color retention and WHC, which can significantly improve the quality and yield of meat products.

3.4 Oligosaccharides and their derivatives

Oligosaccharides are straight chain or branching carbohydrates consisting mainly of 3 to 20 sugar units [185]. Among them, xylo-oligosaccharide and inulin are often used as WRAs. Oligosaccharides have a similar taste to table sugar but are only 20% − 70% sweet. At the same time, oligosaccharides and their derivatives possess biological properties: they promote the growth of intestinal probiotics, enhance intestinal motility, and reduce serum cholesterol and triglycerides [186]. Fig. 6 is a summary of oligosaccharide hydrophilic colloids corresponding to meat products.

Figure 6. Source and structural formula of oligosaccharide SWRA.

3.4.1 Xylo-oligosaccharides (XOS)

Xylan is catalyzed by endonucled-1, 4-β-xylanase to obtain XOS, which can convert part of free water to bound water, and thus has a good freezing protection function for meat products [187]. A study by Wu and Lin et al. evaluated the freezing and thawing stability of meat paste with XOS, sorbitol, sucrose, and TR. It was found that all four sugars could decrease the water loss of the meat paste, with the 8% XOS treatment group having the best freezing and thawing stability [59]. In addition, the XOS prawn meat showed good low temperature protection, because the XOS can improve shrimp myosin two chain consistency and collaborative, reduce the total interaction energy of shrimp myosin and water molecules, replace the shrimp

myosin around the water molecules, so as to stabilize the shrimp myosin in the process of freezing storage structure, improve WHC [188].

3.4.2 Inulin

Inulin is water-soluble and comprised of oligo- and polysaccharides having fructose monomers linked by glycosidic linkages with β-configuration at anomeric C2 and this β-configuration makes inulin resistant to hydrolysis by human gastrointestinal enzymes. Therefore, inulin type fructans have been placed under non-digestible carbohydrates [189,190]. Inulin of chicory is soluble in water (approximately 10% at 25 ℃) and it is recommended to prepare inulin solutions in (50 − 100) ℃ water [103]. However, Keenan et al. [191] noted that more cooking losses were observed in sausages with a higher fat content compared to low-fat products containing inulin, due to inulin's greater ability to form water-trapping gel networks in the former compared to protein and fat. This is similar to the results obtained by Gadekar et al. [88] low fat restructured goat meat products, so inulin is more suitable for low-fat meat products.

3.4.3 Sorbitol

(0.05%). Sorbitol ($C_6H_{14}O_6$) is a component of hexitol, a reduction product of hexose, with a sweetness approximately 60% of that of sucrose and a similar amount of calories [192]. Various sorbitol products are available, including liquid sorbitol, which appears as a colorless, transparent, viscous liquid, and solid sorbitol, which resembles white needle-like crystals or crystalline powder. The sorbitol molecule has a high water absorption capability, as it contains six hydroxyl groups, which form hydrogen bonds to combine the water in the product and the surroundings, so that the product in the placement process reduces the loss of water, and is able to maintain good sensory properties. During storage, the releasable moisture content of surimi from *Nemipterus japonicus* and quality of surimi-based products tends to increase with the storage period of surimi [193], which can be well suppressed by adding 10% soy protein concentrate and 4% mixture (sucrose: sorbitol=1:1) [194]. In addition, Minh et al. [195] soaked dried snakeskin gouram fish with 40% ethanol, 2.0% salt and 1.0% sorbitol and dried them at 46 ºC. The moisture activity of dried *Snakeskin gouram* fish could be maintained at a high level (water activity (AW) = 0.65). At the same time, U-Chupaj et al. [196] used sorbitol-containing marinade (2.8% $KHCO_3$, 2.9% KCl and 1.5% sorbitol) to pickle white-striped chicken breast (meat: marinade=4: 1), higher pH value, moisture content, total cooked yield, protein solubility, hardness, cohesion, chewiness, lower cooking loss, expressible water and shear force were obtained compared with the normal marinade group.

3.4.4 Xylitol

Xylitol ($C_5H_{12}O_5$) is a product of the metabolism of xylose. It is highly water soluble, sweet tasting, and widely distributed in fruits and vegetables [197]. Jang et al. [198] found that semi-dried meat made with sorbitol and xylitol instead of sucrose had higher moisture content, and 5.0% xylitol was the best replacement level with the lowest shear force, which was beneficial to improve water activity and tenderness and prevent lipid oxidation. At the same time, xylitol can not be used by most microorganisms, and even inhibit the growth

of microorganisms, so xylitol in meat products in addition to as SWRA and sweetener, but also plays a role in antibacterial and anti-corrosion. For instance, its synergistic effects with butanediol, glycerin, and other substances, are able to enhance the role of water retention and corrosion protection.

3.4.5 Alginate oligosaccharides (AOS)

AOS are degradation products of alginate, a Marine polysaccharide derived from brown algae, and are composed of α-L-gulonate (G) and β-D-mannoic acid (M), linked by 1, 4-glycosidic bonds [199]. AOS is thought to contain alginate oligomers of 2-25 monomers [200]. Alginate can be degraded to AOS with low polymerization degree (DP) by physical, chemical, enzymatic catalysis (alginate lyase [119]), fermentation, organic synthesis and biosynthesis. AOS have scavenging activity against oxidative radicals and are able to bind to fish myogenic fibronectin to enhance solubility. In studies, TR and AOS in the frozen storage process have been found to slow down the degradation of muscle proteins and the destruction of the muscle tissue structure, however, alginate is not effective in protecting the peeled shrimp against freezing [201]. Chen et al. [202] used myofibrin fragmentation index (MFI), differential scanning calorimetry and SDS-PAGE to study the effects of TR and AOS on MP during shrimp meat refrigeration. The results showed that the addition of TR and alginate oligosaccharide could effectively inhibit the increase of the total sulfhydryl, active sulfhydryl, and carbonyl content, as well as changes in the water migration of MP. Zhang et al. [203] studied conformational changes of myosin in 0.03 g/mL TR and AOS systems using homology modeling and 60 ns molecular dynamics simulation. The doped TR/AOS were found to approximate myosin and to bind to amino acid residues through electrostatic interactions and hydrogen bonds. TR and AOS replaced some of the water molecules surrounding the surface of myosin, thus improving coordination and consistency of the movement of the heavy and light chains (MHC and MLC) of myosin. This reduces the flexibility of the myosin chain and the risk of protein aggregation, stabilizes the conformational structure of myosin in the system, and benefits the WHC. Chao et al. [204] utilized TR, SAL and sodium AOS (concentration 0.5% or 1%) to increase the weight of frozen cooked shrimp, and significantly reduce thawed drip loss and cooking loss. Some studies found the principle is that: (I) small molecules (with large hydration volume) of TR (378 Da) and sodium AOS (400-800 Da) provide good accessibility for functional groups (-OH, -NH, etc.) in muscle proteins so that these functional groups can easily bind inside muscle proteins and hydrogen bond with water molecules. Thus reducing the water loss of shrimp samples; (II) It can substitute for water molecules by forming hydrogen bonds with polar residues of protein molecules in shrimp muscle, stabilizing its structure without water.

