Sustainable Food Technology

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: G. Zhang, H. Mak, Z. Zhang, T. Zhang, Y. Wang, R. Zhang, H. Liu, S. Zhou and B. Wu, *Sustainable Food Technol.*, 2025, DOI: 10.1039/D6FB00080K.

View Article Online
DOI: 10.1039/D6FB00080K

Sustainability spotlight

Chenpi, a medicine and food homology ingredient in China, contains abundant bioactive compounds with various health-promoting benefits. According to the EAT-Lacent Commission, a healthy and the sustainable diet is key to the transition to a sustainable food system and to achieving sustainable development agenda. In this context, the concept of medicine and food homology and the development of Chenpi could offer novel insights and opportunities to ensure global nutrition security by bridging traditional dietary wisdom with the national and global initiatives (e.g. the planetary health diet and the Sustainable Development Goals), thereby promoting the transition towards healthy and sustainable diets and food systems, which aligns well with SDG 2, SDG 3, and SDG 12.

View Article Online
DOI: 10.1039/D6FB00080K

Fully unlocking the potential of Chenpi (*Citri Reticulatae Pericarpium*) as a functional ingredient in food development

Guoqiang Zhang [a;b] *, HioTong Mak [c], Zheng Zhang [b], Ting Zhang [b], Yuanhui Wang [d; e], Run-Yang Zhang [f], Hua-Min Liu [f], Shaobo Zhou [g], Bin Wu [b]

[a] School of Science, Coventry University, Coventry, UK

[b] Institute of Agro-products Storage and Processing, Xinjiang Academy of Agricultural Science, Urumqi 830091, China

[c] Faculty of Health and Life Sciences, Bristol Medical School, University of Bristol, UK

[d] College of Food Science and Engineering, Henan University of Technology, Zhengzhou, 450001, China

[e] Henan Province Wheat-flour Staple Food Engineering Technology Research Centre, Henan University of Technology, Zhengzhou, 450001, China

[f] College of Food Science and Engineering & Institute of Special Oilseed Processing and Technology, Henan University of Technology, Zhengzhou 450001, China

[g] School of Science, Faculty of Engineering and Science, University of Greenwich, Kent, UK

* Corresponding author: Guoqiang Zhang

E-mail address: * ae4214@coventry.ac.uk (Guoqiang Zhang)

View Article Online
DOI: 10.1039/D6FB00080K

Abstract

A shift to a sustainable and healthy diet is key to the establishment of a sustainable food system and the achievement of the sustainable development agenda. To enable this dietary shift, the exploration and development of sustainable, accessible, and affordable ingredients that can be integrated into the daily diet, and the protection and promotion of traditional healthy diets are important actions. In the traditional Chinese diet, Chenpi (*Citri Reticulatae Pericarpium*), is a medicinal and food homology ingredient with extensive health-promoting effects that is widely used for culinary applications and food development. This makes Chenpi a valuable ingredient that contains high potential to contribute to the achievement of widespread sustainable and healthy diet. Therefore, this review provides an overview of the major constituents of Chenpi and current advances into its development and food applications, aiming to maximise its potential in daily diets and contribute to the achievement of sustainable and healthy diets and food systems.

Keywords

Chenpi; Citrus products; Bioactive compounds; Functional ingredient; Medicine and food homology; Sustainable diet

View Article Online
DOI: 10.1039/D6FB00080K

1. Introduction

The rapid increase in global population and food demand, along with the food waste issue in the current food system, exerts significant pressure on the environment and strongly threatens food security and human survival [1,2]. Therefore, the EAT-Lancet Commission proposed a healthy and sustainable reference diet (referred to as the planetary health diet) to promote a global shift in food systems and diets, thereby reducing environmental impact, promoting food system sustainability and human health, and achieving win-win outcomes between humans and the environment [3,4]. To achieve this, a series of actions are required, such as education, food environment interventions and the protection and promotion of healthy traditional diets [4,5]. In this context, the concept of medicine and food homology has received much attention, which emphasises the close connection and mutual transformation between food and medicine [6,7]. In other words, food not only serves food functions to meet human needs, but also contains many pharmacological properties that can promote human health [8]. This dietary concept has encouraged the continued exploration of the potential of all ingredients and their complete utilisation and development in daily diets to meet the demand for natural and healthy foods [9].

Chenpi, also known as *Citri Reticulatae Pericarpium*, originates from the dried or aged peel of *Citrus reticulata* Blanco or its cultivars and has been widely used as both a medicine and food ingredient based on the concept of medicine and food homology in China [10,11]. In addition, in traditional Chinese medicine, Chenpi has many health-promoting benefits, particularly in maintaining gastrointestinal health, such as

View Article Online
DOI: 10.1039/D6FB00080K

relieving indigestion and loss of appetite [12,13]. Besides, many studies have reported and demonstrated the various biological activities of Chenpi, such as antioxidant, anti-inflammatory, and the modulation of gut microbiota [14–17]. This makes Chenpi a valuable ingredient in China and its total market size exceeded 10 billion Chinese yuan in 2021 [18]. However, citrus peel is regarded as a major by-product in citrus fruit processing line, which is scarcely utilised and often considered a waste that is discarded in landfills [19,20]. Importantly, citrus peel contains high potential value and should be considered a valuable ingredient rather than waste [21]. In this regard, utilisation of citrus peel as value ingredients not only reduce food waste generation, but also offer opportunities to produce healthy and sustainable food for human consumption [22]. Nevertheless, re-introducing citrus peel into food supply chain requires the development of appropriate valorisation strategies and the establishment of a new value chain [23,24]. In this regard, the traditional dietary wisdom of Chenpi and its development could present a novel utilisation pathway that transforms citrus peel into healthy, affordable, and sustainable ingredients in the daily diet, thereby reducing citrus waste generation and promoting human health. Therefore, a better understanding of Chenpi and its development and applications can not only further unlock the potential of Chenpi in sustainable and healthy diet, but also promote the sustainable utilisation of citrus resources [25–27].

To this end, this review provides an overview of the major constituents of Chenpi and summarises the recent advances in Chenpi development, particularly in the extraction of bioactive compounds and food applications, aiming to promote a better

View Article Online
DOI: 10.1039/D6FB00080K

understanding of Chenpi and its further development in food products, and to offer new insights for the value innovation of citrus peel to produce a healthier and more sustainable food supply, thereby promoting global human well-being and contributing to healthier and sustainable food systems and diets.

2. Overview of bioactive compounds in Chenpi

Chenpi (*Citri Reticulatae Pericarpium*, Figure 1) is a traditional medicine and food homologous ingredient in China, where 4 varieties are commercially cultivated and consumed, namely *C. reticulata* "Chachi", *C. reticulata* "Dahongpao", *C. reticulata* "Unshiu", and *C. reticulata* "Tangerina" [28,29]. Chenpi contains abundant bioactive constituents such as polysaccharides, alkaloids, carotenoids, terpenoids, and phenolic compounds, which are associated with Chenpi's extensive health benefits, such as antioxidant, anti-inflammatory, anti-hyperglycaemic and anti-hyperlipidaemic activities, as well as the modulation of gut microbiota [16,17,30–33]. Notably, the content of bioactive compounds in Chenpi varies depending on many factors, such as variety, harvesting conditions, drying methods, and storage time (aging) [28,34–37]. Zhu et al. [37] reported that the contents of ascorbic acid and β-carotene decrease with increasing storage (aging) time. In contrast, Chen et al. [36] reported that the total flavonoid content of Chenpi (*Citrus reticulata* 'Chachi') increased during storage (aging), which could be attributed to bacterial biotransformation. During the aging process of Chenpi, the main fungal species, including *Penicillium* and *Aspergillus* actively participate in flavonoid metabolism through their enzymatic activities [38,39]. Tang et al. [40] demonstrated that *Aspergillus tubingensis* converted nobiletin into 3'-

View Article Online
DOI: 10.1039/D6FB00080K

demethylnobiletin during the Chenpi aging processing. In addition, *Aspergillus niger* has been reported to involve the transformation of hesperidin into hesperetin in the aging of Chenpi, thereby enhancing antioxidant capacity [41,42]. On the other hand, a variety of flavonoids exist in the plant cells and are not easy to release to the compact cell wall structures; however, the action of microbial enzymes (e.g. cellulase and β-glucosidase) can disrupt plant cell wall structure and then promote flavonoid released [43,44].

