

REVIEW ARTICLE

A review of food hydrocolloids on cardiovascular health: Alginate, astragalus polysaccharides, carrageenan, fucoidan, lunasin, and psyllium

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ABSTRACT

Food hydrocolloids, derived from natural sources such as plants, algae, and microbes, possess bioactive properties that significantly contribute to cardiovascular health. This review focuses on six key hydrocolloids: alginate, astragalus polysaccharides, carrageenan, fucoidan, lunasin, and psyllium, while also considering other important natural hydrocolloids such as short chain fatty acids (SCFAs), plant-derived food hydrocolloids, plant-derived gums, plant-derived mucilages, pectin, modified citrus pectin, inulin, naringenin, chia seeds, gelatine, whey protein, casein, microbial exopolysaccharides and gums, ulvan, and laminarin. Alginate, from brown seaweed, aids in cardiac tissue regeneration and repair. Astragalus polysaccharides, from the Astragalus plant, provide antioxidant, anti-inflammatory, and immunomodulatory benefits. Carrageenan, sourced from red seaweed, supports lipid profile balance and heart health. Fucoidan, another brown seaweed derivative, offers antihypertensive and lipid-lowering effects. Lunasin, a peptide found in soybeans, oats, and barley, is known for its cholesterol-lowering properties and anti-inflammatory effects. Psyllium, rich in soluble fiber, helps lower LDL cholesterol and improve overall cardiovascular function. These hydrocolloids, along with other mentioned compounds, are utilized in drug formulations, cosmetics, processed foods, and dietary supplements, enhancing food texture and stability while delivering health benefits. Upon consumption, they can be absorbed into the bloodstream or metabolized by gut microbiota into bioactive metabolites. This review examines their effects on cardiovascular function, highlighting their mechanisms in regulating vascular tone, blood pressure, vascular inflammation, and cardiac function. It consolidates current research, emphasizing the potential of these hydrocolloids and related compounds in the prevention and management of cardiovascular diseases (CVDs).

Keywords: Food hydrocolloids; Cardiovascular health; Alginate; Astragalus polysaccharides; Carrageenan; Fucoidan; Lunasin; Psyllium

1. Introduction

Food hydrocolloids represent a diverse class of biological polymers, primarily composed of polysaccharides and proteins [1]. These compounds are characterized by numerous hydroxyl groups that attract water, enabling them to form stable gels or mixtures. This unique property is crucial for the food industry, where hydrocolloids play significant roles in improving the texture, stability, and overall quality of various food products and health supplements [2, 3]. In addition to their functional uses, food hydrocolloids demonstrate a variety of biological effects, leading to growing research interest in their potential health benefits [4].

Among the numerous hydrocolloids, alginate, astragalus polysaccharides, carrageenan, fucoidan, lunasin, and psyllium have emerged as particularly promising due to their potent cardiovascular protective effects. Alginate, extracted from brown seaweed, aids in cardiac tissue regeneration and repair [5, 6].

Carrageenan, sourced from red seaweed, supports lipid profile balance and heart health [7]. Fucoidan, another brown seaweed derivative, has demonstrated antihypertensive, anti-inflammatory, and lipid-lowering properties [8, 9]. Lunasin, a peptide found in soybeans, oats, and barley, is known for its cholesterol-lowering properties and anti-inflammatory effects [10]. Psyllium, rich in soluble fiber, helps lower LDL cholesterol and improve overall cardiovascular function [11]. These hydrocolloids not only enhance the nutritional value of foods but also play a critical role in modulating physiological processes that influence cardiovascular health.

In addition to these key hydrocolloids, other compounds such as short-chain fatty acids (SCFAs), plant-derived food hydrocolloids, plant-derived gums, plant-derived mucilages, pectin, modified citrus pectin, inulin, naringenin, chia seeds, gelatine, whey protein, casein, microbial exopolysaccharides and gums, ulvan, and laminarin also contribute to cardiovascular health.

Studies indicate that food hydrocolloids and their metabolites can positively influence human health, enhancing the nutritional value of foods significantly [1]. Upon consumption, these hydrocolloids may be absorbed directly into the bloodstream or metabolized by gut microbiota into bioactive substances, particularly short-chain fatty acids (SCFAs) such as acetate, propionate,

and butyrate [12]. These metabolites have been shown to exert multiple health benefits, including reducing inflammation, improving gut health, and enhancing immune function [13, 14]. The interaction between food hydrocolloids and gut microbiota has opened new avenues for research into their systemic effects, particularly in cardiovascular health.

Evidence suggests that food hydrocolloids and their metabolites significantly influence cardiovascular health by modulating risk factors such as blood pressure, vascular inflammation, and lipid profiles. For instance, hydrocolloids like guar gum and psyllium have been shown to improve blood pressure regulation and lipid metabolism [10, 15]. In addition, SCFAs derived from the fermentation of hydrocolloids can reduce vascular inflammation and promote endothelial function, further supporting cardiovascular health [11, 14].

This review highlights the current understanding of food hydrocolloids and their bioactive metabolites in relation to cardiovascular health, with a particular focus on alginate, astragalus polysaccharides, carrageenan, fucoidan, lunasin, and psyllium. It will explore their roles in maintaining vascular health, mitigating inflammation and remodeling, influencing cardiac function, and regulating systemic blood pressure. The review also highlights clinical trial data to emphasize the therapeutic potential of these hydrocolloids in managing cardiovascular diseases (CVDs). Preclinical studies using cellular and animal models will be examined to elucidate the mechanisms of action, while identifying limitations in current research and proposing future directions to validate findings. Such efforts will help establish a mechanistic basis for understanding the cardiovascular effects of food hydrocolloids and their metabolites [12]. This review seeks to provide valuable insights for developing dietary strategies and interventions aimed at enhancing cardiovascular health and reducing disease risk.

2. Short chain fatty acids (SCFAs)

Short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate (**Fig. 1**), play a significant role in modulating immune function and inflammatory processes, contributing to the management of hypertension and overall cardiovascular health. For example, propionate has been shown to reduce T-cell responses to angiotensin II, a hormone that can elevate blood pressure, effectively suppressing hypertension in animal models [16]. Additionally, butyrate helps limit

immune responses by inhibiting the production of pro-inflammatory cytokines such as interleukin-6 and tumor necrosis factor-alpha (TNF- α), which collectively aid in lowering blood pressure[14]. Beyond their effects on blood pressure, SCFAs are essential for maintaining gut health, which directly influences cardiovascular health. They support the repair and maintenance of the gut mucosal barrier, preventing harmful bacterial toxins from entering the bloodstream and inhibiting systemic inflammatory responses [12].

Recent evidence underscores the beneficial impacts of SCFAs on cardiac physiology. For instance, propionate has been found to reduce the risk of ventricular tachycardia and improve cardiac electrical stability following myocardial infarction [16]. Butyrate contributes to this protective effect by decreasing inflammation and oxidative stress after myocardial infarction and during ischemia/reperfusion injury [17].

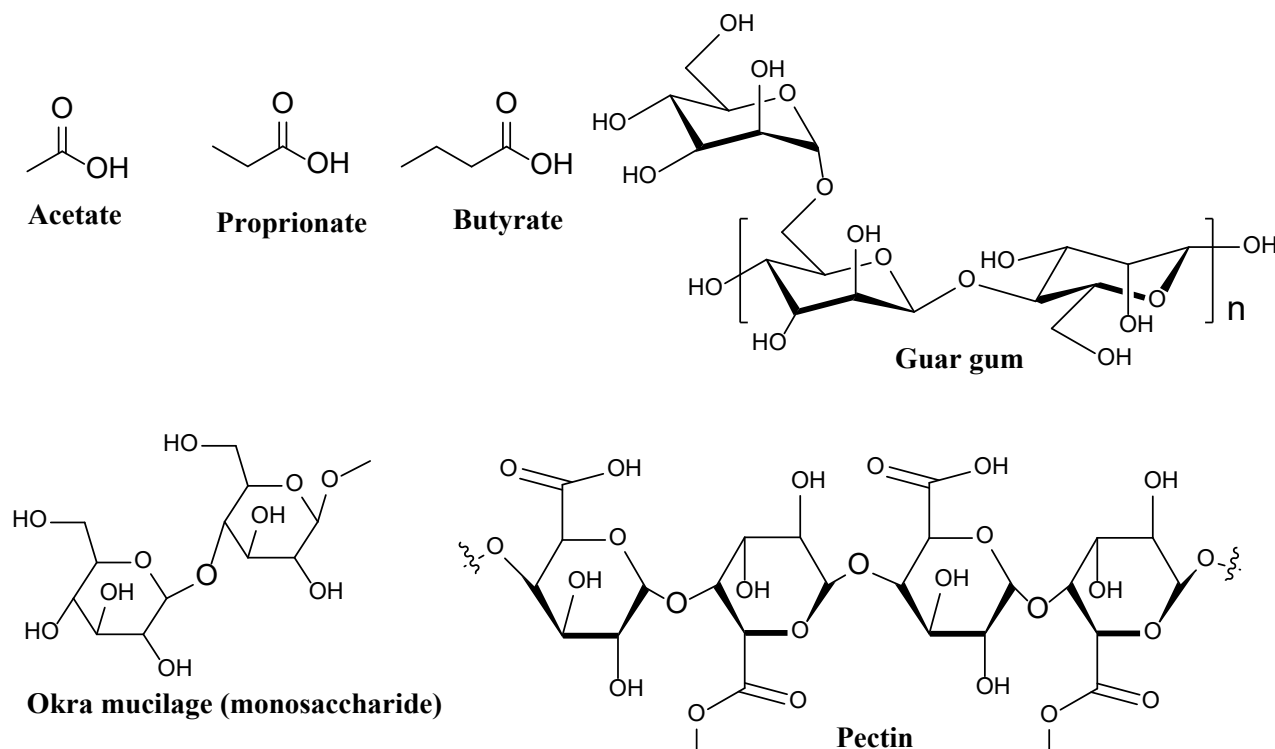


Fig. 1. Structures of some short-chain fatty acids; Molecular structure of guar gum; Molecular structure of okra mucilage (monosaccharide); and Chemical structure of pectin.