3.4.6 Carrageenan oligosaccharides (COS)

By mild acid and enzyme hydrolysis, COS can be obtained that have a low molecular weight and a greater water solubility. Due to their antioxidant capacity in both the cell system and *in vitro*, they can reduce the oxidation of proteins and lipids in the body to improve their WHC [32,205]. Zhang et al. examined whether shrimp pre-soaked with COS and XOS performed positive responses to product under temperature fluctuations (4 ℃ and -18 ℃ cycles, -24 ℃ and -80 ℃ cycles). Both significantly improved WHC, suppressed

frozen-induced protein denaturation, maintained the integrity of muscle tissue, and inhibited ice crystal growth and recrystallization, according to studies [206].

It was also found that thawing loss and cooking loss of fresh water treated samples (controls) increased from 6.08%, 8.85% and 8.50% to 12.28% during the 6-week storage period, respectively. However, for 1.0% and 3.0% COS treated shrimp, thawing loss and cooking loss were significantly reduced within six weeks; that is 5.72%, 6.08%, 5.23% and 5.70%, respectively, significantly lower than the value of fresh water treatment. The rationale may be that small oligosaccharide molecules with large hydration amounts provide great accessibility to functional groups in muscle proteins, which can easily bind inside muscle proteins and H-bond with water molecules, thus reducing the amount of water lost in shrimp samples [32].

In addition, Lan et al. [207] showed that COS can inhibit the reduction of lipid content, total mercaptan content and moisture content in *Vannamei* by repeated freeze-thawed cycles, while delaying protein degradation, denaturement and lipid oxidation, maintaining protein integrity and WHC. COS was used in a study of cryogenic protection of frozen shrimp by Zhang et al. [32], and the results revealed: COS had higher WHC than sodium pyrophosphate, which is the result of its high myofibril protein content and Ca^{2+}-ATPase activity, which slowed the muscle tissue. During the same period, shrimp were replaced by sugar, water molecules on the surface of the myosin form hydrogen bonds with the polarity of amino acid residues, resulting in no water stable structure, improving protein stability during freezing.

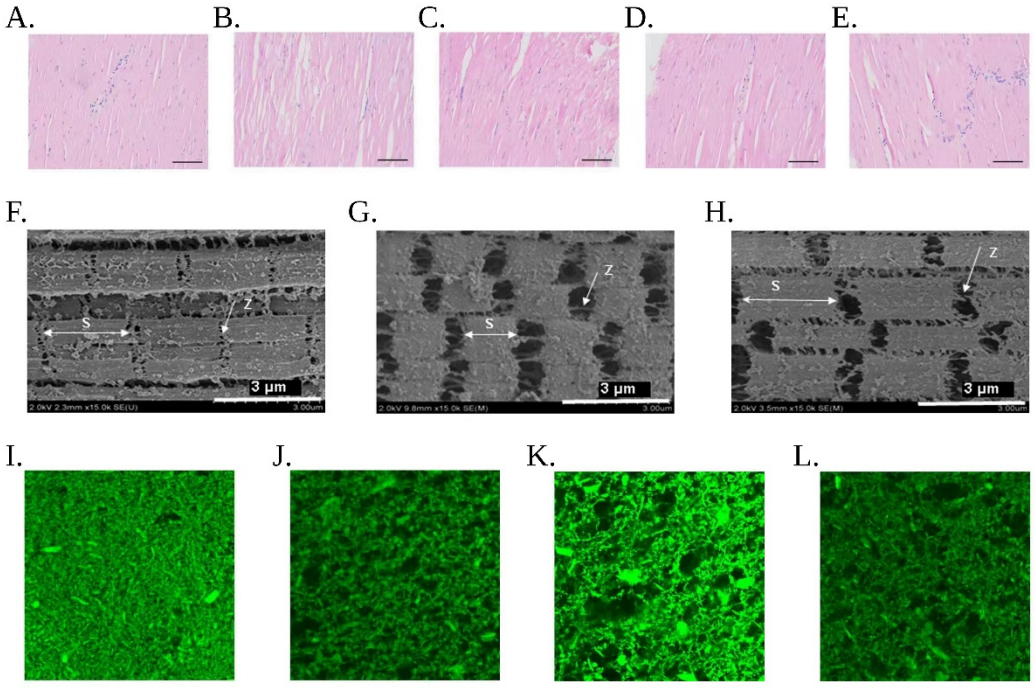

Figure 7. Micrographs of longitudinal-sections of shrimp muscle from the second abdominal segment treated with (A) blank (fresh shrimp muscle (0 d)), (B) control (water, 6 weeks of frozen storage), (C) 1.0% TR, (D) 1.0% AOS and (E) 1.0% sodium pyrophosphate from left to right, magnification was 200× original size, bar length = 100 μm [69]. Copyright 2015, Institute of Food Technologists®; SEM micrographs of longitudinal sections of cooked shrimps with different treatments as follow: (F) without treatment; (G) with 3.5% (w/v) MPC containing 2.5% (w/v) NaCl and (H) 0.25% (w/v) CSWK containing 1% (w/v) $NaHCO_3$ and 2.5% (w/v) NaCl at pH =8 (S for sarcomere, and Z for Z-line) [93]. Copyright 2013, Elsevier Ltd; The microstructures of SAL with different molecular weight on mixed myosin gel: (I) myosin gels, myosin + 0.5% Low-SAL gels, (J) myosin + 0.5% Medium-SAL gels and (K) myosin + 0.5% High-SAL gels) were observed by confocal laser confocal microscope (CLSM) and each sample was taken using a 40× magnification objective [49]. Copyright 2017, Elsevier Ltd.

4. Maintenance of health

Phosphate as a food additive is easily absorbed by the intestine due to its free inorganic properties [208]. Phosphate overload can cause disease to accelerate disease progression in a positive feedback or cyclical cycle, causing lasting damage to the cardiovascular system and an increased risk of coronary artery calcification and death in patients with normal serum phosphate levels. At the same time, it also reduces serum calcium, which promotes the precipitation of calcium phosphate compounds in blood vessel tissues and organs, leading to frequent and continuous release of parathyroid hormones, which can adversely affect bone structure, mineral content and function. In addition, it can accelerate the progression of age-related organ complications, such as muscle and skin atrophy, chronic kidney failure, and increase the risk of diabetes [209–211]. By contrast, not only can SWRAs maintain the general WHC requirements in meat products, but also performs biological functions which are not covered by phosphate (Fig. 8). Moreover, the advantages and disadvantages of SWRAs and Phosphate as WRA are described side by side in Table 1.

Table 1. The advantages and disadvantages of SWRAs and phosphate in taste biological effect and envi-ronmental effect.