Regarding bioactive compounds in Chenpi, approximately 150 phenolic compounds have been identified in Chenpi, among which flavonoids are relatively abundant [45–48]. In the study by Zhang et al. [47], 95 phenolic compounds were identified in the Chenpi, including 92 flavonoids, 2 coumarins, and 1 phenolic acid. In contrast, Bian et al. [48] identified 65 flavonoids and 51 phenolic acids in Chenpi using ultra-high performance liquid chromatography-quadrupole time-of-flight mass spectrometry analysis (UPLC-Q-TOF/MS). In addition, in the study by Chai et al. [46], the authors identified and quantified 35 phenolic compounds in Chenpi using an ultra-performance liquid chromatography (UHPLC) system coupled with a Q-orbitrap mass spectrometer, and subsequently 10 phenolic compounds were identified as major antioxidant contributors through *in vitro* chemical antioxidant capacity test (ABTS assay), including ferulic acid (0.057 – 0.164 mg/g), cis-4-hydroxycinnamic acid (0.009 – 0.037 mg/g), caffeic acid (0.004 – 0.014 mg/g), protocatechuic acid (0.004 – 0.009 mg/g), hesperidin (0.280 – 0.506 mg/g), orientin (0.008 – 0.096 mg/g), rutin (0.016 – 0.104 mg/g), diosmin (0.030 – 0.227 mg/g), isoorientin (0.004 – 0.030 mg/g), and

View Article Online
DOI: 10.1039/D6FB00080K

chrysoeriol (0 – 0.015 mg/g). In addition, Shi et al. [28] used (UPLC) to identify and quantify 9 phenolic compounds (3 phenolic acids and 5 flavonoids) in Chenpi, including protocatechuic acid (0.043 – 0.075 mg/g), vanillic acid (0.085 – 0.114 mg/g), ferulic acid (0.186 – 0.437 mg/g), narirutin (0.452 – 1.159 mg/g), hesperidin (45.863 – 80.389 mg/g), sinensetin (0.483 – 0.583 mg/g), nobiletin (4.062 – 5.358 mg/g), and tangeretin (2.870 – 3.833 mg/g). In terms of dietary fibre, the dietary fibre content in Chenpi reaches 62.87% (w/w), whereas the contents of insoluble dietary fibre (IDF) and soluble dietary fibre (SDF) are 49.61% (w/w) and 13.02% (w/w), respectively [49]. Furthermore, Wang et al. [49] detected uronic acid (129.48 mg galacturonic acid equivalents/g) in Chenpi's SDF, indicating that complex pectic polysaccharides are present in Chenpi. Notably, pectin has many biological activities and is widely used in the food industry as a gelling agent, emulsifier, and thickener [50,51]. This has driven increasing interest in the extraction of polysaccharides from Chenpi as functional or health-promoting ingredients, which will be introduced in Section 4.

3. Key volatile aroma compounds in Chenpi

Flavour is an important parameter of food quality and consumer acceptance, since it determines the overall palatability of food products and the sensory experience of consumers [52–54]. As demand and interest continue to grow for high sensory quality, healthier, and more sustainable food products, this drives the food industry to seek natural functional flavour ingredients in food innovation, aiming to enhance food nutritional quality and provide more attractive flavours to meet consumer demand [55,56]. In this regard, Chenpi, as a high medicinal and food ingredient, presents a

View Article Online
DOI: 10.1039/D6FB00080K

promising option for food development to enhance food flavour and provide additional health benefits [57]. Therefore, the identification of key volatile compounds in Chenpi could help better understand its overall taste and flavour perception and further facilitate its incorporation into suitable food systems [58,59]. Table 1 presents the identified volatile aroma active compounds in Chenpi that contribute to shaping its overall flavour profile.

It can be seen from Table 1, α-pinene (fresh, woody, piney, and herbal), β-myrcene (spicy and woody), d-limonene (citrus, fruity, and spicy), linalool (aniseed, citrus, floral, pleasant scent, and sweet), dimethyl anthranilate (floral, pepper, spicy, and citrusy), γ-terpinene (pine-like smell, woody, lemon-flavoured, sweet, and floral), and 2-methoxy-4-vinylphenol (pungent and floral) are considered to be important contributors to Chenpi flavour, providing fresh, woody, piney, herbal, citrus, fruity, spicy, floral, and sweet notes. In addition, other high-content compounds, such as α-terpineol (floral and woody), octanal (orange flavour), thymol (herbal and medicine), and β-pinene (woody, pine-like smell, herbal, and pungent) enhance the pine-like, floral, citrus, woody, sweet, and herbal notes in Chenpi flavour. Besides, Li et al. [57] reported that the Chenpi aroma (contributing citrus and herbal notes) can enhance the flavour perception of sweetness and saltiness, which has high application potential as a functional flavour agent in sugar and salt-reduced foods.

Notably, the volatile profile of Chenpi is dependent on many factors, including geographical origin, cultivated methods, seasonality, and processing methods and conditions, as well as storage time [28,60–63]. Cao et al. [64] explored the effect of

View Article Online
DOI: 10.1039/D6FB00080K

tree age on volatile compounds of Chenpi and reported that Chenpi obtained from trees aged 5 years exhibited a fresher, more citrus aroma, whereas Chenpi obtained from trees aged 20 years exhibited more pronounced caramel and green leaf notes.

Jiang et al. [65] coupled headspace solid-phase microextraction gas chromatography-mass spectrometry (HS-SPME-GC-MS) with gas chromatography-olfactometry-mass spectrometry (GC-O-MS) to evaluate the changes in aroma compounds of Chenpi (obtained from Xinhui, Guangdong, China) during storage, ranging from 2 to 25 years. The contents of citrus and fruity aroma compounds (i.e. d-limonene and γ-terpinene) decreased during storage, while those with spicy, woody, and herbal aroma notes (i.e. α-farnesene) increased, resulting in an overall rise in spicy, woody, and herbal notes and a reduction in citrus and fruity notes. Similarly, Liu et al. [66] analysed the effect of aging stages on the flavour characteristics of Chenpi (obtained from Xinhui, Guangdong, China), supporting the finding of Liu et al. [66]. The authors employed 5 different aging stages of Chenpi, including 5, 10, 20, 30, and 40 years and reported that the aroma attributes of citrus decreased with the prolongation of aging time, while the fresh, floral, grassy, and woody attributes increased. This change could be attributed to the synergistic effects of multiple reactions, such as oxidative, hydrolytic, and enzymatic reactions, which increase the complexity of volatile compounds and alter the aroma balance rather than only the degradation or transformation of monoterpenes, i.e. d-limonene and γ-terpinene [60].

Zhang et al. [41] found that the lemon, sweet and musk aromas of Chenpi changed to apple, coffee, and pineapple aromas through fermentation using *Aspergillus niger*. In

View Article Online
DOI: 10.1039/D6FB00080K

another study, Shen et al. [67] fermented Chenpi using *Monascus anka* and *Saccharomyces cerevisiae* for 14 days, and discovered that the citrus, sweet, herbal, woody, and pine-like aromas of Chenpi were enhanced, while the pungent odours (e.g. grass, green, and sour) were decreased. In addition, Chen et al. [61] investigated the effect of steaming treatment on the volatile profile of Chenpi and the results showed that short steaming treatment (20 s) could reduce the overall pungency level, thereby improving the sensory quality. In a recent study, Wu et al. [60] reported that enzymatic hydrolysis (using pectinase and papain) can promote the production of various key aroma compounds (associated with fruity, floral, and oily attributes) and alter the overall aroma of Chenpi.

The above studies indicate that processing is a viable approach to modulate the aroma profile of Chenpi, thereby improving flavour quality and consumer acceptance. Nevertheless, more studies are needed to investigate the effects of different processing methods and conditions on the flavour characteristics of Chenpi and discover the mechanisms of flavour formation, thereby providing more information to enhance Chenpi flavour quality and better expand the applications of Chenpi and its derivatives in food innovation. Besides, during the aging processing, the overall flavour and sensory properties of Chenpi can be changed due to the degradation and/or transformation of volatile compounds. Although the value of Chenpi value increases and its unique flavour develops with prolonged storage in the traditional concept in China, this change may influence the sensory quality of the final Chenpi-based products and consumer acceptance when considering different consumer groups

View Article Online
DOI: 10.1039/D6FB00080K

[43,60] In this regard, the identification of flavour differences and consumer acceptance for in future research would guide the subsequent development of Chenpi products.