Overall, SCFAs exhibit the ability to lower inflammation, modulate immune responses, and reduce oxidative damage, potentially preventing cardiac remodeling and decreasing the risk of ventricular arrhythmias [13]. SCFAs are key players in cardiovascular health, exhibiting varied mechanisms that influence blood pressure, inflammation, and overall cardiac function. Further research is necessary to fully understand the complex roles of SCFAs in cardiac physiology and their long-term effects on cardiovascular health.

3. Plant-derived food hydrocolloids

3.1. Plant-derived Gums

Plant-derived gums are complex polysaccharides produced by various plants, playing crucial roles in both food products and pharmaceuticals [18]. These plant-derived gums are recognized for their multifunctional properties and potential health benefits, including the regulation of colon function, prevention of kidney failure, and management of satiety [19]. Most importantly, research has shown that plant-derived gums positively impact cardiovascular health, highlighting their potential as functional ingredients in dietary interventions.

Many plant gums, including guar gum (**Fig. 1**) and locust bean gum, exhibit notable antioxidant activity due to their ability to scavenge free radicals and chelate metals [20]. These antioxidant properties are essential for alleviating oxidative stress, which plays a significant role in the pathogenesis of cardiovascular diseases. Specific studies have indicated that sesquiterpenes from myrrh extracts can reduce the expression of intercellular adhesion molecule-1 (ICAM-1) in human microvascular endothelial cells stimulated with tumour necrosis factor-alpha (TNF- α) [21].

Gum arabic, another significant plant-derived gum, is noted for its ability to lower pro-inflammatory cytokines and inflammatory markers in chronic conditions [22]. Studies have demonstrated that gum arabic can reduce cardiovascular inflammation and cell death caused by water-pipe smoke in mouse models by stimulating Nrf2-dependent antioxidant signaling pathways [22]. The antihypertensive properties of plant-derived gums have also been explored, with clinical studies indicating that gum arabic effectively ameliorates blood pressure increases in both diabetic and healthy individuals [23]. The antihypertensive effects of gums like *Ferula asafoetida* have

been documented, showing reductions in arterial blood pressure in anesthetized rats and suppression of angiotensin II-induced blood pressure elevation [24].

In terms of lipid management, gums such as guar gum (**Fig. 1**) have been shown to effectively lower total cholesterol (TC) and low-density lipoprotein (LDL) cholesterol levels without significantly affecting high-density lipoprotein (HDL) cholesterol [15]. The incorporation of the guar and locust bean gum into the diet may serve as a beneficial strategy for managing cholesterol levels and reducing the risk of cardiovascular diseases.

3.2. Plant-derived mucilages

Mucilages are complex polysaccharide plant hydrocolloids that form within plant cells as part of normal metabolism [25]. They typically exhibit lower water solubility than gums but still demonstrate significant potential for contributing to cardiovascular health [26]. One notable feature of mucilages is their high phenolic content, which endows them with potent antioxidant capabilities. This includes the ability to scavenge free radicals and reduce ferric ions, thereby offering protection against oxidative stress [25]. Mucilages derived from okra (**Fig. 1**) have been shown to exhibit significant antioxidant effects, as evidenced by studies involving diabetic rat models that demonstrate their efficacy in scavenging free radicals [25, 27].

Research on mucilages from *Lallemantia royleana* (Balangu Shirazi) seeds shows impressive DPPH radical scavenging activity, effectively reducing oxidative stress in hypercholesterolemic rats [28]. Furthermore, mucilages extracted from the leaves of *Malva parviflora* and from *Althea rosea* also exhibit the capability to scavenge DPPH free radicals, indicating their potential for mitigating oxidative damage [29]. However, the *in vivo* antioxidant actions of these mucilages, especially within cardiovascular disease models, warrant further investigation.

Preclinical studies have shown mixed results regarding the effects of plant-derived mucilages on blood pressure regulation. Mucilage from *Trigonella foenum-graecum* (fenugreek) has demonstrated the capability to lower cholesterol levels and decrease inflammatory enzyme activity, pointing to its potential therapeutic applications in cardiovascular health [26]. In another

study, okra mucilages have proven effective in lowering blood pressure in a fructose-induced hypertensive rat model [27]. While there is limited clinical evidence supporting the antihypertensive effects of okra, *Althea rosea* mucilage has been shown to inhibit angiotensin-converting enzyme (ACE), suggesting potential antihypertensive properties [29]. However, further research is required to understand the mechanisms and effectiveness of these mucilages in dietary interventions aimed at improving cardiovascular health.

3.3. Pectin

Pectin (**Fig. 1**) is a family of complex oligosaccharides and polysaccharides present in the cell walls of land plants. The chemical structure of pectin varies among plant species, resulting in diverse biological activities and health benefits [1]. Notably, many pectin polysaccharides exhibit significant antioxidant properties. For instance, pectin extracted from apple pomace has been shown to effectively scavenge free radicals and reduce ferric ions, highlighting its role as an antioxidant [30].

In addition to their antioxidant effects, pectin polysaccharides possess notable anti-inflammatory activities that are particularly relevant for chronic inflammatory diseases such as irritable bowel syndrome [21]. Studies show that pectin polysaccharides derived from *Rubus chingii* and *Medicago sativa* L. (alfalfa stem) decrease the expression of pro-inflammatory cytokine genes, including interleukin-6, inducible nitric oxide synthase, and tumour necrosis factor-alpha (TNF- α), in a mouse macrophage cell line stimulated by lipopolysaccharide [21].

Macrophages play a crucial role in the development of atherosclerosis, maintaining a pro-inflammatory environment that contributes to unstable plaque formation and the progression of cardiovascular diseases. The anti-inflammatory actions of pectin polysaccharides suggest a potential therapeutic role in mitigating atherosclerosis by reducing inflammation, which may help stabilize plaques and improve vascular health [31]. Despite these promising findings, further research is required to explore how pectin polysaccharides modulate inflammatory processes and their overall impact on cardiovascular health. A better understanding of these mechanisms will aid in developing dietary interventions that utilize pectin for cardiovascular disease prevention and management.

3.4. *Modified citrus pectin*

Modified citrus pectin (MCP) (**Fig. 2**) has been extensively studied for its cardiovascular effects due to its ability to inhibit galectin-3, a protein critically involved in various cardiovascular conditions such as atherosclerosis, heart failure, cardiac fibrosis, and peripheral artery disease [31]. Evidence indicates that in apolipoprotein E-deficient mice, a diet enriched with 1% MCP reduces atherosclerotic lesions, the presence of macrophages and smooth muscle cells in plaques, and lessens endothelial cell damage [31].

MCP effectively decreases monocyte adhesion to endothelial cells stimulated with oxidized LDL through the inhibition of galectin-3 [32]. In rat models of cardiac hypertrophy, MCP activates the p38 signalling pathway while inhibiting the Gal3/TLR4/JAK2/STAT3 pathway, resulting in reduced expression of hypertrophic genes and improved cardiac function [33]. Additionally, MCP provides protection against cardiac dysfunction and myocardial damage by downregulating galectin-3 and reducing TLR4/MyD88/NF- κ B/p65 signalling, which are critical in mediating inflammatory responses [33]. Evidence emphasizes a broader potential for pectin-based dietary interventions in mitigating cardiovascular issues.

3.5. *Psyllium*

Psyllium (**Fig. 2**) is a polysaccharide derived from the husk of *Plantago ovata* seeds, recognized for its historical use in food and traditional medicine [34]. Two recent meta-analyses of randomized controlled trials reported that psyllium treatment significantly decreased systolic blood pressure when compared to control diets. However, it did not have a significant effect on diastolic pressure. One of the meta-analyses suggested that the decrease in diastolic pressure could be significant for interventions lasting at least 8 weeks [10, 11].

Meta-analyses have also revealed that psyllium reduces total cholesterol (TC), low-density lipoprotein (LDL), non-high-density lipoprotein (non-HDL) cholesterol, and apolipoprotein B concentrations. This reduction in cholesterol levels may translate into a decreased risk of developing atherosclerosis [11, 35]. In a rat model of ischemia/reperfusion, supplementation with

psyllium resulted in decreased myocardial injury. This effect was achieved through the inhibition of apoptosis and antioxidant activities [36].