	SWRA	Ref.	Phosphate	Ref.
Taste effect	Adds flavor and improves texture and appearance. Excessive addition of CS may lead to decreased taste, but it can be prepared by hydrochloride-free CS oligosaccharide to improve taste.	[91,212,213]	Improve the texture and taste. However, when the content exceeds the limit, it will appear soapy taste, bitter taste, crystallization etc.	[11,214]
Biological effect	Anticorrosion; regulate oxidative stress levels, blood lipids and blood sugar, modulate immune response and gut microbiome.	[27–30,215]	Lasting damage to the cardiovascular system and an increased risk of coronary artery calcification and death; frequent and continuous release of parathyroid hormones, which can adversely affect bone structure, mineral content and function; muscle and skin atrophy, chronic kidney failure, and increase the risk of diabetes.	[209–211]
Environm-ental effect	Environmentally friendly.	[216–218]	Water eutrophication; Endanger aquatic animals.	[219–221]

4.1 Regulation of oxidative stress levels

Antioxidant activity is one of the biological functions of most SWRAs [222]. TR protects mouse liver cell lines from oxidative damage, which is increased by Nrf2-dependent antioxidant components [223]. CS monomer, which retains one amino group and two hydroxyl groups, can react with free radicals to achieve the antioxidant activity. This activity increases as low-molecular-weight CS decreases, since shorter chains are less likely to establish intramolecular hydroxyl bonds, resulting in more active hydroxyl and amino groups, which contribute to free radical scavenging activity. Boosting antioxidant enzyme activity while inhibiting lipid peroxidation, CS and its derivatives can delay aging and increase antioxidant capacity [224]. CS partially corrected the REDOX balance caused by the impairment of antioxidant enzymes including

glutathione and peroxidase in a lipopolysaccharide (LPS)-induced sepsis animal model. Meanwhile, clinical research indicates that CS can be utilized as an antioxidant to protect proteins in renal failure. In addition, carrageenin increases superoxide dismutase activity in donor erythrocytes. KGM increases bowel movement frequency, lactic acid bacteria development, and colonic fermentation in healthy individuals, thereby protecting the body from oxidative stress [225–227]. Supplementing with XOS reduced lipid peroxidation and increased glutathione-S-transferase and catalase activities in colonic mucosa and liver, possibly suppressing colon carcinogenesis. The antioxidant and free radical scavenging abilities of XOS were found to be dose-dependent, with the percentage of antioxidant activity gradually increasing to a maximum of 74 percent at a concentration of 6 mg/mL XOS. This potential may be attributed to the effective release of phenolic compounds and the transfer of hydrogen atoms from phenolic compounds to free radicals. There is a possibility that this potential is due to the effective release of phenolic compounds and the transfer of hydrogen atoms from phenolic compounds to free radicals. The antioxidant mechanism of alginate may entail scavenging free radicals by removing hydrogen from carbon-bonded hydrogen atoms [228–230]. AOS demonstrated ABTS and superoxide radical scavenging activities in a concentration- and time-dependent manner that was inversely related to alginate molecular weight. AOS effectively suppresses oxidative stress and is sufficiently resistant to oxidative stress-related illnesses. AOS generated by enzymatic degradation not only prevents oxidative stress-induced neurotoxicity but also suppresses amyloid β formation in an *ex vivo* model of Alzheimer's disease (AD), dependent on the up-regulation of heme oxygenase-1 and γ-glutamylcysteine synthetase in the NF-E2-related factor 2 pathway. AOS pretreatment reduced acute adriamycin-induced cardiotoxicity by decreasing oxidative stress in the heart by down-regulating the protein expression of gp91-phox (also known as NADPH oxidase 2 (NOX2)) and 4-hydroxynonenal (4-HNE). Similarly, pretreatment with AOS suppressed NOX2 and 4-HNE upregulation. Additionally, the antioxidant activity of AOS produced by enzymatic hydrolysis was greater than that of alginate and the polymeric and monomeric forms of acid-hydrolyzed alginate. Cell damage caused by oxidative stress is linked to the aging process and numerous neurological illnesses such as AD. A recent study suggests an impact of pectin polysaccharide on Aβ42, an important molecule for the pathology of AD, by inhibition of its aggregation. Pectin is fermented in the colon by different bacterial genera such as *Bifidobacteria, Lactobacilli, Enterococcus, Eubacterium rectale, Faecalibacterium prausnitzii, Clostridium, Anaerostipes, and Roseburia spp.* to promote their growth. AOS (enzymatic degradation) not only protects NT2 neurons from oxidative stress-induced neurotoxicity but also inhibits the formation of Aβ in an model *in vitro* of AD. The substantial antioxidant capacity of alginate resulted in an inhibitory impact on H_2O_2-induced Aβ production, perhaps as a result of its active oxygen (ROS) scavenging properties. It is possible that oxidative stress-induced neurodegenerative disorders can be controlled by lowering ROS levels. At this moment, AOS (enzymatically degraded, molecular weight: 1300 Da, oral administration: 360 mg/kg/day) containing mannoacid-rich blocks alleviated Alzheimer-type behavioral symptoms induced by scopolamine and Aβ (1-40) in rodents. Studies on human neuroblastoma SH-SY5Y cells *in vitro* suggest that AOS may inhibit ROS generation by

reducing intracellular free calcium excess, which leads to the prevention of ROS generation and apoptosis. Furthermore, AOS binding to Aβ and subsequent suppression of fibril production may contribute to its neuroprotective action [231,232].

4.2 Immune response modulation

As a result of oral administration of a soluble dietary fiber, particularly glucan, serum IgA production was boosted, scratching activity was inhibited, mastocytosis neuropeptide substance P expression was reduced, and skin inflammation and immune responses were inhibited in a mouse model [226]. XOS not only suppressed tumor necrosis factor-α (TNF-α), interleukin-1β (IL-1β), IL-6, and NO expression, but it also boosted IL-10 production in LPS stimulated RAW264.7 cells, as well as dramatically lowered the expression of IL-1β and interferons-γ (IFN-γ) and relieved systemic inflammation [228–230,230]. In addition, AOS effectively suppressed LPS-activated synthesis and secretion of TNF-α, IL-6, and IL-1β, as well as amyloid-β protein (Aβ)-activated production of TNF-α, IL-6, and IL-12, treating neuroinflammation by decreasing microglial activation and attenuating the production of inflammatory mediators [233,234]. Pectin inhibits intestinal inflammation *via* both gut microbiota-dependent and independent mechanisms. The presence of neutral sugar side chains in pectin, as well as the degree of methyl esterification, has a substantial effect on its anti-inflammatory efficacy. Pectin from diverse sources inhibited the release of inflammatory mediators (NO, TNF-α, IL-1β, IL-6) in macrophages in response to LPS stimulation and was also mediated through the suppression of nuclear factor-κB (NF-κB), extracellular signal-regulated kinase 1/2, and c-Jun N-terminal kinase pathways. Further, citrus pectin reduced DSS-induced expression of intercellular adhesion molecule-1, which is involved in neutrophil adhesion to the intestinal mucosa, and inducible nitric oxide synthase (iNOS) in the colon tissu, as well as reduced the expression of membrane-associated mucin-3 and two tight junction proteins, namely occludin and zona obliterans-1, thereby alleviating intestinal inflammation [235–237].