4. Extraction of Chenpi polysaccharides

Polysaccharides are natural bioactive compounds that are widely applied as functional ingredients in the food, pharmaceutical, and cosmetics industries, owing to their favourable physicochemical properties (e.g. gelling and emulsifying properties) and biological activities (e.g. antioxidant, anti-inflammatory, antibacterial, and anti-diabetes activities) [68–71]. With changes in dietary patterns, there is increasing interest in food products with potential health benefits [72,73]. This makes Chenpi polysaccharides valuable and high potential ingredients in functional food development. Notably, many studies have demonstrated that extraction methods determine the physicochemical properties and biological activities of polysaccharides, and consequently affects their value and further applications [74–77]. As mentioned earlier, polysaccharides are important bioactive compounds in Chenpi; therefore, appropriate extraction methods are important for developing high-quality of Chenpi polysaccharides and are key to their commercial applications [78]. Table 2 summarises current advances in the extraction of Chenpi polysaccharides.

Hot water is the most commonly used method for the extraction of polysaccharides, with the advantages of low cost, simple operation, and low equipment requirements [79]. In the study by Yang et al. [80], the yield of Chenpi polysaccharides reached 8.9%

View Article Online
DOI: 10.1039/D6FB00080K

under a liquid-to-solid ratio of 10:1 (w/w) at 65 °C for 120 min. After purification using DEAE Sepharose anion exchange chromatography, the authors reported that the molecular weight of Chenpi polysaccharides was 55.4 kDa, and it mainly consisted of arabinose and galacturonic acid (with a molar ratio of 1:2.3). In another study by Zhou et al. [81], the yield reached 18.6% under extraction conditions of 80 °C for 120 min. Besides, the extracted Chenpi polysaccharides increased the viability of RAW264.7 cell at a concentration of 0.2 mg/mL. In addition, Wang et al. [82] extracted Chenpi polysaccharides using the hot water method and subsequently investigated their monosaccharide composition and the effect of anti-inflammatory on a high-cholesterol-fed (HCF) Casper zebrafish model. The results showed that the molecular weight (MW) of extracted the Chenpi polysaccharide was 9.8 kDa, and the monosaccharide composition consisted of rhamnose (2.9 mol%), arabinose (16.8 mol%), galactose (13.7 mol%), glucose (1.9 mol%), and galacturonic acid (64.7 mol%). Afterwards, in the HFC Casper zebrafish model, dietary treatment with 0.5 wt% of Chenpi polysaccharides significantly reduced ($p < 0.05$) hepatic macrophage infiltration, while treatment at 1 wt% significantly reverted hepatic macrophage infiltration to normalcy. In a recent study, Liang et al. [83] extracted pectic polysaccharide fraction from Chenpi in a liquid-to-solid ratio of (15:1, v/w) at 90 °C for 90 min for 3 extraction cycles, and the yield was 4.28%. Furthermore, the monosaccharides composition analysis results showed that the extracted pectic Chenpi polysaccharide was composed of arabinose (49.26 mol%), galacturonic acid (26.02 mol%), rhamnose (5.25 mol%), glucose (4.34 mol%), mannose (3.26 mol%), and

View Article Online
DOI: 10.1039/D6FB00080K

xylose (0.73 mol%).

In addition to hot water extraction method, acid extraction has also been applied in the extraction of Chenpi polysaccharides. Yue et al. [38] employed acid extraction (using HCl to adjust the pH) to extract Chenpi polysaccharides and optimised the extraction conditions in terms of pH, temperature, and liquid-to-solid ratio. The yield reached 25.77% under the optimised extraction conditions, namely, a liquid-to-solid ratio of 25:1 (v/w), pH of 0.5, and temperature of 80 °C. Notably, HCl (highly corrosive and hazardous solvent) use and it subsequently neutralisation steps can increase the risk of accident and generate waste, which have impact on the human health and the environment [84,85]. From an environmental perspective and the principle of green chemistry, avoiding toxic and hazardous chemicals in the extraction process is important to prevent waste generation, reduce the risk of accident, and support sustainability [86,87]. Therefore, while acid extraction in the above study offers high yield the extraction of Chenpi polysaccharides, its practical application should carefully balance extraction efficiency with environmental and safety considerations.

In another study, Li et al. [88] used ultrasound-assisted extraction method to extract polysaccharides from Chenpi and optimised the extraction conditions using a Box-Behnken design, namely, a liquid-to-material ratio of 30:1 (v/w), pH of 4.4, temperature of 90.0 °C, ultrasonic power of 250.0 W, and extraction time of 20 min. Under these conditions, the polysaccharide yield reached 7.0%. After purification, the molecular weight of the extracted Chenpi polysaccharide was 122.0 kDa, and the monosaccharide composition was galacturonic acid (51.17%), arabinose (25.63%),

View Article Online
DOI: 10.1039/D6FB00080K

galactose (12.25%), and glucose (5.46%). In addition, the authors observed that the extracted Chenpi polysaccharide exhibited antidiabetic and anti-obesogenic properties and modulated gut microbiota, which stimulated the growth of *Lactobacillus johnsonii* and normalised the levels of plasma total triacylglycerol (TG), total cholesterol (CHO), low-density lipoprotein-cholesterol (LDL-C), alanine aminotransferase (ALT), and aspartate aminotransferase (AST) in a high-fat-diet mice model following oral dosage at 60mg/kg for 4 weeks. Notably, although UAE can significantly reduce extraction time and solvent usage compared to conventional hot water extraction, its scalability remains important considerations for industrial application [89,90]. In the large volume, the ultrasound waves difficult to achieve uniform, resulting uneven energy distribution and uneven extraction efficiency [91]. Therefore, the results may give an overly positive view of its performance in practical applications [92]. To this end, further research is needed to explore on pilot-scale or industry scale to provide more comparable results for practical applications.

In a recent study by Liu et al. [93], the authors established a liquid fermentation method (using *Bacillus licheniformis* at 5%, v/v for 12 h) to obtain Chenpi polysaccharides. The obtained Chenpi polysaccharide (MW of 3.72 kDa) was composed of arabinose (31.75%), galactose (24.77%), galacturonic acid (20.94%), fucose (7.83%), rhamnose (7.53%), glucose (4.08%), mannose (1.93%), and glucuronic acid (1.15%). Besides, the authors used an *in vitro* fermentation method to evaluate the prebiotic effect of the obtained Chenpi polysaccharide, and the results showed that the obtained polysaccharide promoted the growth of *Bacteroides*,

View Article Online
DOI: 10.1039/D6FB00080K

Parabacteroides, and *Collinsella*, while reducing the relative abundance of *Shigella* and *Klebsiella*.

Overall, the above studies make a promising progress in the extraction of polysaccharides from Chenpi and exhibit their promoting health effects. However, the existing studies mainly focus on hot water extraction, while the applications of other methods are relatively limited. Therefore, further studies could explore more extraction methods on the extraction polysaccharides from Chenpi to provide more comparable results to increase extraction efficiency and obtain high quality products for further applications [94,95]. Besides, the biological activities of polysaccharides are closely associated with their structures, such as molecular weight (MW) and monosaccharide composition [96,97]. Liang et al. [98] evaluated the structure-activity relationship of black garlic polysaccharides and found that the higher uronic acid content and lower MW were associated with higher antioxidant capacity, with MW exhibiting a greater influence. In another study, Liang et al. [99] analysed the relationship between the structural features of goji berry polysaccharides and antioxidant and anti-aging activities. The results showed that the antioxidant capacity was positively correlated with galacturonic acid (GalA) content, while the neutral multi-branched chains may contribute to anti-aging activity. To date, research on the structure-activity relationship of Chenpi polysaccharides remains limited. Therefore, future studies could focus on establishing the relationship between the structural features (e.g., monosaccharide composition and molecular weight) and the different biological activities of Chenpi polysaccharides, which would facilitate the production

View Article Online
DOI: 10.1039/D6FB00080K

of Chenpi polysaccharide with enhanced biological activity and expand their appliable scenarios [100–102].

5. Food applications

Chenpi, as a traditional medicine and food monology ingredient, has been widely introduced processed into various food products in China, such as snack, tea beverage, and bakery products (Figure 2) [103,104]. The famous Chenpi tea beverage is Ganpu tea, which is commonly made from Chenpi and Pu-erh tea [62]. In addition, the traditional Chenpi snack, nine-processed Chenpi, is produced using “nine-processed” processing technique, which includes multiple steps, such as selection (CP1), soaking (CP2), keeping fresh, peeling, pickling (CP3), draining, seasoning, repeated drying, and finally storage (aging, CP4) [39,105]. Notably, “nine-processed” method could take longer time and high energy consumption, leading to a substantial environmental footprint and not meeting the not meeting the concept of energy-saving and sustainable development [106]. Therefore, it is necessary to explore new processing techniques to quickly improve the quality of Chenpi’s product and to meet the concept of sustainable development. Considering environmental burden and sustainable food system, emerging technologies could be investigated to replace and/or minimise traditional “nine-processed” method steps in the production of traditional Chenpi snack. Fermentation, as an eco-friendly, technologically flexible, method, has been demonstrated its potential in the production of Chenpi’ products, which not only be used for minising the impact of environment but also improving the quality of Chenpi [40,93,107]. Therefore, continues exploring the fermentation method in the Chenpi

View Article Online
DOI: 10.1039/D6FB00080K

product production and comparing traditional processing method (nine-processed technique) would contribute to the sustainability and diversification of Chenpi product production [67].