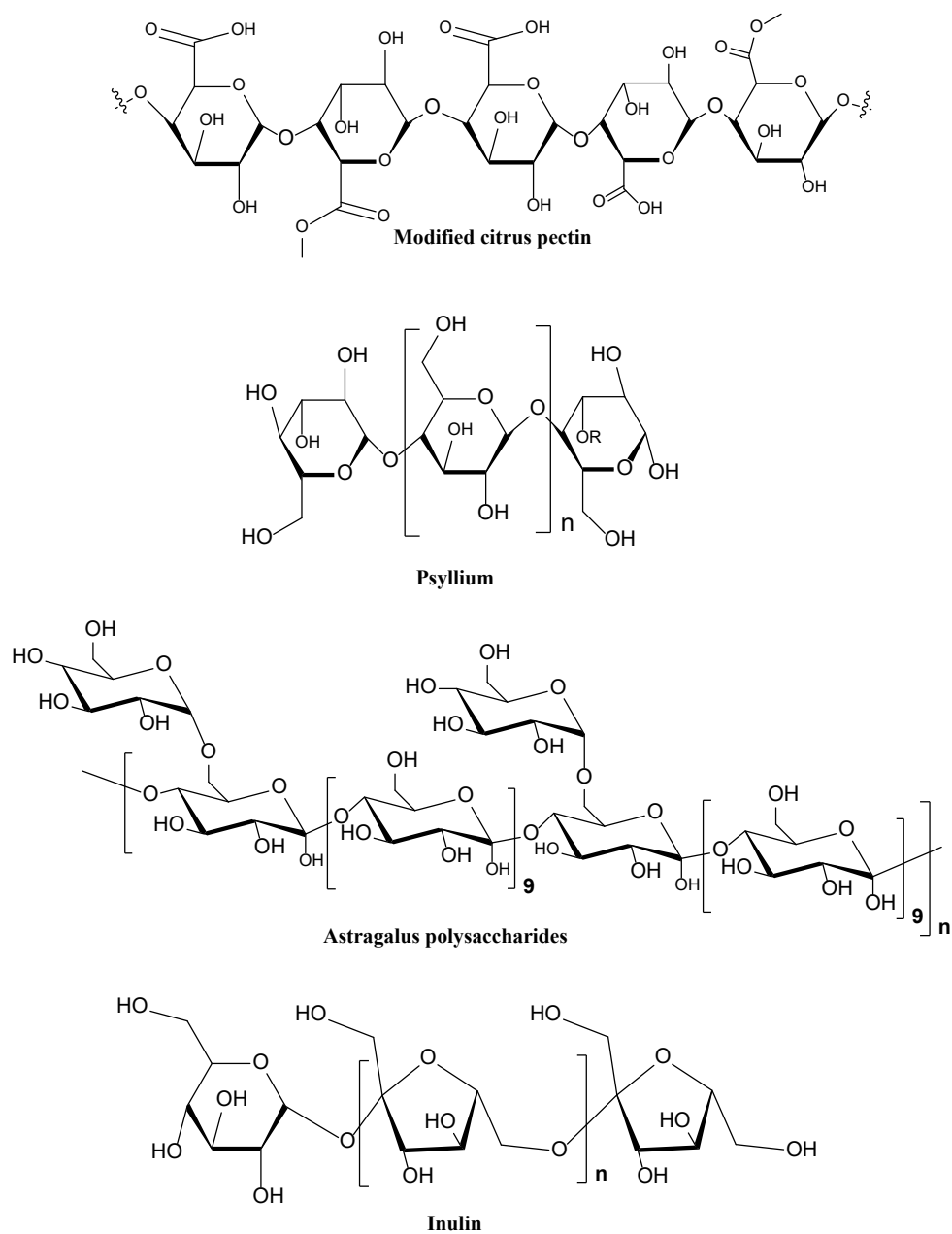


Fig. 2. Structure of modified citrus pectin; Structure of psyllium; Structure of Astragalus polysaccharides; and Structure of inulin.

Psyllium shows a lot of potential as both an additive to food products and pharmaceuticals, and it may also act as a cardioprotective agent with impact on lowering total cholesterol (TC), low-density lipoprotein (LDL) cholesterol, non-HDL cholesterol, and apolipoprotein B, potentially decreasing the risk of atherosclerosis. However, more research is needed to understand how psyllium can enhance the nutritional value of commonly used products [34]. There are few studies assessing the role of psyllium in the pathogenesis of atherosclerosis, especially concerning vascular inflammation and remodeling. However, no studies have yet investigated the role of psyllium on pro-inflammatory cytokine concentrations, cellular adhesion molecule expression, or leukocyte adhesion [11].

Several epidemiologic studies have highlighted the inverse relationship between dietary fiber intake and cardiovascular events. This relationship is mediated by the regulation of serum lipids [37, 38]. However, these studies are limited by potential discrepancies between the actual and reported dietary fiber intake of respondents. Moreover, the wide variety of dietary fibers available makes it challenging to isolate the specific impact of psyllium. Thus, both preclinical and clinical studies, particularly randomized controlled trials, are needed to understand and characterize the importance of psyllium on the cardiovascular system.

3.6. *Astragalus polysaccharides*

Astragalus polysaccharide (APS) (Fig. 2) is a bioactive, water-soluble polysaccharide extracted from the roots of *Astragalus membranaceus*, a plant widely used in traditional Chinese medicine for its therapeutic properties [39]. APS has gained significant attention for its cardioprotective effects, particularly in mitigating cardiovascular disorders such as endothelial dysfunction, cardiomyopathy, hypertension, and atherosclerosis. In models of overexercise-induced myocardial injury, APS has been shown to reduce cardiac injury markers by 50 to 80%, primarily through the activation of the AMPK pathway, which decreases inflammation and oxidative stress [40]. This mechanism is particularly relevant in preventing cardiac remodeling, a key factor in the progression of heart failure. APS has also demonstrated protective effects in viral myocarditis by improving survival rates and cardiac function while reducing inflammation through the inhibition of the TLR-4/NF- κ B signaling pathway [41].

In diabetic cardiomyopathy models, APS has been shown to mitigate oxidative stress and cardiomyocyte apoptosis, which are critical contributors to heart failure in diabetic patients [42]. Furthermore, in models of doxorubicin-induced cardiomyopathy, APS effectively reduced oxidative stress and cardiomyocyte apoptosis by inhibiting the p38 MAPK signaling pathway, highlighting its potential as an adjunct therapy for chemotherapy-induced cardiotoxicity [42]. In addition to its antioxidant and anti-inflammatory effects, APS significantly lowered systolic blood pressure by 40-50 mmHg. It also decreased renal tubule injury and collagen deposition within the kidney while improving renal function in models of hypertension induced by DOCA (deoxycorticosterone acetate) and angiotensin II. This was accomplished by inhibiting the transforming growth factor-beta1/integrin-linked kinase (TGF- β 1/ILK) signaling cascade [43]. These findings suggest that APS could be a valuable therapeutic agent for managing hypertension and associated renal complications.

APS achieves these effects through various mechanisms. It enhances immune organ indices, promotes the proliferation of immune cells, stimulates the release of cytokines, scavenges free radicals, inhibits tumor cell growth and metastasis, improves insulin sensitivity, and protects various organs from damage [44]. Importantly, APS exhibits low toxicity and minimal side effects, making it an especially promising candidate for clinical applications [45].

Similar findings were reported in a diabetic cardiomyopathy model [46]. In a doxorubicin-induced cardiomyopathy model, pretreatment with APS reduced oxidative stress by 50% and decreased cardiomyocyte apoptosis through inhibition of the p38 MAPK pathway [42]. While the effects were less pronounced compared to other models, APS also reduced the increase in ROS produced in endothelial cells stimulated by homocysteine [47]. Some fractions of APS have shown more potent free radical scavenging activity, with APS3-I being more effective than APS2-I, leading to greater impacts on cell viability [48].

Overall, a growing body of preclinical evidence highlights the potent cardioprotective potential of Astragalus polysaccharides in a variety of models. Other compounds found in the Astragalus plant, such as flavonoids, also demonstrate beneficial health effects. For instance, in a model of atherosclerosis induced by a high-cholesterol diet, total flavonoids from Astragalus

reduced plasma total cholesterol by 34-38% and LDL cholesterol by 43-44%, while increasing HDL cholesterol by 173% [49]. This translated to a decrease in the aortic fatty streak area and reduced aortic cholesterol content [49].

In addition to its cardiovascular benefits, APS has been shown to enhance immune function and reduce systemic inflammation, which are critical in preventing atherosclerosis and other inflammatory cardiovascular diseases [39]. The therapeutic potential of APS is further supported by its ability to modulate gut microbiota, promoting the production of short-chain fatty acids (SCFAs) that contribute to cardiovascular health [12]. Thus, *Astragalus* plants as a whole show therapeutic promise, which warrants further investigation through clinical trials, especially due to their relatively safe clinical profile and historic use in traditional Chinese.

3.7. Inulin

Inulin (**Fig. 2**) is a polysaccharide derived from various plants, including chicory root (*Cichorium intybus*), Jerusalem artichokes, and agave. Its structure consists of fructose subunits linked by β -(2 $\rightarrow$ 1) bonds, with a terminal glucose molecule [19]. Inulin is resistant to digestion and functions as a prebiotic, promoting the growth of beneficial gut bacteria such as *Bifidobacterium* and *Lactobacillus*. These bacteria ferment inulin, producing short-chain fatty acids (SCFAs), which are crucial for maintaining gut health and cardiovascular function [4, 19].

Research demonstrates that inulin supplementation is associated with decreased atherosclerotic lesions and improvements in gut dysbiosis, along with reductions in cholesterol and systemic inflammation [50]. In a study involving ApoE^{-/-} mice fed a Western diet, inulin led to a reduction of approximately 20% in atherosclerotic lesions, favourable changes in gut microbiota composition, and decreased levels of total cholesterol (TC), triglycerides (TG), and pro-inflammatory cytokines [50]. Similar findings were reported in a randomized controlled trial (RCT) involving 52 women with type 2 diabetes, where participants were given an oligofructose-enriched inulin dietary supplement for 8 weeks [20]. The intervention resulted in decreased fasting plasma glucose, HbA1c, TC, LDL, oxidative stress, and atherogenic ratios (TC/HDL and LDL/HDL) while increasing total antioxidant capacity [20]. However, a meta-analysis indicated that inulin does not significantly lower blood pressure in the general population [4]. This

observation aligns with findings that hypertensive patients typically respond more favourably to antihypertensive therapy compared to those without hypertension.

3.8. Naringenin

Naringenin is a phenolic compound (**Fig. 3**) found in citrus fruits, tomatoes, figs, nuts, and beans, existing in two forms: naringenin (aglycone) and naringin (glycoside) [51]. This compound exhibits a range of beneficial properties, including antioxidant, anti-inflammatory, antitumor, antihyperlipidemic, antihypertensive, and cardioprotective effects [51].

Research indicates that naringenin reduces aortic fatty streaks and decreases the expression of monocyte chemoattractant protein-1 (MCP-1) and vascular cell adhesion molecule-1 (VCAM-1) in animal models [52]. In studies with rats, naringenin effectively reduces reactive oxygen species (ROS), enhances superoxide dismutase (SOD) activity, and inhibits the migration and proliferation of vascular smooth muscle cells (vSMCs), demonstrating its anti-atherogenic potential [53].