Various types of probiotics can ferment short-chain fatty acids (SCFAs) (acetate, propionic acid, butyrate, etc.), which have various immune-boosting properties, using pectin, FG, resistant starch, and other carbon sources [238]. SCFAs-induced GPR43-dependent signaling, including mitogen-activated protein kinases pathway activation, promotes neutrophil recruitment and alters neutrophil effector functions (TNF-α and C-X-C motif ligand 8 production, NF-κB activation), as well as the inhibition and subsequent modulation of certain transcription factor expression via histone deacetylases (PU.1, Rel B) to inhibit dendritic cell development. Butyrate caused human dendritic cells to mature more slowly, reducing their ability to activate T cells and generate pro-inflammatory cytokines (IL-12 p40, IFN-γ). Regarding adaptive immunity, SCFAs influence the proliferation and differentiation of T lymphocytes by increasing Treg production and impacting Th1, Th2, and Th17 cell differentiation and activation. SCFAs enhance B cell development and contribute to gut and systemic antibody production, in addition to their actions on intestinal T cells. They boosted X-box binding protein 1 and Aicda gene expression as well as cellular metabolism in mouse and human B cells to promote and support antibody synthesis, all of which help to regulate the gait system [236], secondary lymphoid tissues, and peripheral circulation [226].

Furthermore, several SWRAs have anti-tumor potential through immunomodulatory mechanisms. CS, for instance, has been shown to suppress the proliferation, metastasis, and invasion of several cancer cells, including liver cancer, cervical cancer, colon cancer, and lung cancer, via the AMP-activated (AMPK) protein kinase/NF-κB cyclin D1. Downregulation of ribosomal protein S6 and mechanism metallo proteinase-9 (MMP-9), as well as differentiation group and MMP-2 expression, significantly suppressed the proliferation and metastasis of human gastric cancer cells (SGC-7901) in a dose-dependent manner. At the same time, CS of 1-3 kDa suppresses cytokine-induced proinflammatory invasiveness as well as the generation of NO and iNOS in the colorectal adenocarcinoma cell line human HT29. Moreover, it directly reduces tumor cell growth by causing apoptosis and improving immunity (inducing T lymphocyte proliferation by increasing the production of lymphokines) [239]. Sulfate residues in carrageenins have an important role in anti-cancer and anti-metastatic activities by preventing cancer cells from interacting with basement membranes, decreasing tumor cell proliferation, and inhibiting tumor cell adherence to diverse substrates [240]. Enzymatically hydrolyzed AOS has been found to inhibit osteosarcoma development in a concentration-dependent manner. Resistant starch has a definite anti-colon cancer effect, but the exact mechanism is unknown, and the majority of current theories suggest that butyrate plays a role [231,232,241].

4.3 Modulating the gut microbiome

TR is esterified to TR lipids (such as TR 6,6 dimycolate, TDM) as part of the cell wall by *Mycobacteria*, *Nocardia*, and *Corynebacterium* species, indicating that TR metabolism has the potential to affect bacterial virulence, and certain pathogen-specific drug development is promising [242]. TR, according to Daisy Martinon et al., might be employed as a possible preventative therapy for SARS-CoV-2 infection and transmission [243]. Below pH 6.5, CS has antibacterial action, which is attributed to CS: (I) The positively charged -NH^{3+} group can connect to the negatively charged membrane components of harmful bacteria, causing the cell wall to burst; (II) preferentially binding metal ions, preventing toxin synthesis and microbial development as a chelator; (III) activating and binding cell wall components, causing the bacterial cell wall to decompose and die; (IV) interfering with and suppressing mRNA and protein production by entering microorganism nuclei and binding to DNA [224]. In addition to providing a protective barrier, edible biopolymer films can be used as examples of transporters for bioactive mixtures for the purpose of enhancing the quality of food. The mechanism of action depends on the cell wall structure, which interferes directly with growth. Aflatoxin B1 toxicity in ducklings is reduced by KGM [244–246]. KGM has the ability to attach to pathogens and either promote or hinder their clearance from the body. The antibacterial activity of AOS appears to be enhanced when the G content exceeds 85 percent. On the other hand, significant antimicrobial activity against *Pseudomonas aeruginosa* was observed when AOS with a mean sulfuration of 6.8 were examined, whereas all other tested algal oligosaccharides showed little antibacterial activity [234,234,247]. Inulin, in addition to increasing the number and rate of growth of biological nitrogen-fixed bacteria, can also inhibit the proliferation of harmful pathogens such as *E. coli*, *Campylobacter jejuni*, *Salmonella enteritidis*, or *Clostridium perfringens*, and has a positive effect on the intestinal associated lymphoid tissues, which

contributes to enhancing immunity against harmful pathogens [190,248,249]. Furthermore, studies *in vitro* have shown that XOS supplements create lactic acid and acetic acid, which aid in the growth of *Bifidobacterium* and *Lactobacillus* strains while inhibiting the formation of pathogenic bacteria [250,251]. Aside from that, microorganisms such as *Streptococcus pneumoniae* and *Streptococcus mutans* are inhibited in their proliferation by xylitol [252,253].

In addition, the gut microbiome is a key environmental factor in regulating the body's metabolism, Affect the occurrence and development of lipid metabolism and blood sugar metabolism, For example, *Lactobacillus curvatus* alone or together with *Lactobacillus plantarum* can synergistically reduce plasma and liver cholesterol in obese subjects. and *Bifidobacterium spp.* decreased levels of circulating triglycerides and low density lipoprotein (LDL) and increased levels of high density lipoprotein, these effects were mainly dependent on the positive impact of intestinal flora on SCFA and bile Acids and lipopolysaccharides, gut permeability and inflammation, ttrimethylamine/ttrimethylamine N-oxid [254,255]. Here, XG and KGM were able to increase the content of SCFAs and regulate the composition of the microbiome over time [256]. SAL regulates 20 major genera of gut microbes, helps to improve the profile of serum metabolites, including lipid molecules, branched-chain amino acids, and vitamin D and E metabolites, improves body fat and weight gain, and regulates hyperglyca [257]. At the same time, the study of Frida et al. proved that pectin and GG could increase caecal abundance in *Akkermansia*, GG could also increase caecal abundance in *Bifidobacterium* tenfold, and increase SCFAs in total blood and caecal [258]. In another study, these two fibers decreased the cecal abundance of *Oscillospira* and an unclassified genus in *Ruminococcaceae*, and increased that of an unclassified family in RF32. In other words, GG (mainly medium-molecular-weight) and pectin are important for their ability to modulate cecal bile acids formation, gut microbiota composition, and high-fat diet induced inflammation [259]. In addition, LMP decreased the abundance of Proteobacteria, and increased the relative abundance of *Akkermansia*, *Lactobacillus*, *Oscillospirales* and *Ruminococcaceae* inhibit the growth of pathogenic bacteria, relieve intestinal functional metabolic disorders, reverse the potential risk of related complications, effectively reduce blood sugar, regulate lipid metabolism, and have significant antioxidant capacity and the ability to promote SCFAs secretion [260].