In addition to the above, Peng et al. [108] developed a functional jelly product that was made of Chenpi, orange juice, and pectin, and reported that the jelly exhibited excellent antioxidant capacity as determined by *in vitro* chemical assay [ABTS of 88.87 μmol Trolox equivalents (TE)/g, DPPH of 12.44 μmol TE/g, and FRAP of 28.24 μmol TE/g]. In another study, Zhang et al. [109] employed Chenpi in soy yogurt development. In the formulation, Chenpi partly replaced soybean in the yogurt formulation at 1%, 2%, 3%, and 4%, w/w. The results showed that Chenpi addition (2% - 4%) increased the total acid value of yoghurt. Furthermore, Chenpi addition (1% - 3%) increased the adhesiveness and chewiness of yoghurt. In terms of rheological properties, 1% Chenpi addition showed the highest apparent viscosity, while 4% Chenpi addition was lowest apparent viscosity. This difference could be attributed to the Chenpi pectin polysaccharide; the appropriate Chenpi pectin addition as a filler could fill the spaces of protein aggregates to enhance the gel strength, while excessive Chenpi pectin addition may interfere the cross-linking of protein aggregates and then hinder formation of gel network, resulting in a weaking gel network [109,110]. In the sensory evaluation, the soybean yoghurt contained 2% Chenpi had the highest sensory scores among all products in terms of overall acceptance, colour, texture, odour, and flavour.

In a recent study, Zhang et al. [111] developed a cold brew Chenpi beverage and explored the effects of different assisted extraction methods, namely, high pressure

View Article Online
DOI: 10.1039/D6FB00080K

processing (HPP), ultrasound-assisted (UAE), and combination of HPP and UAE, on the flavour quality of the final Chenpi beverage. The results showed that the combination of HPP and UAE significantly promoted the release of volatile flavor substances (fatty and woody aroma-related compound) from Chenpi and endowed the Chenpi cold brew with a richer woody aroma.

Overall, the above studies exhibit the potential of Chenpi in food development and point to a novel avenue for further food innovation. Nevertheless, outside of Asia, Chenpi is an uncommon ingredient in most countries and is scarcely utilised and introduced into the daily diets, which could affect the acceptance of Chenpi-based food products and their further promotion [112,113]. Food selection is a complex process and varies depending on multiple factors, such as cultural contexts, eating habits, and personal taste experience; therefore, it is necessary to explore the consumer performance and perception on the Chenpi-based food products in different groups and countries, which can in turn guide further formulation optimisation and innovation and promote theirs widespread acceptance [114–116]. Besides, the above studies report promising antioxidant activity of Chenpi-based food on *in vitro* chemical assays (e.g. DPPH and ABTS), these results may not directly translate into pharmacologically relevant concentration into the human body [117]. There are increasing evidence that phenolic compounds in different food matrix affect their bioavailability, and consequently biological potential in the human body [118–121]. Ribnicky et al. [122] reported that anthocyanins from blueberry to a protein-rich matrix were more bioaccessible. In the study by Mandalari et al. [123], the biscuit

View Article Online
DOI: 10.1039/D6FB00080K

matrix decreased bioaccessibility of flavonols from almond skin. Given that, future studies could conduct on the *in vivo* approaches to evaluate the interaction between phenolic compounds from Chenpi and different food matrix and its consequently phenolic bioavailability to better understand its derived health benefits.

6. Industrial Scalability and Techno-Economic Considerations

According to the above, Chenpi shows potential as a valuable functional ingredient for sustainable diets, which can provide a promising insight into utilisation of citrus processing by-products into high value-added ingredients [124]. However, the large-scale industrial production of Chenpi from citrus waste requires careful consideration of scalability and techno-economic feasibility. Firstly, the quality of citrus peel varies widely depending on citrus variety, cultivation conditions, and processing methods [125]. Therefore, establishing quality standardisation and standardised processing protocols is important to ensure raw materials with maximum retention of bioactive compounds and pharmacological efficacy, as well as to support their reproducibility in industrial applications [126,127]. Additionally, in terms of extraction of high value-added ingredients, advanced extraction technologies (e.g. UAE) show high efficiency and environmental benefits, but may face barriers to industrial scale-up, including high energy costs, equipment limitations, and maintenance requirements [128,129]. In this regard, a comprehensive techno-economic analysis is necessary; in addition, optimising process and combination of different techniques could overcome the mentioned limitations, thereby enhancing selectively, reducing cost, and then fostering industry applications [130,131]. On the other hands, consumer acceptance

View Article Online
DOI: 10.1039/D6FB00080K

is important for the commercial success of Chenpi-based products [132]. Expansion of a wider range of Chenpi-based products and systematic consumer studies focusing on consumer perception and willingness are important to meet the diversified needs of different consumer groups, contributing to their market successful and be widely promoted and incorporated into daily diets [133,134].

7. Conclusions

Chenpi, one of the widely recognised and used medicinal and edible ingredients in the traditional Chinese diet, contains abundant bioactive compounds with extensive pharmacological benefits, such as antioxidant, anti-inflammatory, and the modulation of gut microbiota. This makes Chenpi a valuable ingredient, and its wider utilisation in the daily diet could contribute to a shift towards a sustainable and healthy diet. However, efforts to develop Chenpi-based health products and widely integrate them into the daily diet continue to address some challenges. Firstly, Chenpi is uncommon ingredient in most countries, and most customers lack the understanding of Chenpi, therefore, strengthening science communication and promoting the utilisation method are important directions for future development. In terms of bioactive compounds extraction, the extraction method determines the quality and functions of target extracted compounds; therefore, more studies are needed in the extraction field to enhance the product quality, which could further expand the applications. In terms of functional food development, further studies could focus on the expansion of a wider range of Chenpi-based products to meet the diversified needs of different consumer groups.

View Article Online
DOI: 10.1039/D6FB00080K

Competing interests

The authors declare that they have no competing or interests.

Acknowledgements

The authors acknowledge the financial support from the 'Xinjiang Tianshan Talent' Cultivation Program (No. 2022TSYCLJ0040) and the Key R&D Special Project of Xinjiang Autonomous Region (No. 2022B02026). The graphical abstract image was created using some icons from Biorender.com.

Authorship contribution statement

Guoqiang Zhang: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. **HioTong Mak**: Resource, Visualization. **Zheng Zhang**: Writing – review & editing. **Ting Zhang:** Writing – review & editing. **Yuanhui Wang**: Writing – review & editing, Resource. **Run-Yang Zhang**: Writing – review & editing**.** **Hua-Min Liu:** Writing – review & editing**. Shaobo Zhou:** Writing – review & editing. **Bin Wu:** Writing – review & editing, funding acquisition.

References

1. Li X, Wang X, Engel BA, Hua E, Sun S, Wu P, et al. Integrating environmental footprints and planetary boundaries for assessing environmental sustainability in food production. Sustain Prod Consum. 2024;48:205–18. https://doi.org/10.1016/j.spc.2024.05.018

2. Zhang G, Wang Y, Wu B. Advancing sustainable food innovation with house cricket (Acheta domesticus) and mealworm (Tenebrio molitor): Nutrition, applications, and product quality. J Agric Food Res. 2026;25:102565. https://doi.org/10.1016/j.jafr.2025.102565

View Article Online
DOI: 10.1039/D6FB00080K

3. Li Y, He P, Shan Y, Li Y, Hang Y, Shao S, et al. Reducing climate change impacts from the global food system through diet shifts. Nat Clim Chang. 2024;14:943–53. https://doi.org/10.1038/s41558-024-02084-1

4. Rockström J, Thilsted SH, Willett WC, Gordon LJ, Herrero M, Hicks CC, et al. The EAT–Lancet Commission on healthy, sustainable, and just food systems. The Lancet. 2025;406:1625–700. https://doi.org/10.1016/S0140-6736(25)01201-2

5. Guo Y, He P, Searchinger TD, Chen Y, Springmann M, Zhou M, et al. Environmental and human health trade-offs in potential Chinese dietary shifts. One Earth. 2022;5:268–82. https://doi.org/10.1016/j.oneear.2022.02.002