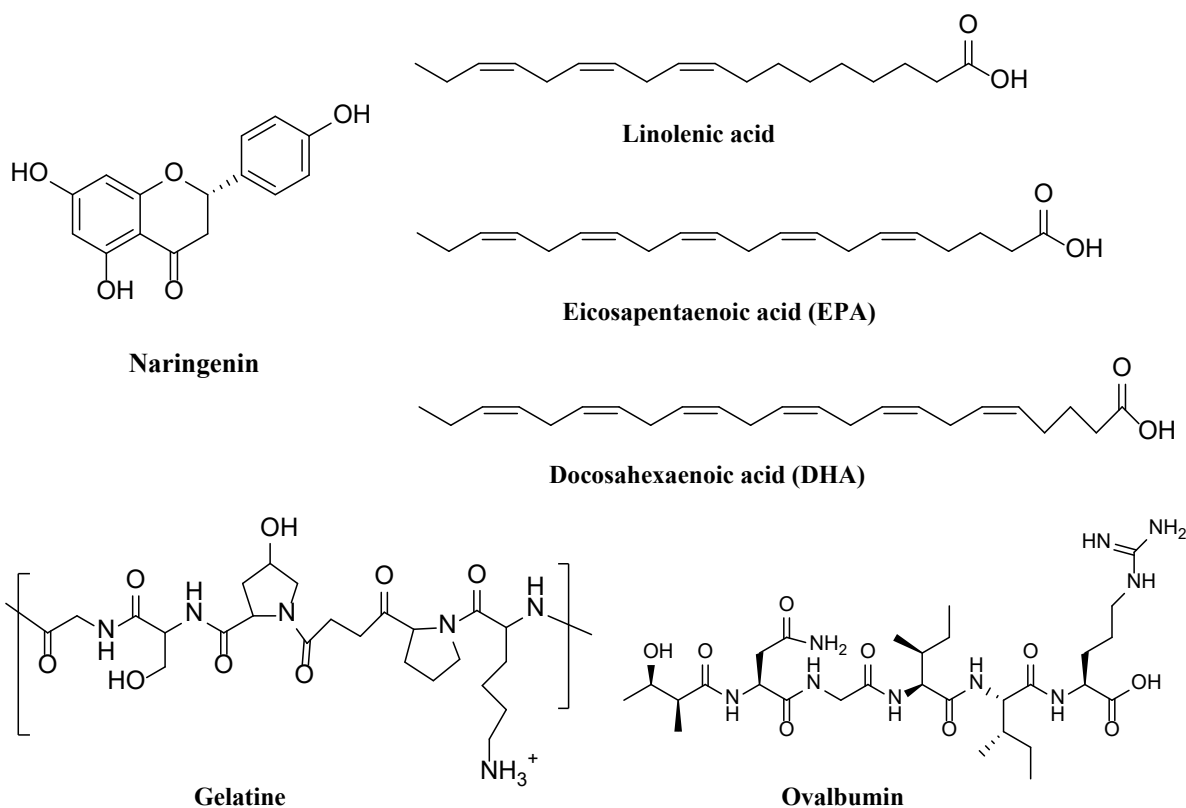


Fig. 3. Molecular structure of naringenin; Structures of some well-known omega-3 fatty acids; Structure of gelatine; and Structure of ovalbumin as egg-derived protein.

Naringenin positively influences lipid profiles by regulating low-density lipoprotein (LDL) and triglyceride (TG) levels, increasing high-density lipoprotein (HDL), and suppressing oxidative stress and inflammatory markers [54]. It inhibits the extracellular signal-regulated kinase (ERK) and PI3K/Akt pathways, which are involved in reducing cardiac fibrosis and hypertrophy [55]. Naringenin also activates peroxisome proliferator-activated receptors (PPARs), leading to increased levels of antihypertensive epoxyeicosatrienoic acids (EETs) and upregulation of CYP2J3, providing protective effects against diabetic cardiac myopathy [56].

Moreover, naringin, the glycosidic form of naringenin, has been shown to enhance the expression of the cardioprotective protein Sirtuin 1 (SIRT1), reduce ROS production, and suppress TNF- α and IL-6 levels in aging mice [57]. Naringin also protected against isoproterenol-induced cardiac damage in hypertensive and normotensive rats by restoring KCl-induced contractility, reducing clot formation, and exhibiting antioxidant activity [55]. These findings highlight the multifaceted roles of naringenin in mitigating cardiovascular dysfunction, making it a promising candidate for further exploration as a therapeutic agent.

3.9. Lunasin

Lunasin is a 43-amino acid bioactive peptide, weighing approximately 5 kDa, that was first isolated from soybean. It features a unique Arg-Gly-Asp (RGD) cell adhesion motif that is believed to underlie its bioactive properties [58]. Purified lunasin and lunasin-like peptides have demonstrated significant anti-inflammatory effects *in vitro*. At concentrations of 10–50 μ M, lunasin suppressed lipopolysaccharide (LPS)-mediated inflammation in RAW 264.7 macrophages by downregulating pro-inflammatory markers such as IL-6, IL-1 β , NO, iNOS, COX-2, PGE-2, and NF- κ B activity, effectively blocking the NF- κ B pathway [59]. Similarly, in THP-1 human macrophages, lunasin (50 μ M) inhibited LPS-induced inflammation by reducing COX-2, iNOS, NO, phosphorylated Akt, NF- κ B p65, PGE-2, and TNF- α levels. The interaction of lunasin with α V β 3 integrin, a marker for atherosclerotic lesions, downregulated Akt-mediated NF- κ B signaling, suggesting its potential in mitigating cardiovascular disease (CVD) risk factors [60].

In vivo studies further support the protective role of lunasin. It significantly reduced oxidative stress-induced vascular endothelial cell damage and attenuated atherosclerotic plaque formation in apolipoprotein E-deficient (ApoE^{-/-}) mice fed a high-fat diet. Lunasin upregulated heme oxygenase-1 (HO-1) via the PI3K/Akt/Nrf2/ARE pathway, decreased ROS production, and modulated mitochondrial activity by reducing cytochrome c release, caspase-9 and caspase-3 activation, and Bax expression while increasing Bcl-2 levels to prevent endothelial apoptosis [61]. Additionally, lunasin mitigated oxidized LDL (ox-LDL)-induced inflammation in human umbilical vein endothelial cells (HUVECs) by suppressing VCAM-1 and E-selectin overexpression. It also upregulated Kruppel-like factor 2 (KLF2), known for its anti-inflammatory and anti-atherothrombosis properties, through the MEK5/ERK5 pathway [32].

Lunasin has also shown potential in lipid regulation. It reduced LDL levels by directly suppressing HMG-CoA reductase expression and enhancing the activity of LDL receptors (LDLR), thereby improving plasma LDL clearance [62]. Moreover, lunasin increased the levels of LDLR and facilitated hepatic LDL uptake by inhibiting proprotein convertase subtilisin/kexin type 9 (PCSK9) expression. This inhibition occurred via suppression of hepatocyte nuclear factor-1 α (HNF-1 α) in both HepG2 cells and ApoE^{-/-} mice [63]. Co-administration of lunasin (5 μ M) with simvastatin (1 μ M) in HepG2 cells for 24 hours reversed statin-induced PCSK9 upregulation, enhancing LDL uptake. In ApoE^{-/-} mice, combined therapy with simvastatin and lunasin over 4 weeks reduced hepatic PCSK9 levels, increased LDLR expression, and significantly lowered plasma TC and LDL-C levels [64].

However, a randomized controlled trial (RCT) involving individuals with at least two cardiometabolic risk factors found no significant changes in TC, LDL, TG, serum glucose (SG), or body mass index (BMI) after 8 weeks of lunasin-enriched soy extract (335 mg/day) [65]. Despite this, the preclinical evidence supports the therapeutic potential of lunasin. Further exploration into lunasin as an adjuvant therapy for CVD is warranted. Studies with larger sample sizes, higher doses, or focus on specific subgroups, such as those with more severe hypercholesterolemia, may provide additional clinical support for its use.

3.10. Chia Seeds

Chia seeds (*Salvia hispanica* L.) are native to Central and South America and have a rich history of use by the Aztecs and Mayans. These seeds are abundant in omega-3 fatty acids (**Fig. 3**), fibre, protein, and antioxidants, contributing to their nutritional value [66]. Evidence indicates that chia seeds support heart health by reducing low-density lipoprotein (LDL) cholesterol and triglycerides (TG), while simultaneously increasing high-density lipoprotein (HDL) cholesterol. This effect is primarily attributed to their alpha-linolenic acid (ALA) content [67]. The high fibre content of chia seeds aids in maintaining blood pressure and improving arterial health [68]. Moreover, chia seeds have been shown to reduce inflammation, enhance glucose regulation, and combat oxidative stress [69].

A 12-week study involving type 2 diabetic patients who consumed thirty-seven grams of chia seeds daily reported a reduction in systolic blood pressure of over six mmHg and a significant decrease in high-sensitivity C-reactive protein levels, suggesting anti-inflammatory effects [68]. Various animal studies have provided additional insights into the potential cardiovascular benefits of chia seeds. Recent study using a rat model of high-fat diet-induced obesity found that chia seed supplementation improved cardiac antioxidant defences, reduced left ventricle collagen deposition, and alleviated dyslipidaemia [69]. Chia seed extract has been noted to induce vasodilation via a nitric oxide (NO)-cGMP-related mechanism [70], further supporting cardiovascular health. While promising, further research is needed to confirm the long-term effects and optimal dosing of chia seeds.