4.4 Regulation of blood lipids

TR alleviates metabolic diseases by activating autophagy in specific tissue compartments, and is considered to be highly promising metabolic therapeutic agent. It has shown resistance to atherosclerosis [261] and dyslipidemia in several animal models, as well as blocked fructose-induced hepatic triglyceride accumulation. The properties of CS include lowering blood pressure and cholesterol, inhibiting fat absorption, promoting intestinal peristalsis, and enhancing immunity [224]. CS interacts with bile acids and cholesterol in the intestinal lumen to promote fecal cholesterol and triglycerides. In addition, it can activate peroxisome proliferator-activated receptor-alpha (PPARα) and modulate downstream cytochrome P_{450} and alcohol oxidase 1 involved in fatty acid catabolism, as well as improving AMPK phosphorylation and reducing lipid-expressing proteins (sterol-regulatory element binding protein 1c and PPARγ). In addition to controlling

lipogenic transcription factors, CS was shown to induce transcriptional repression of many lipogenic genes, including fatty acid synthase, acetyl-CoA carboxylase (ACC) and 3-hydroxy-3-methylglutaryl-CoA reductase in liver and fatty acid transport protein 1 and fatty acid binding protein in adipose tissue of HF rats [80,262].

A number of dietary fibers, including GG, carrageenan, KGM, pectin, LBG, inulin, alginate, XOS, and more, increase food viscosity, reduce gastrointestinal transport, cause satiety, slow down the diffusion of enzymes, substrates, nutrients, and carbohydrates in the intestine [236,244,263–267], as well as reduce carbohydrate absorption. Thus, intestinal glucose absorption decreases, affecting insulin sensitivity in healthy individuals as well as cholesterol metabolism, resulting in lowered cholesterol levels [227]. In related studies, it was pointed out that patients taking KGM had statistically significant reductions in total cholesterol, LDL, triglyceride, body weight, and fasting blood glucose [227]. KGM-induced viscosity contributes to reducing postprandial stimulation of 3-hydroxy-3-methylglutaryl CoA reductase and has anti-obesity and insulin-sensitized adipokines [268]. Improved lipid levels by enhancing fecal excretion of neutral sterols and bile acids. Bile is reabsorbed less when carrageenan binds to bile. During the process of replenishing the bile acid pool, cholesterol in the serum is further reduced, which further lowers serum cholesterol levels. Fermentation of carrageenan in the large intestine also reduces cholesterol biosynthesis. LMP can significantly inhibit pancreatic lipase, thereby reducing fat absorption, and the inhibition mechanism is the strong interaction between free carboxyl groups in pectin and amino acids in the active site of lipase [236,269]. Xylitol slows gastric emptying, increases satiety, reduces food intake and shows indicators of hypoglycemia and hypoinsulinemia. Some of the steatosis-reducing effects of XOS may be attributed to higher glycine and lower hypoxanthine levels. The preventive effect of XOS on hepatic steatosis may be related to the reduction of adipose tissue inflammation, which is accompanied by an increase in protein kinase B (Akt) phosphorylation in liver and epididymal adipose tissue. In addition, XOS increased fecal glycine and reduced branched-chain amino acids, aromatic amino acids, hypoxanthine, and isovaleric acids, which could partially explain the steatosis effect of XOS [228]. After that, the lipid-lowering effect of AOS (molecular weight: < 10 KDa) depends on the inhibition of cholesterol uptake. AOS upregulates LDL expression and intracellular uptake of LDL uptake by hepatocytes and decreases plasma LDL cholesterol levels. The up-regulation of LDLR by AOS was dependent on PI3K/Akt/glycogen synthase kinase 3β-mediated activation of sterol responsive element binding protein-2, as well as the down-regulation of protein converting enzyme subtilisin/theobromine type 9, which reduces LDLR degradation in hepatocytes. In addition to this, lipid accumulation in the liver of alginate-fed rats depends on the viscosity of alginate, as only high viscosity alginate can reduce lipid accumulation [232,234,247,270].

4.5 Regulation of blood sugar

TR improves cardiac function and reduces fasting blood glucose, glucose and insulin tolerance in acute ischemic injury and chronic cardiomyopathy models of left ventricular remodeling [271], also, induces insulin sensitivity through a PPARγ-dependent mechanism in mice, and although peripheral oral bioavailability is low (about 1%), oral TR attenuates non-alcoholic fatty liver and insulin resistance, as well as secondary

cardiomyopathy [272]. Additionally, CS can prevent type II diabetes by altering intestinal flora and reducing endotoxin and microbial-mediated inflammation [224]. Previous studies have shown that CS could mediate the translocation of glucose transporter gene 4 and the up-regulation of Akt phosphorylation to induce glucose uptake in the skeletal muscle of streptozotocin induced diabetic rats while reducing the expression of phosphoenolpyruvate carboxykinase and the phosphorylation of p38 protein in the liver [239]. The gelation of SAL in the stomach appears to be essential for this effect, and alginate may inhibit glucose absorption by reducing gastric emptying and nutrient absorption due to the stickiness of the gastric contents [263,273,274]. Sorbitol is passively absorbed slowly in the small intestine at a much lower rate than glucose and fructose. Sorbitol is first converted to fructose by sorbitol dehydrogenase, then to fructose 6-phosphate, and finally metabolized by the glycolytic pathway after absorption. A rise in blood glucose is not caused by sorbitol metabolism, as it is not regulated by insulin. Meanwhile, according to the glycemic response test, sorbitol has an ultra-low glycemic index (GI) of around 10, which belongs to the low GI component (less than 50) [275–277].

4.6 Others

Adding KGM to a low-fiber diet may promote bowel movement frequency in healthy adults. Xylitol has been used to prevent acute otitis media, rhinosinusitis and dental caries [278–280]. In addition, xylitol reduces dental caries by inhibiting glucosyl transferase, which prevents the utilization of glucose by the mutant and its adhesion to the tooth surface. XOS supplementation had a positive effect on bone properties, possibly caused by cecal wall weight and pH, intestinal mucosal morphology, and associated calcium transporters. Therefore, an appropriate dose of XOS can be viewed as a promising adjunctive strategy to reach peak bone mass in adolescents [250]. Low molecular weight potassium alginate (mean molecular weight: 1800 Da, intake: 100-500 mg/kg) reduced blood pressure in spontaneously hypertensive rats and attenuated the elevation of blood pressure in hypertensive deoxycorticosterone salt models through a mechanism involving increased urinary sodium excretion. Treatment with very low molecular weight AOS sodium salts (polymerization: 2 and 3, intake: 8% w/w (diet)) alleviates spontaneous hypertension. Therefore, the antihypertensive effect of AOS sodium is most likely due to its direct effect on the cardiovascular system rather than inhibiting salt absorption in the gut [263,273,274,281]. GG is a water soluble fiber that can be applied for the formation of bulk laxatives, promoting regular bowel movements [282]. LBG is beneficial for reducing inflammation and inflammatory bowel diseases, and in different degrees, relieves constipation and related chronic functional bowel diseases, such as diverticulosis, Crohn's disease, colitis, and irritable bowel syndrome [265,283,284]. It is also effective against cholera and diarrhea. Also, unabsorbed sorbitol can stimulate intestinal peristalsis through osmotic pressure, which exhibits diuretic and laxative effects [285]. A study also showed that FG protected the gastric mucosa against ethanol ulcers [286].