6. Wang L, Zhu X, Liu H, Sun B. Medicine and food homology substances: A review of bioactive ingredients, pharmacological effects and applications. Food Chem. 2025;463:141111. https://doi.org/10.1016/j.foodchem.2024.141111

7. Ma A, Zou F, Zhang R, Zhao X. The effects and underlying mechanisms of medicine and food homologous flowers on the prevention and treatment of related diseases. J Food Biochem. 2022;46. https://doi.org/10.1111/jfbc.14430

8. Liu Z, Sun S, Zhang Y, Zhao H, Xu C, Liu Y, et al. Food as Medicine: Integrating Food-Medicine Homology into Foods for Special Medical Purposes for Targeted Symptom Management and Nutritional Support. Food Reviews International. 2026;1–35. https://doi.org/10.1080/87559129.2026.2639506

9. Zhou S, Huang Y, Chu W. Medicine-food homology substances: Ecological engineers of gut microbiota for precision nutrition. Food and Humanity. 2026;6:101007. https://doi.org/10.1016/j.foohum.2026.101007

10. Zheng C, Zheng H, Ye Z, Li Q. Chenpi years identification based on terahertz spectral data and time series deep learning. Applied Food Research. 2025;5:101463. https://doi.org/10.1016/j.afres.2025.101463

11. Li XK, Tang LJ, Li ZY, Qiu D, Yang ZL, Zhang XY, et al. Geographical origin discrimination of Chenpi using machine learning and enhanced mid-level data fusion. NPJ Sci Food. 2025;9:17. https://doi.org/10.1038/s41538-025-00376-0

12. Li F, Lu Y, Li C, Huang R, Tian E, Tan E, et al. trnL-trnF copy number is inversely correlated with storage time of Guang Chenpi, the aged sun-dried peels of Citrus reticulata 'Chachi'. J Stored Prod Res. 2022;97:101982. https://doi.org/10.1016/j.jspr.2022.101982

13. Sun X, Deng H, Shan B, Shan Y, Huang J, Feng X, et al. Flavonoids contribute most to discriminating aged Guang Chenpi (*Citrus reticulata* 'Chachi') by spectrum-effect relationship analysis between LC-Q-Orbitrap/MS fingerprint and ameliorating spleen deficiency activity. Food Sci Nutr. 2023;11:7039–60. https://doi.org/10.1002/fsn3.3629

14. Falduto M, Smedile F, Zhang M, Zheng T, Zhu J, Huang Q, et al. Anti-obesity effects of Chenpi: an artificial gastrointestinal system study. Microb Biotechnol. 2022;15:874–85. https://doi.org/10.1111/1751-7915.14005

15. Li A, Wang N, Li N, Li B, Yan F, Song Y, et al. Modulation effect of *chenpi* extract on gut microbiota in high-fat diet-induced obese C57BL/6 mice. J Food Biochem. 2021;45. https://doi.org/10.1111/jfbc.13541

16. Cen Z, Chen Z, Wang D, Zuo Y, Peng J, Chen J, et al. Guang Chenpi Extract as a

View Article Online
DOI: 10.1039/D6FB00080K

Multifunctional Phytotherapeutic: Enhanced Effects with Ergothioneine and Polydeoxyribonucleotide on Redox Homeostasis and Tissue Resilience. Pharmaceuticals. 2026;19:293. https://doi.org/10.3390/ph19020293

17. Xu L, Liu W, Wu X, Chen T, Gao Y, Huang J, et al. *Citri Reticulatae Pericarpium* improves obesity in OVX mice by regulating the gut microbiota and suppressing appetite. Food Funct. 2025;16:9545–61. https://doi.org/10.1039/D5FO03974F

18. Tan E, Li F, Lin X, Ma S, Zhang G, Zhou H, et al. Comparative study on comprehensive quality of Xinhui chenpi by two main plant propagation techniques. Food Sci Nutr. 2023;11:1104–12. https://doi.org/10.1002/fsn3.3148

19. Sharma P, Vishvakarma R, Gautam K, Vimal A, Kumar Gaur V, Farooqui A, et al. Valorization of citrus peel waste for the sustainable production of value-added products. Bioresour Technol. 2022;351:127064. https://doi.org/10.1016/j.biortech.2022.127064

20. Peng Q, Zhang Y, Zhu M, Bao F, Deng J, Li W. Polymethoxyflavones from citrus peel: advances in extraction methods, biological properties, and potential applications. Crit Rev Food Sci Nutr. 2024;64:5618–30. https://doi.org/10.1080/10408398.2022.2156476

21. Augustin MA, Sanguansri L, Fox EM, Cobiac L, Cole MB. Recovery of wasted fruit and vegetables for improving sustainable diets. Trends Food Sci Technol. 2020;95:75–85. https://doi.org/10.1016/j.tifs.2019.11.010

22. Zhang G, Li Z, Chatzifragkou A, Charalampopoulos D. Effect of processing methods on the phytochemical content of melon seeds (Cucumis melo L.). Future Foods. 2024;10:100399. https://doi.org/10.1016/j.fufo.2024.100399

23. Manzoor S, Fayaz U, Dar AH, Dash KK, Shams R, Bashir I, et al. Sustainable development goals through reducing food loss and food waste: A comprehensive review. Future Foods. 2024;9:100362. https://doi.org/10.1016/j.fufo.2024.100362

24. Zhang G, Guo J, Guo J. A sustainable approach in pumpkin seed oil processing line: Recent advances in pumpkin seed oil and oil processing by-products. Food Chem X. 2025;26:102259. https://doi.org/10.1016/j.fochx.2025.102259

25. Granato D, Zabetakis I, Koidis A. Sustainability, nutrition, and scientific advances of functional foods under the new EU and global legislation initiatives. J Funct Foods. 2023;109:105793. https://doi.org/10.1016/j.jff.2023.105793

26. Kumar A, Kumar S, Komal, Ramchiary N, Singh P. Role of Traditional Ethnobotanical Knowledge and Indigenous Communities in Achieving Sustainable Development Goals. Sustainability. 2021;13:3062. https://doi.org/10.3390/su13063062

27. Sun-Waterhouse D-X, Chen X-Y, Liu Z-H, I.N. Waterhouse G, Kang W-Y. Transformation from traditional medicine-food homology to modern food-medicine homology. Food & Medicine Homology. 2024;1:9420014. https://doi.org/10.26599/FMH.2024.9420014

28. Shi J, Peng L, Chen W, Qiao W, Wang K, Xu Y, et al. Evaluation of chemical components and quality in Xinhui Chenpi (*Citrus reticulata* 'Chachi') with two different storage times by <scp>GC–MS</scp> and <scp>UPLC</scp>. Food Sci Nutr. 2024;12:5036–51. https://doi.org/10.1002/fsn3.4154

29. Yu X, Sun S, Guo Y, Liu Y, Yang D, Li G, et al. Citri Reticulatae Pericarpium (Chenpi):

View Article Online
DOI: 10.1039/D6FB00080K

Botany, ethnopharmacology, phytochemistry, and pharmacology of a frequently used traditional Chinese medicine. J Ethnopharmacol. 2018;220:265–82. https://doi.org/10.1016/j.jep.2018.03.031

30. Wang Y, Zhang X, Zhou C, Khan H, Fu M, Cheang WS. Citri Reticulatae Pericarpium (Chenpi) Protects against Endothelial Dysfunction and Vascular Inflammation in Diabetic Rats. Nutrients. 2022;14:5221. https://doi.org/10.3390/nu14245221

31. Qian Y, Gao Z, Wang C, Ma J, Li G, Fu F, et al. Effects of Different Treatment Methods of Dried Citrus Peel (Chenpi) on Intestinal Microflora and Short-Chain Fatty Acids in Healthy Mice. Front Nutr. 2021;8. https://doi.org/10.3389/fnut.2021.702559

32. Zhang M, Zhu J, Zhang X, Zhao D, Ma Y, Li D, et al. Aged citrus peel (*chenpi*) extract causes dynamic alteration of colonic microbiota in high-fat diet induced obese mice. Food Funct. 2020;11:2667–78. https://doi.org/10.1039/C9FO02907A

33. Wang Q, Qiu Z, Chen Y, Song Y, Zhou A, Cao Y, et al. Review of recent advances on health benefits, microbial transformations, and authenticity identification of *Citri reticulatae* Pericarpium bioactive compounds. Crit Rev Food Sci Nutr. 2024;64:10332–60. https://doi.org/10.1080/10408398.2023.2222834

34. Xu G, Zhao J, Yao J, Xu Y, Yuan X, Pan S. Effects of aging on the fine structure, chain conformation, and morphology of Chenpi polysaccharides. Carbohydr Polym. 2025;349:122970. https://doi.org/10.1016/j.carbpol.2024.122970