4. Animal-derived food hydrocolloids

4.1. Gelatine

Gelatine (**Fig. 3**) is a protein hydrocolloid derived from collagen, primarily sourced from pigs and cows, although fish gelatine is gaining popularity [2]. Gelatine and its peptides exhibit antioxidant properties by neutralizing free radicals and chelating metal ions [2]. This activity protects blood vessels from oxidative damage and enhances antioxidant enzyme activity [71].

Specifically, gelatine derived from carp (*Cyprinus carpio*) skin has been shown to increase antioxidant activity in rat models [71].

Similar antihypertensive effects have been observed with peptides from other fish gelatines, which also possess anti-inflammatory and anti-atherosclerotic properties [72]. Peptides derived from skate gelatine have been reported to reduce inflammation and the formation of atherosclerotic plaques [72]. Additionally, collagen peptides extracted from salmon skin have demonstrated the ability to diminish inflammation and plaque development in mouse models [73]. Gelatine hydrolysates from camel skin showed powerful inhibition of both pancreatic lipase and cholesterol esterase, resulting in an anti-hypercholesterolaemic effect [74]. These preliminary *in vitro* findings suggest it is worthwhile to explore whether these peptides show similar anti-hypercholesterolaemic effects in animal models [74].

More importantly, understanding whether these peptides can prevent the development of atherosclerosis is crucial for assessing their potential therapeutic applications. Further research in this area may provide valuable insights into the cardioprotective benefits of gelatine-derived peptides and their role in managing cholesterol levels and cardiovascular health.

4.2 Egg-derived proteins

Eggs are a highly nutritious food source containing various proteins known for their potential to support heart health [75]. Egg whites predominantly contain proteins such as ovalbumin (**Fig. 3**), ovotransferrin, and ovomucoid, while yolks are rich in low-density lipoprotein (LDL), high-density lipoprotein (HDL), and other vital components [75]. Preclinical studies indicate that egg-derived peptides can improve blood pressure and arterial function through multiple mechanisms. The ovalbumin derivative ovokinin induces vasodilation by activating the bradykinin B2 receptor [76]. Ovotransferrin peptides are known to inhibit angiotensin-converting enzyme (ACE), contributing to their antihypertensive effects [77].

Egg-derived peptides also provide protective effects against atherosclerosis by reducing inflammation and preventing vascular damage [78]. This treatment prevents apoptosis through the NOX1 pathway, which plays a key role in oxidative stress. Such action helps inhibit the

upregulation of inflammatory cascades, including the NF- κ B pathway, while regulating the expression of caspase-3 [78]. Studies show that egg white proteins can lower harmful substances in the bloodstream while improving blood vessel function. Notably, ovotransferrin peptides specifically reduce inflammation and oxidative stress in human vein endothelial cells [77]. Further research is needed to explore the cardiovascular benefits of egg yolk.

4.3. Whey protein

Whey protein, derived from milk, consists of several components including α -lactalbumin, β -lactoglobulin (**Fig. 4**), bovine serum albumin, immunoglobulins, and functional components like lactoferrin and glycomacropeptide [79]. It is rich in branched-chain amino acids, which play important roles in regulating metabolism, blood glucose, and neural function [79]. A randomized controlled trial (RCT) demonstrated that whey protein supplementation reduced systolic and diastolic blood pressure by approximately 3-4% over a 12-week period and decreased arterial stiffness by 14% [80]. However, evidence regarding its antihypertensive effects remains mixed, with some studies indicating significant reductions in blood pressure [80, 81].

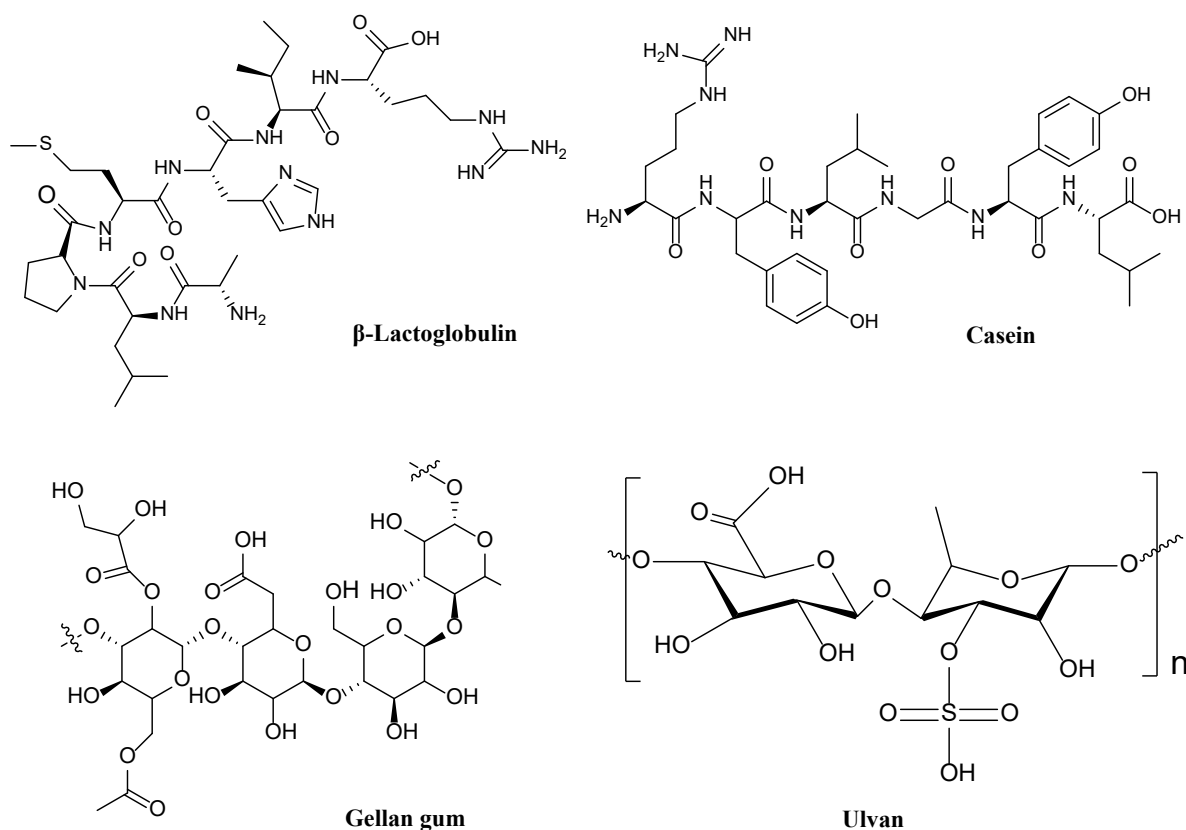


Fig. 4. Structure of beta-lactoglobulin; Structure of casein as bovin milk protein; Structure of gellan gum as high-molecular-weight microbial exopolysaccharides; and Structure of sulphated polysaccharide ulvan.

Whey protein hydrolysates and derivatives, such as lactokinins, contribute to antihypertensive effects by inhibiting angiotensin-converting enzyme (ACE) and decreasing endothelin-1 release from endothelial cells [82]. Moreover, whey protein has been shown to downregulate pro-inflammatory gene expression and reduce the expression of adhesion molecules in endothelial cells, thereby decreasing systemic inflammation [79]. In terms of lipid management, whey protein has demonstrated modest anti-hypercholesterolemic effects [56]. In studies involving ApoE knockout mice, whey protein reduced circulating cholesterol levels by upregulating cholesterol transporters and decreasing serum cytokine levels, resulting in fewer aortic atherosclerotic lesions [56]. These comprehensive cardiovascular benefits emphasize the importance of whey protein as a functional food component. However, further investigations are essential to optimize its use and fully establish its therapeutic potential.

4.4. Casein

Casein is the predominant protein in milk (**Fig. 4**), accounting for approximately 80% of bovine milk proteins. This milk protein is notable for its unique structure, which allows it to form a gel or curd in the stomach, leading to slower digestion and prolonged absorption of amino acids [83]. Upon hydrolysis, casein can yield bioactive peptides like isoleucine-proline-proline (IPP) and valine-proline-proline, which have been linked to various health benefits, including cardiovascular health [84]. Preclinical studies suggest that casein may help manage high blood pressure by inhibiting ACE and increasing nitric oxide (NO) production, contributing to lower blood pressure [85]. This dual mechanism of action, blocking the ACE pathway while simultaneously enhancing nitric oxide availability, can promote vascular relaxation and improve endothelial function, making casein a potential dietary intervention for hypertension.

Clinical trials have reported modest reductions in blood pressure associated with casein consumption, with systolic pressure decreasing by approximately 3 to 7 mmHg and diastolic pressure by 1 to 3 mmHg [85]. The antihypertensive effects of casein can vary based on factors such as dosage, duration of intake, and individual metabolic responses. However, definitive studies in human populations are required to validate these findings and clarify the important role of casein in cardiovascular health.

5. Algal and microbial-derived food hydrocolloids

5.1 Microbial exopolysaccharides and gums

Microbial exopolysaccharides and gums are high-molecular-weight polysaccharides produced by various microorganisms, sharing similarities with plant-derived gums [3]. These compounds have gained recognition for their versatility and functionality in food products, packaging, and coatings. Most common examples of microbial exopolysaccharides include xanthan gum, gellan gum (**Fig. 4**), dextran, and curdlan [3]. Due to their unique structural properties and biological activities, there is significant interest in synthesizing novel

exopolysaccharides that exhibit enhanced bioactivity and specific functional attributes, particularly in optimizing their antioxidant potential and health benefits.

Recent studies have begun to explore the cardiovascular effects of microbial exopolysaccharides. For instance, an exopolysaccharide derived from *Lactobacillus casei* LC2W was found to reduce systolic blood pressure in hypertensive rat models, illustrating its potential as a therapeutic agent for hypertension management [86]. Furthermore, kefiran, sourced from *Lactobacillus kefiranofaciens*, has demonstrated notable antihypertensive effects by inhibiting ACE, a key regulator of blood pressure [87]. Kefir, which naturally contains kefiran, has further been shown to provide protection against heart damage and improve blood vessel function in rat models, suggesting its therapeutic potential for cardiovascular health [88].