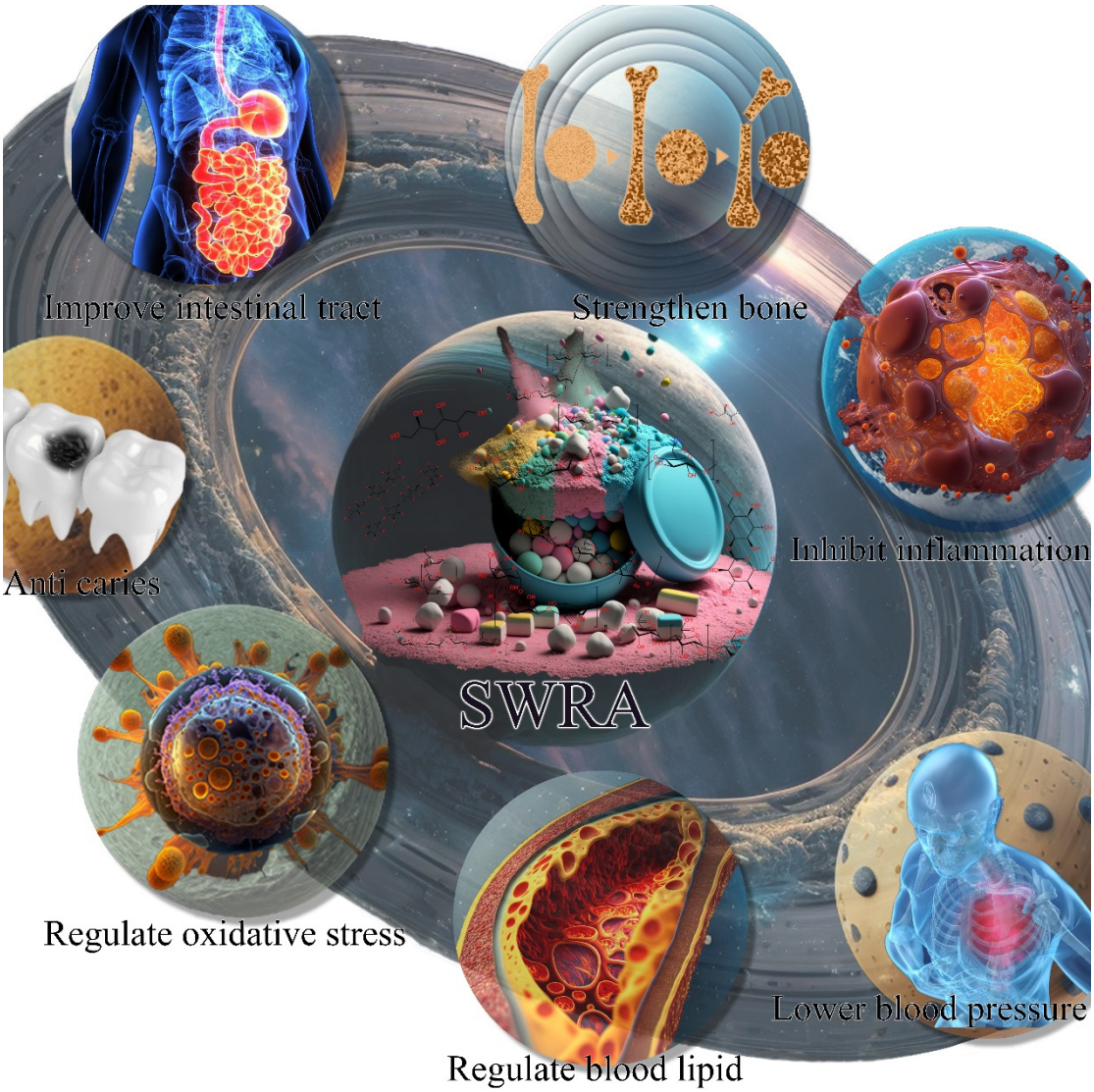

Figure 8. Biological functions of various SWRAs.

5. Extraction technology of SWRA

The specific steps of the extraction and processing process of SWRA will vary depending on the material source. KGM, LBG, and GG can be obtained by thermal mechanical treatment of raw materials, ethanol precipitation, drying, grinding and other ordinary processing, while partial extraction of SWRA requires further processing of raw materials [287–289]. The main classifications of chemical, physical and enzymatic methods and their applicability to SWRA extraction have been summarized in Table 2.

Table 2. The main extraction process of SWRA.

Extraction method	Main category	Main application	Applicable SWRA	Ref.
Chemical method	Acid treatment	Hydrochloric acid, phosphoric acid, sulfuric acid, nitric acid, acetic acid, citric acid, lactic acid, hydrofluoric acid, tartaric acid, malic acid, hydrogen peroxide.	COS, aligiate, sorbitol, MDS, LBG, CS, xylitol.	[288,290–296]
	Alkali treatment	NaOH, KOH, $Ca(OH)_2$.	KCG, GG, CS, alginate, pectin, xylitol.	[287,289,294,295,297–302]
Physical method		Water extraction method	Inulin, FG, pectin, carrageenan, XOS, LBG.	[292,303–307]

	Ultrasonic assisted	Inulin, CS, TR, FG, KCG, COS, pectin, alginate, AOS, XOS, xylitol.	[308–311]
	Microwave assisted	KCG, COS, inulin, alginate, FG, pectin, AOS, xylitol, CS.	[305,312–315]
Enzyme method	Cellulase	Alginate, CS, carrageenan, COS, AOS, pectin, inulin.	[292,316–319]
	Lyase	AOS, alginate, pectin.	[295,320–322]
	Protease	Pectin, inulin, alginate, carrageenan, CS, COS.	[316,318,323]

5.1 Chemical method

Chemical method is mainly acid treatment and alkali treatment. In addition to the processes described in Table 2, some SWRAs require further processing to extract. For example, CS can be obtained from chitin demineralized by HCl treatment, followed by heated alkali deproteinization and deacetylation. The original algae were pretreated with 0.1% formaldehyde, dissolved in dilute acid (usually HCl), and the alkaline solution was added to the harvested insoluble alginate, resulting in SAL in aqueous solution [298]. Following filtration, SAL solution was precipitated directly into SAL, calcium alginate, or alginate solution using ethanol, calcium chloride, or dilute hydrochloric acid [295]. The algae named *Kappaphycus sp.* most commonly applied for the preparation of carrageenan are treated with a hot alkaline solution to obtain an algal atmosphere, and then added to alcohol (mainly isopropyl alcohol) or potassium chloride solution, thus precipitated to obtain carrageenan [292]. At the same time, AOS, COS and XOS can be prepared from SAL, carrageenan and xylose through acid hydrolysis and hydroxy-peroxide polymerization, resulting in obtaining additives with improved solubility and enhanced biological activity, among which hydrogen peroxide is given priority because the by-product is water [321,324,325]. Moreover, the ion-exchange resin, activated carbon, pH regulation, microbial adaptation, and the subsequent chemical catalysis, electrical conversion, and series of steps (solvent volatilization, cooling to reduce solubility, precipitation or salting out, etc.) can all be applied to facilitate not only the crystallization of xylitol but also the extraction of other SWRAs [294,326,327]. It is crucial to emphasize, however, that a chemical extract such as hydrochloric acid, nitric acid, or sulfuric acid is corrosive, unsafe for application, has a great impact on the environment, and yield is low. At the same time, the complexity of the reaction progress cannot be effectively controlled, which results in the formation of secondary compounds that are difficult to remove, which requires producers to develop green extraction schemes and new methods [291,305].