35. Tian C, Xu H, Li J, Han Z. Characteristics and intestinal immunomodulating activities of water-soluble pectic polysaccharides from Chenpi with different storage periods. J Sci Food Agric. 2018;98:3752–7. https://doi.org/10.1002/jsfa.8888

36. Chen L, Xiao G, Xu Y, Cheang WS, Wu J, Yu Y, et al. Effects of aging on the bioactive flavonoids and fungal diversity of Pericarpium Citri Reticulatae (Citrus reticulata 'Chachi'). LWT. 2024;200:116135. https://doi.org/10.1016/j.lwt.2024.116135

37. Zhu Y, Zhu Y, Liu X, Qi J. Change in nutrients of Citri Reticulatae 'Chachi' in relation to browning during aging. Journal of Food Composition and Analysis. 2022;107:104351. https://doi.org/10.1016/j.jfca.2021.104351

38. Yue F, Zhang F, Qu Q, Wang C, Qin Y, Ma L, et al. Effects of ageing time on the properties of polysaccharide in tangerine peel and its bacterial community. Food Chem. 2023;417:135812. https://doi.org/10.1016/j.foodchem.2023.135812

39. Fu M, Wang Y, Zhu X, Li M, Yu Y, Wu J, et al. Metabolomics reveal changes of flavonoids during processing of "nine-processed" tangerine peel (Jiuzhi Chenpi). LWT. 2024;214:117132. https://doi.org/10.1016/j.lwt.2024.117132

40. Tang Z, Miao Y, Lu H, Chen C, Li S, Zhang W. Aging of Citri Reticulatae pericarpium: Flavonoid metabolite dynamics, fungal community succession, and functional analysis of key transformation strains. Food Research International. 2026;227:118220. https://doi.org/10.1016/j.foodres.2025.118220

41. Zhang Y, Tong X, Chen B, Wu S, Wang X, Zheng Q, et al. Novel application of HS-GC-IMS for characteristic fingerprints and flavor compound variations in citrus reticulatae pericarpium during storage with different Aspergillus niger fermentation. Food Chem X. 2023;18:100653. https://doi.org/10.1016/j.fochx.2023.100653

42. Liu R, Tao Y, Xu T, Wu T, Yu Q, Pan S, et al. Antioxidant activity increased due to dynamic changes of flavonoids in orange peel during *Aspergillus niger* fermentation.

View Article Online
DOI: 10.1039/D6FB00080K

Int J Food Sci Technol. 2023;58:3329–36. https://doi.org/10.1111/ijfs.16239

43. Fu Y, Wang C, Gao Z, Liao Y, Peng M, Fu F, et al. Microbes: Drivers of Chenpi manufacturing, biotransformation, and physiological effects. Food Chem. 2025;464:141631. https://doi.org/10.1016/j.foodchem.2024.141631

44. Xie J, Wei F, Luo L, Dai L, Zeng L, Wang X. Effect of cell wall-disruption processes on wall disruption, antioxidant activity and nutrients in tea pollen. Int J Food Sci Technol. 2022;57:3361–74. https://doi.org/10.1111/ijfs.15612

45. Shi J, Peng L, Chen W, Qiao W, Wang K, Xu Y, et al. Evaluation of chemical components and quality in Xinhui Chenpi (*Citrus reticulata* 'Chachi') with two different storage times by <scp>GC–MS</scp> and <scp>UPLC</scp>. Food Sci Nutr. 2024;12:5036–51. https://doi.org/10.1002/fsn3.4154

46. Chai H, Li X, Chen S, Lin D, Cai R, Yang A, et al. Comparative Study Between Orah Mandarin Peel and Traditional Mandarin Peels (Chenpi) Based on Data-Repository-Enabled Ultra-High-Performance Liquid Chromatography-Quadrupole-Orbitrap-Mass Spectrometry Analysis. Chem Biodivers. 2025;22. https://doi.org/10.1002/cbdv.202501661

47. Zhang J, Wu X, Qiu J, Zhang L, Zhang Y, Qiu X, et al. Comprehensive Comparison on the Chemical Profile of Guang Chen Pi at Different Ripeness Stages Using Untargeted and Pseudotargeted Metabolomics. J Agric Food Chem. 2020;68:8483–95. https://doi.org/10.1021/acs.jafc.0c02904

48. Bian X, Xie X, Cai J, Zhao Y, Miao W, Chen X, et al. Dynamic changes of phenolic acids and antioxidant activity of Citri Reticulatae Pericarpium during aging processes. Food Chem. 2022;373:131399. https://doi.org/10.1016/j.foodchem.2021.131399

49. Wang L, Xu H, Yuan F, Pan Q, Fan R, Gao Y. Physicochemical characterization of five types of citrus dietary fibers. Biocatal Agric Biotechnol. 2015;4:250–8. https://doi.org/10.1016/j.bcab.2015.02.003

50. Xiang T, Yang R, Li L, Lin H, Kai G. Research progress and application of pectin: A review. J Food Sci. 2024;89:6985–7007. https://doi.org/10.1111/1750-3841.17438

51. Roy S, Priyadarshi R, Łopusiewicz Ł, Biswas D, Chandel V, Rhim J-W. Recent progress in pectin extraction, characterization, and pectin-based films for active food packaging applications: A review. Int J Biol Macromol. 2023;239:124248. https://doi.org/10.1016/j.ijbiomac.2023.124248

52. K R R, Gopi S, Balakrishnan P. Introduction to Flavor and Fragrance in Food Processing. 2022. p. 1–19. https://doi.org/10.1021/bk-2022-1433.ch001

53. Jiang H, Yang S, Tian H, Sun B. Research progress in the use of liquid-liquid extraction for food flavour analysis. Trends Food Sci Technol. 2023;132:138–49. https://doi.org/10.1016/j.tifs.2023.01.005

54. Yang Y, Wang Y, Li B, Chen C, Zhao Y, Pan L, et al. Analysis of microbial diversity of traditional Chinese starters and screening of special flavor yeast for Chinese baked flatbread. Front Nutr. 2026;12. https://doi.org/10.3389/fnut.2025.1755466

55. Siewe FB, Makebe CW, Claudette Bakisu Muala W, Laya A, Raymond Nkongho N, Meliko MO, et al. Advances in processing, reaction pathways, stabilisation and food applications of natural seafood flavourings. Food Biosci. 2024;58:103627. https://doi.org/10.1016/j.fbio.2024.103627

View Article Online
DOI: 10.1039/D6FB00080K

56. Kothe CI, Carøe C, Mazel F, Zilber D, Cruz-Morales P, Mohellibi N, et al. Novel misos shape distinct microbial ecologies: opportunities for flavourful sustainable food innovation. Food Research International. 2024;189:114490. https://doi.org/10.1016/j.foodres.2024.114490

57. Li H, Lin L, Feng Y, Zhao M. Exploration of optimal preparation strategy of Chenpi (pericarps of Citrus reticulata Blanco) flavouring essence with great application potential in sugar and salt-reduced foods. Food Research International. 2024;175:113669. https://doi.org/10.1016/j.foodres.2023.113669

58. Wang Y-H, Yang Y-Y, Li H-Q, Zhang Q-D, Xu F, Li Z-J. Characterization of aroma-active compounds in steamed breads fermented with Chinese traditional sourdough. LWT. 2021;152:112347. https://doi.org/10.1016/j.lwt.2021.112347

59. Urlass S, Wu Y, Nguyen TTL, Winberg P, Turner MS, Smyth H. Unravelling the aroma and flavour of algae for future food applications. Trends Food Sci Technol. 2023;138:370–81. https://doi.org/10.1016/j.tifs.2023.06.018

60. Wu S, Song X, Huo G, Li L, Huo M, Zhao M, et al. Elucidation of the diverse molecular signatures and transformation pathways of flavor metabolites in age-stratified citri reticulatae pericarpium (ChenPi) and their enzymatic hydrolysates: A perspective from the flavor space. Food Research International. 2026;225:118054. https://doi.org/10.1016/j.foodres.2025.118054

61. Chen S, Chen Z, O'Neill Rothenberg D, Long Y, Li H, Zeng X, et al. Short-term steaming during processing impacts the quality of Citri Reticulatae 'Chachi' peel. Food Chem. 2024;447:138964. https://doi.org/10.1016/j.foodchem.2024.138964

62. Deng X, He S, Han Y, Chen Y. Metabolites profiling reveals the dynamic changes of non-volatiles in Pu-erh during Ganpu tea processing. Food Chem X. 2023;19:100774. https://doi.org/10.1016/j.fochx.2023.100774