Further supporting the cardiovascular benefits of microbial exopolysaccharides, an exopolysaccharide derived from *Lachnum* YM130 exhibited protective effects by reducing heart damage in diabetic mice, indicating its potential in managing diabetes-related cardiovascular complications [89]. Similarly, an exopolysaccharide from *Lactiplantibacillus paraplantarum* NCCP 962 showed the ability to lower cholesterol levels *in vitro*, highlighting its role in lipid management and potential relevance in atherosclerosis prevention [90].

These compounds not only impact blood pressure regulation but also contribute to overall cardiovascular health through their antioxidant and anti-inflammatory properties, making them promising candidates for functional foods and supplements. As the body of evidence supporting the cardiovascular benefits of microbial exopolysaccharides continues to grow, understanding their mechanisms of action can illuminate their therapeutic potential.

5.2. Ulvan

Ulvan is a bioactive sulphated polysaccharide (**Fig. 4**) derived from green macroalgae of the genus *Ulva* [91]. This polysaccharide is particularly noteworthy due to its diverse structural variations and bioactivity, which have drawn increasing attention for potential health benefits. Multiple species of *Ulva*, such as *Ulva intestinalis*, *Ulva lactuca*, and *Ulva australis* (formerly

Ulva pertusa) (Chlorophyta), have been studied for their ulvan content, demonstrating remarkable antioxidant capabilities [91].

Research shows that ulvan effectively scavenges free radicals, including DPPH, superoxide, and hydroxyl radicals, which are major contributors to oxidative stress [92]. Furthermore, ulvan has the ability to chelate metal ions, which can further mitigate oxidative damage by preventing metal-catalysed free radical generation. These antioxidant properties make ulvan a potent candidate for protecting against cellular damage associated with various diseases, including cardiovascular conditions [92]. In an animal model of hyperlipidaemia, ulvan derived from *Ulva australis* was shown to increase levels of antioxidant enzymes while simultaneously decreasing malondialdehyde concentrations, a marker of oxidative stress [93]. This dual effect highlights the potential of ulvan to enhance antioxidant defences while also ameliorating the harmful effects of lipid-induced oxidative stress, which is often a precursor to cardiovascular diseases.

The findings regarding ulvan suggest that polysaccharides from different *Ulva* species may serve as promising cardioprotective agents in food products. However, before ulvan can be recommended as a dietary supplement for cardiovascular disease prevention, comprehensive clinical studies, particularly randomized controlled trials, are necessary to establish its bioactivity and efficacy within the cardiovascular system [91]. Further investigations would offer valuable insights into optimal dosing regimens and potential interactions with existing treatments or dietary patterns.

5.3. *Fucoidan*

Fucoidan is a sulfated polysaccharide (**Fig. 5**) derived primarily from brown algae, as well as certain animal species. Its complex structure and bioactive properties have garnered considerable attention in research, particularly for its potential role in promoting cardiovascular health. Recent studies have demonstrated that fucoidan exhibits antihypertensive effects, significantly decreasing diastolic blood pressure in overweight and obese adults [94]. This makes fucoidan a promising natural compound for managing hypertension effectively. Mechanistically, fucoidan has been shown to induce vasorelaxation in the rat thoracic aorta through a series of cellular signaling events. It achieves this by phosphorylating endothelial nitric oxide synthase

(eNOS) and Akt, which leads to increased production of nitric oxide (NO) and cyclic guanosine monophosphate (cGMP) [95]. Both NO and cGMP are crucial mediators of vascular relaxation, thereby contributing to lower blood pressure. Additionally, fucoidan may lower blood pressure through the inhibition of angiotensin-converting enzyme (ACE), a key enzyme involved in the regulation of blood pressure [9].

Studies have also highlighted the antioxidant potential of fucoidan extracted from various species of brown algae [96-98]. Fucoidan has been shown to significantly decrease cellular apoptosis in Vero kidney epithelial cells and zebrafish exposed to hydrogen peroxide. This protective effect is attributed to its reactive oxygen species (ROS) scavenging activity and its ability to upregulate the nuclear factor erythroid 2-related factor 2 (Nrf2) pathway. The upregulation of Nrf2 results in increased levels of various antioxidant enzymes, including catalase and superoxide dismutase (SOD), which play a crucial role in mitigating oxidative stress [99].

In addition to its roles in blood pressure regulation and antioxidant defense, fucoidan has demonstrated lipid-lowering effects. Research shows that fucoidan enhances fatty acid beta-oxidation while downregulating cholesterol-related proteins, including HMG-CoA reductase and sterol regulatory element-binding protein-2 (SREBP-2) [8]. These actions contribute to improved lipid profiles and decreased risk factors associated with atherosclerosis. Notably, in studies involving ApoE-deficient mice fed a high-fat diet, fucoidan was found to reduce the thickness of atherosclerotic plaques, levels of lipid peroxidation, and foam cell accumulation [100]. These protective effects are linked to enhanced foam cell autophagy and inhibition of the NLRP3 inflammasome, which is a key player in inflammatory responses associated with cardiovascular diseases [101].

Fucoidan has also been shown to protect against subacute diazinon-induced oxidative damage in cardiac, hepatic, and renal tissues, further underscoring its potential as a therapeutic agent for mitigating environmental toxin-induced cardiovascular damage [102]. Overall, the array of cardiovascular benefits associated with fucoidan, ranging from antihypertensive effects and antioxidant activity to lipid management, highlights its potential as a functional food ingredient and therapeutic agent [9, 101]. However, further investigation is necessary to determine whether

isolating fucoidan from specific algae species yields greater health benefits and to effectively translate promising preclinical findings into clinically applicable interventions.

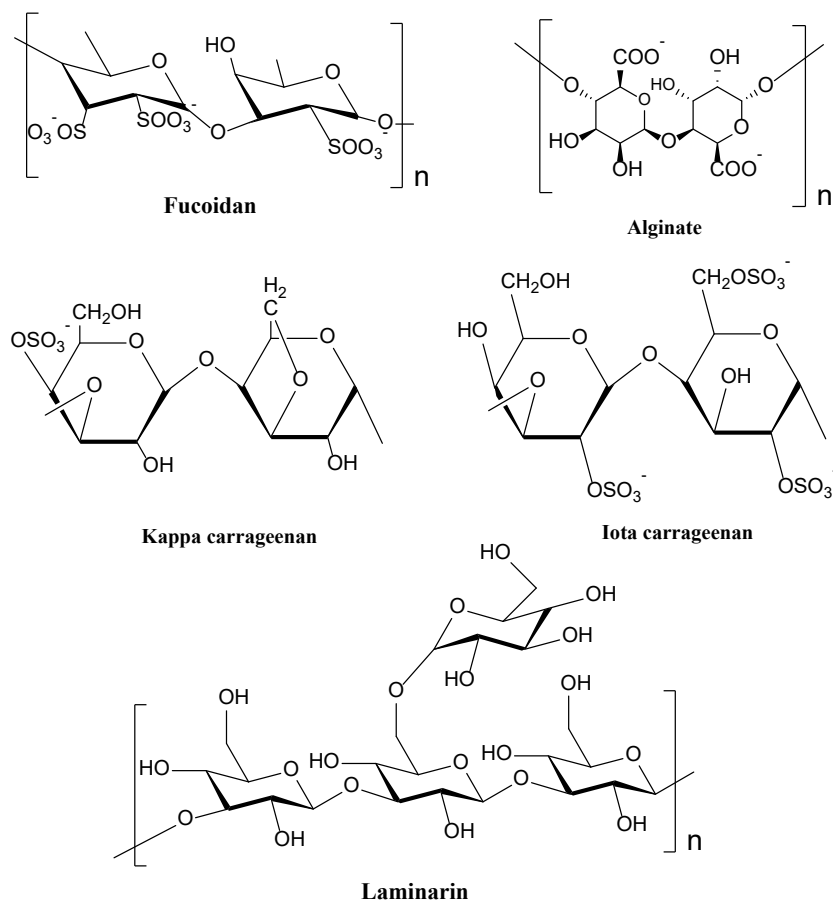


Fig. 5. Structure of focoidan a sulphated polysaccharide; Structure of alginate; Structure of carrageenans and laminarin

5.4. Alginate

Alginate is a naturally occurring polymer derived primarily from brown seaweed (**Fig. 5**), as well as certain bacterial species. Its unique gel-forming properties, low cost, and non-toxic nature have led to its widespread use in various medical, food, and cosmetic applications [103]. Preclinical studies have shown that alginate, particularly in the forms of sodium and potassium alginate oligosaccharides, may reduce high blood pressure in various rat models of hypertension.

These models include spontaneously hypertensive rats (SHRs), rats with hypertension induced by DOCA salt, and those with kidney-related hypertension [6, 104, 105]. The exact mechanisms by which alginate lowers blood pressure are not fully understood. Initially, it was believed that alginate increased sodium excretion, thereby reducing blood volume and pressure [6].

However, subsequent studies have questioned this hypothesis. For example, alginate treatment did not affect sodium excretion in salt-sensitive rats, suggesting a direct interaction with blood vessels [105]. Another study analyzing different seaweeds and their alginate content found no correlation between alginate levels and sodium excretion [104]. Further research indicated that potassium alginate oligosaccharides might alter gut microbiota, leading to the production of bioactive substances that help lower blood pressure [106]. Thus, alginate oligosaccharides appear to lower blood pressure both directly by affecting blood vessels and indirectly by modifying gut microbiota.