5.2 Physical method

Water extraction method (namely solid-liquid extraction method) is widely utilized in the extraction of pectin, FG, inulin and LBG based on the characteristics of strong water penetration to plant tissue, high extraction efficiency, simple operation, safety and economy [288,304,305,328]. As a new extraction process, ultrasound is intended to play a "cavitation effect" to destroy cells, promote the release of plant contents, effectively reduce and eliminate the blocking layer between the water phase, increase the mass transfer efficiency, and contribute to the diffusion of solute [308,310,329]. In the industrial setting, ultrasonic technology is much simpler, takes less time, and relies less on enzymes to extract the required biochemical

components of algae [292,330,331]. Partial depolymerization of chitooligosaccharide with average molecular weight reduced from 2000 kDa to 450 kDa or from 300 kDa to 50 kDa can be obtained through irradiation hydrolysis with low frequency ultrasound (20 kHz) [332,333]. In addition, microwave extraction is carried out by radiating microrays into the solvent and through the cell wall to the cell interior, as well as microwave energy increases the internal temperature and pressure of the cell so that the cell wall breaks and releases its contents [311,312,315,334]. As a promising option for sustainable extraction of SWRA, ultrasound and microwaves lower energy and reagent consumption, shorten the extraction time, and improve safety. Nowadays, the application of ultrasound to extract carrageenan from *K. alvarezii* can achieve higher yields in a shorter time than traditional extraction, while not changing the chemical structure of carrageenan [292]. Ultrasonic, ultraviolet, gamma radiation, ozone, and microwave assisted have been widely employed in the preparation of chitooligosaccharide, AOS, inulin, XOS and other SWRAs, among which gamma irradiation is considered to be the most energy saving and effective alginate degradation procedure [291,321,325,328,329]. The physical method will make an important contribution to the extraction of SWRA in the future due to its advantages of being low cost, simple to operate, causing less pollution to the environment, as well as requiring a short extraction time. It does, however, have some disadvantages, including a low yield of oligosaccharides and a large footprint [324].

5.3 Enzymatic and fermentation methods

Enzyme technology is a biotechnology that has become increasingly popular in recent years for extracting active ingredients [316]. Utilizing enzymes can reduce the extraction conditions, decompose plant tissues in a relatively mild environment, and facilitate the release and extraction of the contained compounds [316,320,323]. In addition to enzyme assisted extraction summarized in Table 2, SWRA was produced using specific enzymes. The deproteinization and deacetylation of CS can be carried out enzymatically at a relatively mild temperature (25-29 ^{o}C). Meanwhile, CS hydrolysis involves the application of chitosanase and other non-specific enzymes that are capable of controlling the molecular weight distribution [298]. The degrading of alginate cell walls to release free alginate was accomplished with the aid of alginate lyase, sea current polysaccharide enzyme and other enzymes. In combination with the hydrolysis of cellulase, pectinase and protease, alginate was extracted from kelp that significantly reduced protein and polyphenol pollution as compared to acid treatment [295]. Endocellulase, exocellulase, and beta-glucosidase can be combined to completely hydrolyze cellulose microfibers in cell walls to release carrageenan in cells. Additionally, carrageenase, cellulase, and amylase can be employed as biological tools to produce COS, while immobilization technology is capable of reducing processing costs, facilitating control of depolymerization, and increasing feasibility [324]. Combining inulin glycoenzyme assisted extraction with hot water extraction can reduce the polymer composition of inulin and increase its stability [328]. The enzymes applied to produce XOS include β-xylosidase, glycosynthase and endoxylanase, which can be economical, rapid and environmentally friendly without the need for any special equipment or undesirable by-products [325]. In industrial settings, however, enzymes utilized for certain products, such as CS, are much more expensive and

less efficient than chemical methods, and protein residues cannot be removed. Also, the restricted enzyme activity and strict reaction conditions prevent the widespread application of enzyme methods to the industrial scale production of SWRA [292,298].

In this scenario, fermentation approaches offer a number of alternatives to the high cost of enzymes, which can be reduced as a result of the rapid reproduction of microorganisms while secreting enzymes into the reactor under optimal conditions [310]. Commercially, XG is produced by fermenting glucose with the plant-related bacterium *X. campestris* [335]. Alginate depolymerization was performed on *Gracilibacillus* A7, *Bacillus subtilis* KCTC 11782BP, *Bacillus litoralis* strain M3, *Flavobacterium* sp. strain LXA, and *Pseudoalteromonas agarovorans* CHO-12 resulting in 92.60% purity and 91.70% yield of AOS [321]. Note that fermentation processes may be lengthy, inefficient (remaining proteins are not reacting, DD values are low, etc.), lactic acid fermentation in CS preparation typically takes about 21 days or more, and fermentation requires certain microbial strains that may not be available within biosafe countries near its borders [292,310,336].

To summarize, chemical processes in industrial processes produce wastewater that can cause severe environmental problems and the treatment of acidic and alkaline wastewater can also be costly [296,327,337]. As an alternative to traditional inorganic acids, environmentally friendly acids such as citric acid extracted from organic sources, acids from fungi, and acetic acid whose by-product is highly water-soluble, are applied to reduce the pH required for efficient extraction and increase the sustainability of extraction. Alternatively, replacing NaOH with KOH in alkali treatment will be an environmentally and commercially viable alternative strategy in the future, since KOH does not generate sodium ion by-products that pollute the environment, can be added to fertilizer as a necessary element, and, most importantly, is more effective in extracting and removing by-products [298]. In addition, it is also necessary to enhance the selectivity with an enzymatic method to reduce by-products and side reactions and improve the biological activity of products, as well as intensify the reaction with microwave or ultrasonic [312,313,334]. As a result of site-specific engineering in catalytic modules and active sites, it is possible to produce substrate-specific AOS products, such as the dual-function endonuclide alginate lyase [321]. In contrast to conventional acid hydrolysis, microwave-assisted oligosaccharide hydrolysis is more convenient, environmentally friendly, and efficient [338]. Physical and enzyme modification is considered an environmentally friendly method of starch modification, which is considered "clean label ingredients" since they contain no synthetic or artificial ingredients [290,337]. In addition, the application of ion exchange resin, anion exchange chromatography, solid phase extraction and membrane filtration technology to further purification rather than chemical treatment of residual substances in the subsequent process is also a future trend of development, such as the utilization of membrane filtration technology in the preparation of AOS to purify degradation products [3,321,326]. Therefore, the focus of future research should be on the combination and integration of processes, testing the optimal combination of different raw materials with chemical, physical, biological and purification techniques to obtain economically viable and health-promoting products with optimal production efficiency.