63. Li T-X, Xiong F-Y, Cai W, Fang Y-N, Yang X, Li J-X, et al. Chemical compositions and bioactivity of essential oils of Citri Reticulata Pericarpium Viride from three provinces in China. Food Sci Biotechnol. 2026;35:1147–57. https://doi.org/10.1007/s10068-026-02112-0

64. Cao K, Yao C, Xiao J, Huang R, Qin Z, Shi Y, et al. Elucidation of dynamic evolution patterns of non-volatile and volatile compounds in peel of Citrus reticulata cv. Chachiensis with different tree ages: a metabolomics-based analysis. Food Research International. 2026;227:118254. https://doi.org/10.1016/j.foodres.2025.118254

65. Jiang K, Xu K, Wang J, Meng F, Wang B. Based on HS-SPME-GC-MS combined with GC-O-MS to analyze the changes of aroma compounds in the aging process of Citri Reticulatae Pericarpium. Food Biosci. 2023;54:102798. https://doi.org/10.1016/j.fbio.2023.102798

66. Liu H, Fu M, Wu J, Yu Y, Si W, Xu Y, et al. Flavor characterization of aged Citri Reticulatae Pericarpium from core regions: An integrative approach utilizing GC-IMS, GC–MS, E-nose, E-tongue, and chemometrics. Food Chem. 2025;490:144995. https://doi.org/10.1016/j.foodchem.2025.144995

67. Shen F, Wang T, Zhang R, Zhong B, Wu Z. Metabolism and release of characteristic components and their enzymatic mechanisms in Pericarpium Citri Reticulatae co-fermentation. Food Chem. 2024;432:137227.

View Article Online
DOI: 10.1039/D6FB00080K

https://doi.org/10.1016/j.foodchem.2023.137227

68. Liu T, Zhao M, Zhang Y, Xu R, Fu Z, Jin T, et al. Polysaccharides from Phellinus linteus attenuate type 2 diabetes mellitus in rats via modulation of gut microbiota and bile acid metabolism. Int J Biol Macromol. 2024;262:130062. https://doi.org/10.1016/j.ijbiomac.2024.130062

69. Chen G, Jiang N, Zheng J, Hu H, Yang H, Lin A, et al. Structural characterization and anti-inflammatory activity of polysaccharides from Astragalus membranaceus. Int J Biol Macromol. 2023;241:124386. https://doi.org/10.1016/j.ijbiomac.2023.124386

70. Wang S, Li G, Zhang X, Wang Y, Qiang Y, Wang B, et al. Structural characterization and antioxidant activity of Polygonatum sibiricum polysaccharides. Carbohydr Polym. 2022;291:119524. https://doi.org/10.1016/j.carbpol.2022.119524

71. Qiao Y, Shen Y, Jiang H, Li D, Li B. Structural characterization, antioxidant and antibacterial activity of three pectin polysaccharides from blueberry. Int J Biol Macromol. 2024;262:129707. https://doi.org/10.1016/j.ijbiomac.2024.129707

72. Zhang G, Liu L. Insights into potential value and sustainable utilisation of pumpkin peel: A review. Future Foods. 2025;11:100575. https://doi.org/10.1016/j.fufo.2025.100575

73. Dixit V, Joseph Kamal SW, Bajrang Chole P, Dayal D, Chaubey KK, Pal AK, et al. Functional Foods: Exploring the Health Benefits of Bioactive Compounds from Plant and Animal Sources. J Food Qual. 2023;2023:1–22. https://doi.org/10.1155/2023/5546753

74. Wang X, Su Y, Su J, Xue J, Zhang R, Li X, et al. Optimization of Enzyme−Assisted Aqueous Extraction of Polysaccharide from Acanthopanax senticosus and Comparison of Physicochemical Properties and Bioactivities of Polysaccharides with Different Molecular Weights. Molecules. 2023;28:6585. https://doi.org/10.3390/molecules28186585

75. Zhang Z, Lv G, Song T, Xu Z, Wang M. Effects of different extraction methods on the structural and biological properties of Hericium coralloides polysaccharides. Food Chem. 2024;445:138752. https://doi.org/10.1016/j.foodchem.2024.138752

76. Wei Q, Zhang Y. Ultrasound-assisted polysaccharide extraction from Cercis chinensis and properites, antioxidant activity of polysaccharide. Ultrason Sonochem. 2023;96:106422. https://doi.org/10.1016/j.ultsonch.2023.106422

77. Premarathna AD, Ahmed TAE, Kulshreshtha G, Humayun S, Shormeh Darko CN, Rjabovs V, et al. Polysaccharides from red seaweeds: Effect of extraction methods on physicochemical characteristics and antioxidant activities. Food Hydrocoll. 2024;147:109307. https://doi.org/10.1016/j.foodhyd.2023.109307

78. Zhang G, Li Z, Liu L, Xiang Q. Road to valorisation of melon seeds (*Cucumis melo* L.): a comprehensive review of nutritional profiles, biological activities, and food applications. Sustainable Food Technology. 2024; https://doi.org/10.1039/D4FB00119B

79. Huang G, Chen F, Yang W, Huang H. Preparation, deproteinization and comparison of bioactive polysaccharides. Trends Food Sci Technol. 2021;109:564–8. https://doi.org/10.1016/j.tifs.2021.01.038

80. Yang J, Wen L, Zhao Y, Jiang Y, Tian M, Liu H, et al. Structure identification of an

arabinogalacturonan in Citrus reticulata Blanco ‘Chachiensis’ peel. Food Hydrocoll. 2018;84:481–8. https://doi.org/10.1016/j.foodhyd.2018.06.022

81. Zhou T, Jiang Y, Wen L, Yang B. Characterization of polysaccharide structure in Citrus reticulate ‘Chachi’ peel during storage and their bioactivity. Carbohydr Res. 2021;508:108398. https://doi.org/10.1016/j.carres.2021.108398

82. Wang L, Li W, Li Y, Chen G, Zhao L, Li W, et al. Dried tangerine peel polysaccharide (DTPP) alleviates hepatic steatosis by suppressing TLR4/MD-2-mediated inflammation and endoplasmic reticulum stress. Bioorg Chem. 2024;147:107369. https://doi.org/10.1016/j.bioorg.2024.107369

83. Liang H, Liang Y, Wu L, Lin L, Yao Y, Deng J, et al. Pretreatment with Citrus reticulata ‘Chachi’ Polysaccharide Alleviates Alcohol-Induced Gastric Ulcer by Inhibiting NLRP3/ASC/Caspase-1 and Nrf2/HO-1 Signaling Pathways. Nutrients. 2025;17:2062. https://doi.org/10.3390/nu17132062

84. Castiello C, Junghanns P, Mergel A, Jacob C, Ducho C, Valente S, et al. GreenMedChem: the challenge in the next decade toward eco-friendly compounds and processes in drug design. Green Chemistry. 2023;25:2109–69. https://doi.org/10.1039/D2GC03772F

85. Venugopal V, Sasidharan A, Rustad T. Green Chemistry to Valorize Seafood Side Streams: An Ecofriendly Roadmap toward Sustainability. J Agric Food Chem. 2023;71:17494–509. https://doi.org/10.1021/acs.jafc.3c03126

86. López-Lorente ÁI, Pena-Pereira F, Pedersen-Bjergaard S, Zuin VG, Ozkan SA, Psillakis E. The ten principles of green sample preparation. TrAC Trends in Analytical Chemistry. 2022;148:116530. https://doi.org/10.1016/j.trac.2022.116530

87. Kurul F, Doruk B, Topkaya SN. Principles of green chemistry: building a sustainable future. Discover Chemistry. 2025;2:68. https://doi.org/10.1007/s44371-025-00152-9

88. Li Y, Li Z, Chen B, Hou Y, Wen Y, Gan L, et al. Ultrasonic assisted extraction, characterization and gut microbiota-dependent anti-obesity effect of polysaccharide from Pericarpium Citri Reticulatae ‘Chachiensis’. Ultrason Sonochem. 2023;95:106383. https://doi.org/10.1016/j.ultsonch.2023.106383

89. Deng Y, Wang W, Zhao S, Yang X, Xu W, Guo M, et al. Ultrasound-assisted extraction of lipids as food components: Mechanism, solvent, feedstock, quality evaluation and coupled technologies – A review. Trends Food Sci Technol. 2022;122:83–96. https://doi.org/10.1016/j.tifs.2022.01.034

90. Sethi S, Rathod VK. Recent advances in ultrasound-assisted extraction of natural products using novel solvents: a mini-review. Curr Opin Chem Eng. 2025;48:101132. https://doi.org/10.1016/j.coche.2025.101132

91. Roobab U, Aadil RM, Kurup SS, Maqsood S. Comparative evaluation of ultrasound-assisted extraction with other green extraction methods for sustainable recycling and processing of date palm bioresources and by-products: A review of recent research. Ultrason Sonochem. 2025;114:107252. https://doi.org/10.1016/j.ultsonch.2025.107252

92. Lian JZ, Liu T, Yang J, Zhu H, Chalermchotiwong N, Grain Y, et al. Sustainable extraction of bioactive compounds: a life cycle perspective on technologies, solvents, and process scale-up. RSC Sustainability. 2026;4:1180–202.