In addition to its antihypertensive effects, alginate may also reduce inflammation and promote heart health. Alginate oligosaccharides have demonstrated antioxidant activity and the ability to neutralize harmful hydroxyl free radicals *in vitro* [97, 107]. Later research showed that alginate oligosaccharides protect human umbilical vein endothelial cells (HUVECs) exposed to hydrogen peroxide via the integrin- α /FAK/PI3K signaling pathway. This protection involves downregulating pro-apoptotic proteins such as caspase-3 and Bax, and upregulating Bcl-2 [5]. Alginate has been shown to reduce the expression of intracellular adhesion molecule-1 (ICAM-1) and the production of nitric oxide and hydrogen peroxide in HUVECs challenged with tumor necrosis factor- α (TNF- α) [108].

Studies involving murine models of myocardial ischemia or reperfusion injury have demonstrated that alginate oligosaccharides can prevent cell death by addressing endoplasmic reticulum stress. They significantly reduce oxidative stress in cardiac tissue and improve cardiac function after episodes of restricted blood flow and subsequent restoration [63]. In animal studies, particularly those involving mice on a high-fat diet, alginate polysaccharides were found to lower plasma levels of triglycerides and low-density lipoprotein (LDL) while also decreasing markers of inflammation [50]. The hypolipidemic effect is likely due to alterations in gut microbiota, which

produce short-chain fatty acids (SCFAs) that influence metabolism. Additionally, alginate enhances the uptake of LDL cholesterol into liver cells (hepatocytes) by activating sterol-response element binding protein 2 (SREBP-2) and inhibiting proprotein convertase subtilisin/kexin type 9 (PSK9), a protein involved in cholesterol regulation [50, 109]. A pilot study further supported these findings by showing improved cholesterol uptake in overweight male patients, highlighting alginate's potential as a supplement for managing cholesterol levels and supporting heart health [110].

Furthermore, alginate's role in cardiovascular health extends to its potential use in drug delivery systems. Alginate's gel-forming ability makes it an excellent candidate for encapsulating bioactive compounds, ensuring their controlled release and targeted delivery. This property is particularly beneficial for delivering cardiovascular drugs, as it can enhance their efficacy and reduce side effects. Alginate-based hydrogels have been explored for their ability to deliver growth factors and stem cells to damaged cardiac tissue, promoting regeneration and repair [111]. Overall, these studies collectively highlight the various beneficial effects of alginate, including its anti-inflammatory properties, ability to reduce oxidative stress, and role in improving lipid metabolism. These findings mark alginate as a promising compound for cardiovascular health interventions. Future research should focus on clinical trials to validate these preclinical findings and explore the full therapeutic potential of alginate in human subjects.

The versatility of alginate makes it an attractive ingredient in the food industry for thickening, stabilizing, and improving the texture of products, while in the medical field, it is utilized in wound dressings, drug delivery systems, and tissue engineering. Research has indicated that alginate oligosaccharides, particularly sodium and potassium forms, exhibit promising antihypertensive effects. Preclinical studies have demonstrated reductions in high blood pressure across various rat models of hypertension [105]. Although the precise mechanism by which alginate lowers blood pressure is still under investigation, early findings suggest that alginate may facilitate increased sodium excretion. This increased excretion can lead to a decrease in blood volume, thereby lowering blood pressure. In addition to its effects on blood pressure, alginate polysaccharides have also been found to positively influence lipid profiles. Animal studies show that alginate can lower plasma levels of triglycerides and low-density lipoprotein (LDL)

cholesterol while also decreasing markers of inflammation. This hypolipidemic effect is thought to be connected to alterations in gut microbiota, leading to the production of short-chain fatty acids (SCFAs). These SCFAs play a key role in modulating metabolic processes and influencing cardiovascular health by improving lipid metabolism [50].

Further elucidating its lipid-regulating capabilities, alginate enhances the uptake of LDL cholesterol into liver cells (hepatocytes). This is accomplished by activating sterol regulatory element-binding protein 2 (SREBP-2) and inhibiting proprotein convertase subtilisin/kexin type 9 (PCSK9), a crucial protein involved in cholesterol homeostasis [50, 109]. By improving cholesterol uptake in this manner, alginate displays functional properties that could mitigate cardiovascular risk factors. In a pilot study involving overweight male patients, researchers observed improved cholesterol uptake following alginate supplementation. This finding supports the potential of alginate as a beneficial dietary supplement for managing cholesterol levels and promoting heart health [110]. Overall, alginate exhibits anti-inflammatory properties, reduces oxidative stress, and enhances lipid metabolism, indicating its promise for cardiovascular health interventions.

5.5. Carrageenan

Carrageenans (CG) are natural substances extracted from various species of marine red algae, with *Chondrus crispus* being one of the most notable sources (**Fig. 5**). This type of algae is rich in essential nutrients, including vitamins, minerals, omega-3 fatty acids, and polyunsaturated fatty acids, making carrageenan a popular ingredient in food and health products [112]. Carrageenans can be classified into three main types based on their distinct chemical structures: Kappa (κ), Lambda (λ), and Iota (ι). This classification is determined by the variations in the number and arrangement of sulphate groups and sugar units, specifically called carrabiose [113]. The different types of carrageenan exhibit unique functionalities and applications in food formulations, thickening agents, and stabilizers.

Research has shown that κ -CG (*Kappa carrageenan*) can effectively improve lipid profiles by increasing high-density lipoprotein cholesterol (HDL-C) levels while simultaneously reducing total cholesterol (TC), triglycerides (TG), and low-density lipoprotein cholesterol (LDL-C) levels

[114]. This lipid-modulating effect is particularly relevant, as elevated levels of TC and LDL-C are well-documented risk factors for cardiovascular disease. In individuals with ischemic heart disease (IHD), carrageenan supplementation has led to remarkable reductions in total cholesterol by 16.5% and LDL cholesterol by 33.5%, along with decreases in inflammatory markers associated with cardiovascular risk [112].

Moreover, research involving *Sarconema filiforme*, a species rich in carrageenan, demonstrated its ability to decrease body weight, abdominal fat, liver fat, and plasma cholesterol levels in rats consuming a high-carbohydrate and high-fat diet [115]. These studies further showed that carrageenan effectively lowered blood pressure and improved liver function in obese rats, suggesting that carrageenan may act as a prebiotic, providing anti-inflammatory effects that contribute to cardiovascular health [115]. The mechanisms by which carrageenan lowers lipid levels are multifaceted. One primary action is increasing the viscosity and bulk of intestinal contents, resulting in slowed digestion and absorption. This delay in the digestive process helps to decrease hepatic lipid production and cholesterol absorption [116].

In addition, carrageenan binds to bile salts, preventing them from being reabsorbed back into the bloodstream. When the levels of bile salts decrease, the liver is stimulated to produce more bile salts, using cholesterol as a building block. This increased demand for cholesterol encourages the mobilization of LDL cholesterol and TG particles, leading to changes in overall cholesterol levels in the body [117]. The prebiotic effects of carrageenan contribute to its cardiovascular benefits. By promoting the growth of beneficial gut bacteria, carrageenan helps produce short-chain fatty acids (SCFAs) such as butyrate, propionate, and acetate. These SCFAs have been shown to improve lipid metabolism, reduce inflammation, and enhance gut barrier function, all of which are important for cardiovascular health [115]. The anti-inflammatory properties of carrageenan are significant. Chronic inflammation is a key factor in the development of atherosclerosis and other cardiovascular diseases. By reducing markers of inflammation such as CRP, fibrinogen, and leukocyte counts, carrageenan helps mitigate the inflammatory processes that contribute to cardiovascular disease progression [7, 114].

Research indicates that carrageenan is not only beneficial for improving the nutritional value of food but also plays an important role in regulating cholesterol levels and enhancing overall heart health. Its various mechanisms of action, which include regulating lipids and providing anti-inflammatory benefits, make carrageenan a valuable ingredient in dietary strategies aimed at maintaining cardiovascular health. By incorporating carrageenan into diets, individuals may better manage their cholesterol levels and improve their cardiovascular health. Overall, carrageenan not only enhances the nutritional value of foods but also plays a significant role in regulating cholesterol levels and improving cardiovascular health. Thus, it is crucial to investigate the long-term effects and optimal dosages of carrageenan supplementation in human populations to fully understand its cardiovascular benefits.

5.6. Laminarin

Laminarin is a polysaccharide (β -(1,3)-*D*-glucan) derived from various species of brown seaweed (**Fig. 5**), particularly *Laminaria hyperborea*. This bioactive carbohydrate possesses numerous health benefits, making it a focus of research in nutrition and supplementation. Laminarin has been shown to contribute to immune regulation, blood sugar control, blood pressure reduction, and exhibit antioxidant actions [118, 119]. Its multifaceted effects highlight its potential as a functional food ingredient.

Research shows that laminarin can reduce the risk of atherosclerosis and lower lipid levels, particularly in animal models that are fed high-fat diets [118]. It plays a pivotal role in improving lipid profiles by decreasing levels of low-density lipoprotein (LDL), total cholesterol (TC), and triglycerides (TG), while simultaneously increasing high-density lipoprotein (HDL) levels. Notably, laminarin promotes faecal cholesterol excretion by reducing intestinal cholesterol absorption, which is mediated by the downregulation of the Niemann-Pick C1-like 1 (NPC1L1) transporter, a key player in dietary cholesterol uptake [119]. This mechanism underscores laminarin's potential in managing cholesterol levels and reducing cardiovascular disease risk factors.

In addition, laminarin may enhance lipid profiles through modulating insulin signalling pathways, which in turn reduces the hepatic production of very low-density lipoprotein (vLDL)

[120]. This insulin sensitization effect could contribute to improved lipid metabolism, thereby offering additional cardiovascular protective benefits. In recent studies, it has also been observed that the biological activity of laminarin can be enhanced through chemical modifications, such as the addition of phosphate or sulphate groups [121]. For example, sulphated laminarin has been shown to restore endothelium-dependent relaxation in the thoracic aorta and alleviate detrimental changes in endothelial cells, particularly in lysosomal and mitochondrial structures in models of vascular damage [121]. These modifications may amplify the cardioprotective properties of laminarin and further its applicability in therapeutic settings. Overall, the multifaceted actions of laminarin suggest that it could be a valuable dietary component with potential health benefits for cardiovascular health. Further research is essential to thoroughly understand its mechanisms and to evaluate its efficacy in human clinical trials.