6. Challenges and improving strategies

It should be noted, however, that in Fig. 9: (I) The WHC of SWRA is generally weaker than phosphate under the same dosage, which requires the addition of a greater quantity of SWRA to meet the actual demand, thus increasing the cost of application [339]; (II) The single application of SWRAs such as CS, KCG and GG could improve the WHC of meat products, but adversely affect viscosity, hardness, and shear force, as well as alter the color and flavor; (III) The excessive addition of SWRAs, such as GG, pectin, and sorbitol, will cause colon relaxation and abdominal discomfort [189,340]; in people with low salivary flow [341], frequent application of sorbitol may pose a slight cariogenic risk, as well as a slight interruption of antioxidant defenses. When taken in large doses or with insufficient water, dietary fibers such as FG may cause intestinal obstruction.

Accordingly, the improvement measures for each point are as follows: (I) As a further measure to aid WHC, ultrasound, high static pressure, and vacuum processing are recommended [25,342]. Treatment with ultrasound can promote protein cross-linking by activating endogenous glutamine transaminase and protease in surimi to form more non-covalent and disulfide bonds, thus significantly improving the WHC, gel strength and microstructure of surimi gels, and also improving hardness and chewability [343,344]. In addition, Zhang et al. demonstrated that 200 MPa is the optimal pressure for hydrophobic interactions and high pressure strengthened the hydrogen bonds of MP gels at pressures of 300 MPa and above. Bound water has a lower water mobility, and at the same time, more free water is attracted to proteins or trapped in gel structures and transferred to bound or fixed water with increased pressure [345].

(II) It is currently possible to improve the effect of WHC by combining it with a range of other substances, which not only reduces the application cost but also ensures desirable food characteristics. For example, by combining dietary fiber with a high oil-holding capacity (which stabilizes the fat in the product), changes in the viscosity and texture of certain formulations can be avoided [346]. It is worth mentioning that the strategy of ultrasonic treatment with 60 W combined with WRA showed better water retention effect, and the hardness, elasticity and chewability of the texture characteristics were significantly changed. Meanwhile, also significantly delayed the development of total volatile alkali nitrogen content, myofibrillar protein content and muscle protein Ca^{2+}-ATPase activity, and maintained the integrity of tissue structure [342]. In addition, the combination of vacuum and ultrasound can improve the WHC of adductor muscle in cooking loss, and the mastication and elasticity are the best compared with other groups. Moreover, vacuum treatment can enhance the shear force and hardness of adductor muscle most effectively [347]. The combination of high pressure, sodium caseinate and KGM significantly reduced the amount of KGM, and also ensured superior water holding capacity and coagulation properties [348]. On the other hand, adding 0.3% CS oligosaccharides to plasma glucose in spontaneously diabetic male GK rats reduced it by approximately 19%, and there are no other side effects [349]. In short, combined use with ultrasound, high static pressure, vacuum, other substances or control of starch, CS, alginate and other special purpose substances modification degree will be a very promising development direction in the future.

(III) In order to avoid excessive addition of SWRA, comprehensive labeling is necessary to achieve quantitative limitation. Currently, consumers favor more "natural", "healthy", and "familiar" products, and these options require the food industry to develop "clean label" foods with a limited number of ingredients and without European Union inventory number (E-Numbers) additives and/or substances unfamiliar to consumers [176]. Subsequently, the multiple water retention mechanisms of SWRA should be utilized to further study and optimize its application scope and adaptation to meet different processing conditions and meat product varieties. For SWRAs to be developed in the future, full consideration must be given to safety, nutritional value, and market demand, while enhancing cooperation and exchanges with manufacturers and regulatory bodies.

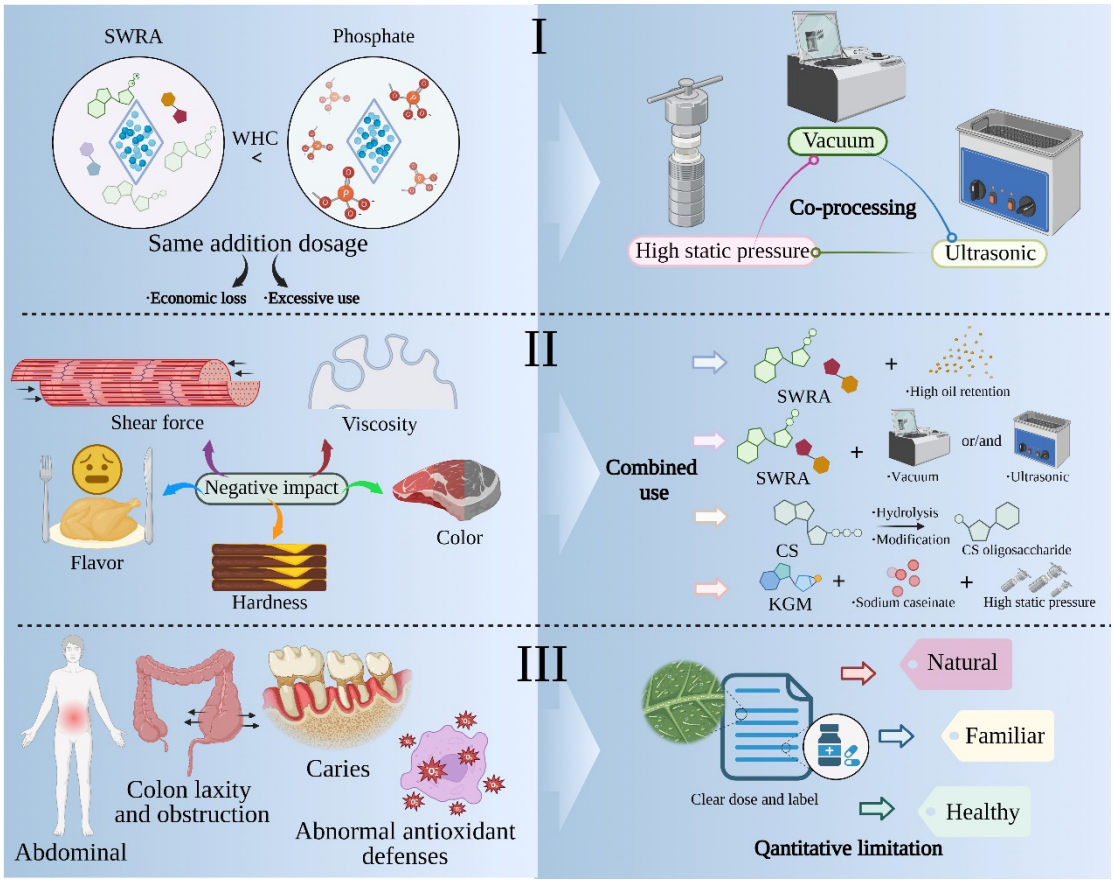

Figure 9. The challenges (left) and improvement strategies (right) of SWRA applications in meat products.

7. Conclusion

Future food processing will increasingly apply phosphate-free WRA due to the side effects of phosphate WRA. Besides having various WHC mechanisms (which allows it to be more flexible in adapting to various processing conditions), SWRA also shows excellent WHC properties that make it an ideal choice for meat processing. As consumers become more aware of the benefits of healthy eating and therapeutic foods, SWRA has the potential to meet market demands because of its numerous health benefits. In the processing of meat products, SWRA offers a new opportunity. To ensure product safety and nutrition, it is promising to explore the applications of more beneficial SWRAs to replace phosphate in future meat products.

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Declaration of Conflicting interest

Authors have no conflict of interest to declare.

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