6. Future prospect

The future of research on food hydrocolloids holds immense potential for advancing cardiovascular health. Several key areas require further exploration to fully harness their therapeutic benefits. The study of alginate should focus on understanding its molecular mechanisms, such as its interaction with blood vessels and gut microbiota, to optimize its antihypertensive and lipid-lowering effects. Large-scale clinical trials are needed to validate its efficacy and safety in human populations. These studies should focus on diverse populations to account for variations in genetic, dietary, and lifestyle factors [3].

Astragalus polysaccharides require well-designed, large-scale human trials to validate their efficacy, safety, and optimal dosages. Further investigation into their molecular mechanisms, such as their ability to inhibit the TGF- β 1/ILK pathway or activate the AMPK pathway, could lead to targeted therapies for conditions like hypertension and cardiomyopathy [40, 43]. The exploration of their interactions with gut microbiota to produce bioactive metabolites, such as short-chain fatty acids (SCFAs), could provide insights into their systemic effects on cardiovascular health [12].

The most effective types and sources of carrageenan need to be identified to maximize its health benefits. Clinical trials are essential to confirm its lipid-lowering and anti-inflammatory properties in human populations. Large-scale clinical trials for fucoidan are critical to confirm its antihypertensive, antioxidant, and lipid-lowering properties. The mechanisms, such as its role in

modulating the Nrf2 pathway or inducing vasorelaxation through NO and cGMP production, need to be understood to enable innovative therapies [95,100]. Potential synergistic effects with other dietary components, such as probiotics or antioxidants, should be investigated to enhance its therapeutic efficacy [122]. Identifying the most effective sources of fucoidan, such as specific brown algae species, is also essential to maximize its health benefits [123].

Further exploration into the molecular mechanisms and interactions with cardiovascular risk factors for lunasin is necessary. Studies with larger sample sizes, higher doses, or focus on specific subgroups, such as those with more severe hypercholesterolemia, may provide additional clinical support for its use. More research on psyllium is needed to understand its role in the pathogenesis of atherosclerosis, especially concerning vascular inflammation and remodeling. Both preclinical and clinical studies, particularly randomized controlled trials, are needed to characterize the importance of psyllium on the cardiovascular system.

In addition to these key hydrocolloids, other compounds such as short-chain fatty acids (SCFAs), plant-derived food hydrocolloids, plant-derived gums, plant-derived mucilages, pectin, modified citrus pectin, inulin, naringenin, chia seeds, gelatine, whey protein, casein, microbial exopolysaccharides and gums, ulvan, and laminarin also require further research. The development of personalized dietary interventions based on individual genetic, metabolic, and gut microbiota profiles could optimize the cardiovascular benefits of these hydrocolloids [116]. Moreover, the assessment of the environmental impact of large-scale production of these hydrocolloids and the assurance of their safety in long-term use will be critical for their integration into mainstream dietary practices [102]. By addressing these research priorities, these hydrocolloids could become cornerstone components of dietary strategies aimed at preventing and managing cardiovascular diseases. Their potential to improve heart health on a global scale emphasizes the importance of continued investment in this promising field.

7. Discussion

The exploration of food hydrocolloids has unveiled a fascinating array of bioactive compounds with significant implications for cardiovascular health. These natural substances, derived from plants, algae, and microbes, offer a promising avenue for enhancing heart health

through various mechanisms. Alginate, sourced from brown seaweed, stands out for its ability to reduce high blood pressure and improve lipid metabolism. Preclinical studies reviewed have shown that alginate, particularly in the forms of sodium and potassium alginate oligosaccharides, may reduce high blood pressure in various rat models of hypertension [6, 104, 105, 124]. Its interaction with blood vessels and gut microbiota suggests a multifaceted approach to cardiovascular health, making it a valuable addition to dietary strategies [106].

Astragalus polysaccharides, extracted from the roots of *Astragalus membranaceus*, have demonstrated remarkable cardioprotective effects. By reducing oxidative stress, mitigating cardiac injury, and improving endothelial function, these polysaccharides offer a potent means of enhancing cardiovascular health [40-43]. Their antioxidant, anti-inflammatory, and immunomodulatory activities further underscore their therapeutic potential [44, 45].

Carrageenan, obtained from marine red algae, has shown efficacy in improving lipid profiles and reducing inflammation. Its ability to regulate cholesterol levels and enhance overall heart health positions it as a promising candidate for cardiovascular interventions [7, 112]. The diverse chemical structures of carrageenan, including Kappa, Lambda, and Iota types, contribute to its varied health benefits [113].

Fucoidan, a sulfated polysaccharide from brown algae, has exhibited antihypertensive, antioxidant, and lipid-lowering properties. Through mechanisms such as inducing vasorelaxation and modulating the Nrf2 pathway, fucoidan offers a comprehensive approach to managing hypertension and atherosclerosis [95, 99]. Its ability to bind bile salts and promote cholesterol metabolism further enhances its cardiovascular benefits [117].

Lunasin, a bioactive peptide from soybean, has demonstrated significant anti-inflammatory effects and potential in lipid regulation. By reducing oxidative stress-induced vascular endothelial cell damage and attenuating atherosclerotic plaque formation, lunasin emerges as a promising therapeutic agent for cardiovascular health [61]. Its unique cell adhesion motif and interaction with integrins highlight its role in mitigating cardiovascular disease risk factors [60].

Psyllium, derived from the husk of *Plantago ovata* seeds, has shown beneficial effects on blood pressure and lipid profiles. Its antioxidant activities and ability to reduce myocardial injury support its role as a cardioprotective agent [10, 11, 35, 36]. The long-standing use of psyllium in traditional medicine underscores its potential for enhancing cardiovascular health [34].

In addition to these key hydrocolloids, other compounds such as short-chain fatty acids (SCFAs), plant-derived food hydrocolloids, plant-derived gums, plant-derived mucilages, pectin, modified citrus pectin, inulin, naringenin, chia seeds, gelatine, whey protein, casein, microbial exopolysaccharides and gums, ulvan, and laminarin also contribute to cardiovascular health. These compounds offer various mechanisms of action, including blood pressure regulation, lipid profile modulation, and anti-inflammatory effects, highlighting their potential as integral components of dietary strategies aimed at preventing and managing cardiovascular diseases.

The collective findings from this review suggest that food hydrocolloids could play a transformative role in cardiovascular health management. Their diverse mechanisms of action, ranging from blood pressure regulation to lipid profile modulation and anti-inflammatory effects, highlight their potential as integral components of dietary strategies aimed at preventing and managing cardiovascular diseases. As research progresses, these hydrocolloids may offer innovative solutions for improving heart health and reducing the global burden of cardiovascular diseases. The integration of these natural compounds into everyday diets could pave the way for more holistic and effective approaches to cardiovascular wellness.

8. Conclusion

This review highlights the significant role of food hydrocolloids and their bioactive metabolites in regulating cardiovascular function. Alginate, astragalus polysaccharides, carrageenan, fucoidan, lunasin, and psyllium each contribute unique mechanisms and benefits, offering a multifaceted approach to heart health. Alginate, derived from brown seaweed, has shown potential in reducing high blood pressure, mitigating inflammation, and improving lipid metabolism. Astragalus polysaccharides, extracted from the roots of *Astragalus membranaceus*, have demonstrated potent cardioprotective effects, including reducing oxidative stress, mitigating

cardiac injury, and improving endothelial function. Carrageenan, obtained from marine red algae, has been shown to improve lipid profiles and exhibit anti-inflammatory properties. Fucoidan, a sulfated polysaccharide from brown algae, has exhibited antihypertensive, antioxidant, and lipid-lowering properties. Lunasin, a bioactive peptide from soybean, has demonstrated significant anti-inflammatory effects and potential in lipid regulation. Psyllium, derived from the husk of *Plantago ovata* seeds, has shown beneficial effects on blood pressure and lipid profiles. In addition to these key hydrocolloids, other compounds such as short-chain fatty acids (SCFAs), plant-derived food hydrocolloids, plant-derived gums, plant-derived mucilages, pectin, modified citrus pectin, inulin, naringenin, chia seeds, gelatine, whey protein, casein, microbial exopolysaccharides and gums, ulvan, and laminarin also contribute to cardiovascular health.

Although preliminary research highlights their therapeutic benefits, most of the current evidence comes from preclinical studies and small-scale human trials. This necessitates caution in drawing definitive conclusions. Further research is essential to confirm their efficacy, establish appropriate dosages, and evaluate long-term safety. As the field advances, a deeper understanding of the interactions between diet, gut health, and cardiovascular function will lead to innovative dietary interventions. By addressing current research gaps and advancing clinical validation, these hydrocolloids could play a transformative role in reducing the global burden of cardiovascular diseases. Their potential to improve heart health on a global scale emphasizes the importance of continued investment in this promising field.

CRedit authorship contribution statement

Ajay K Pandey: Formal analysis, investigation and writing original draft preparation, review and editing; **Emmanuella Ezewudo:** investigation and writing original draft preparation, review and editing; **Nazia Hoque:** writing original draft preparation, review and editing; **Anjali T Pandey:** investigation and writing original draft preparation, review and editing; **Sreelakshmi Menon:** writing original draft preparation, review and editing; **Nimi Simon:** writing original draft preparation, review and editing; **Baharehsadat Rasouli:** writing original draft preparation, review and editing; **Emran Habibi:** Software drawing structures, writing review and editing; **Satyajit D. Sarker:** Writing review and editing; **Lutfun Nahar:** Conceptualization, methodology, validation and writing review and editing; **Raquibul Hasan:** Conceptualization, methodology, validation and writing review and editing.

Declaration of competing interest

The authors declare no competing interests.

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