View Article Online
DOI: 10.1039/D6FB00080K

https://doi.org/10.1039/D5SU00832H

93. Liu Y, Huang Y, Hu H, Yang H, Xiong L, Zheng J, et al. Structural characterization and probiotic activity of Chenpi polysaccharides prepared by fermentation with Bacillus licheniformis. Food Biosci. 2025;74:107789. https://doi.org/10.1016/j.fbio.2025.107789

94. Hu W, Yu A, Bi H, Gong Y, Wang H, Kuang H, et al. Recent advances in Artemisia argyi Levl. et Vant. polysaccharides: Extractions, purifications, structural characteristics, pharmacological activities, and existing and potential applications. Int J Biol Macromol. 2024;279:135250. https://doi.org/10.1016/j.ijbiomac.2024.135250

95. Otero P, Carpena M, Garcia-Oliveira P, Echave J, Soria-Lopez A, Garcia-Perez P, et al. Seaweed polysaccharides: Emerging extraction technologies, chemical modifications and bioactive properties. Crit Rev Food Sci Nutr. 2023;63:1901–29. https://doi.org/10.1080/10408398.2021.1969534

96. Wang B, Yan L, Guo S, Wen L, Yu M, Feng L, et al. Structural Elucidation, Modification, and Structure-Activity Relationship of Polysaccharides in Chinese Herbs: A Review. Front Nutr. 2022;9. https://doi.org/10.3389/fnut.2022.908175

97. Wang J, Wang L, Zhou H, Liang X, Zhang M, Tang Y, et al. The isolation, structural features and biological activities of polysaccharide from Ligusticum chuanxiong: A review. Carbohydr Polym. 2022;285:118971. https://doi.org/10.1016/j.carbpol.2021.118971

98. Liang J, Zhao Y, Yang F, Zheng L, Ma Y, Liu Q, et al. Preparation and structure-activity relationship of highly active black garlic polysaccharides. Int J Biol Macromol. 2022;220:601–12. https://doi.org/10.1016/j.ijbiomac.2022.08.115

99. Liang X, Liu M, Wei Y, Tong L, Guo S, Kang H, et al. Structural characteristics and structure-activity relationship of four polysaccharides from Lycii fructus. Int J Biol Macromol. 2023;253:127256. https://doi.org/10.1016/j.ijbiomac.2023.127256

100. Shi L, He Q, Li J, Liu Y, Cao Y, Liu Y, et al. Polysaccharides in fruits: Biological activities, structures, and structure-activity relationships and influencing factors-A review. Food Chem. 2024;451:139408. https://doi.org/10.1016/j.foodchem.2024.139408

101. Hu B, Zhang S, Wang Z, Han Q, Zhang D, Zheng Y, et al. Degradation Method, Structural Characteristics, Biological Activity and Structure-Activity Relationship of Degraded Polysaccharides. Food Reviews International. 2024;40:2378–407. https://doi.org/10.1080/87559129.2023.2273933

102. Ji X, Guo J, Cao T, Zhang T, Liu Y, Yan Y. Review on mechanisms and structure-activity relationship of hypoglycemic effects of polysaccharides from natural resources. Food Science and Human Wellness. 2023;12:1969–80. https://doi.org/10.1016/j.fshw.2023.03.017

103. Li Y, Chen Y, Zhou Y, He J, Zhou Q, Wang M. Unveiling the potentials and action mechanisms of *Citri reticulatae* Pericarpium as an anti-inflammatory food. Food Front. 2025;6:163–84. https://doi.org/10.1002/fft2.506

104. Lu X, Zhao C, Shi H, Liao Y, Xu F, Du H, et al. Nutrients and bioactives in citrus fruits: Different citrus varieties, fruit parts, and growth stages. Crit Rev Food Sci Nutr. 2023;63:2018–41. https://doi.org/10.1080/10408398.2021.1969891

View Article Online
DOI: 10.1039/D6FB00080K

105. Fu M, Wang Y, Yu Y, Wen J, Cheong MS, Cheang WS, et al. Changes of volatile substance composition during processing of nine-processed tangerine peel (Jiuzhi Chenpi) determined by gas chromatography-ion mobility spectrometry. Front Nutr. 2022;9. https://doi.org/10.3389/fnut.2022.963655

106. Wang R, Li P, Chen S, Guo J, Liu Y, Shen H, et al. Elucidating the effects of nine-steaming-nine-drying on the morphology, metabolomic profile, and active ingredients of Polygonatum sibiricum Redouté. Frontiers in Food Science and Technology. 2025;5. https://doi.org/10.3389/frfst.2025.1666149

107. Sun J, Mao X. An environmental friendly process for Antarctic krill (Euphausia superba) utilization using fermentation technology. J Clean Prod. 2016;127:618–23. https://doi.org/10.1016/j.jclepro.2016.04.020

108. Peng M, Gao Z, Liao Y, Guo J, Shan Y. Development of Citrus-Based Functional Jelly and an Investigation of Its Anti-Obesity and Antioxidant Properties. Antioxidants. 2022;11:2418. https://doi.org/10.3390/antiox11122418

109. Zhang R, Zhang J, Zhang Y, Zhang H, Cao Y, Xu W. Effects of Citri Reticulatae Pericarpium on the physicochemical, rheological, and sensory properties of soy yogurt. LWT. 2025;234:118569. https://doi.org/10.1016/j.lwt.2025.118569

110. Mary PR, Mutturi S, Kapoor M. Non-enzymatically hydrolyzed guar gum and orange peel fibre together stabilize the low-fat, set-type yogurt: A techno-functional study. Food Hydrocoll. 2022;122:107100. https://doi.org/10.1016/j.foodhyd.2021.107100

111. Zhang J, Shi K, Li B, Chen C, Jia S, Liu Y. Effects of High Pressure Processing and Ultrasound-Assisted Extraction on Physicochemical Properties, Antioxidant Activity and Flavor Compounds of Cold Brew Citri Reticulatae Pericarpium Beverage. Foods. 2026;15:757. https://doi.org/10.3390/foods15040757

112. Zhang G, Wang Y, Liang Z, Guo J, Wu B. Nutritional value and advances of mealworm (Tenebrio molitor) as a sustainable functional ingredient in bakery products: A key step toward sustainable diets. Future Foods. 2025;12:100716. https://doi.org/10.1016/j.fufo.2025.100716

113. Faria AA, Kang J. It's not just about the food: Motivators of food patterns and their link with sustainable food neophobia. Appetite. 2022;174:106008. https://doi.org/10.1016/j.appet.2022.106008

114. García-Barón SE, Carmona-Escutia RP, Herrera-López EJ, Leyva-Trinidad DA, Gschaedler-Mathis A. Consumers' Drivers of Perception and Preference of Fermented Food Products and Beverages: A Systematic Review. Foods. 2025;14:713. https://doi.org/10.3390/foods14050713

115. Estay K, Proserpio C, Cattaneo C, Laureati M. Children's food neophobia across different socioeconomic backgrounds in Chile: Exploring acceptance and willingness to try unfamiliar vegetables. Food Qual Prefer. 2025;129:105511. https://doi.org/10.1016/j.foodqual.2025.105511

116. Günden C, Atakan P, Yercan M, Mattas K, Knez M. Consumer Response to Novel Foods: A Review of Behavioral Barriers and Drivers. Foods. 2024;13:2051. https://doi.org/10.3390/foods13132051

117. Granato D, Mocan A, Câmara JS. Is a higher ingestion of phenolic compounds the

View Article Online
DOI: 10.1039/D6FB00080K

best dietary strategy? A scientific opinion on the deleterious effects of polyphenols in vivo. Trends Food Sci Technol. 2020;98:162–6. https://doi.org/10.1016/j.tifs.2020.01.010

118. Arce-Reynoso A, Mateos R, Mendivil EJ, Zamora-Gasga VM, Sáyago-Ayerdi SG. Bioavailability of bioactive compounds in Hibiscus sabdariffa beverage as a potential anti-inflammatory. Food Research International. 2023;174:113581. https://doi.org/10.1016/j.foodres.2023.113581

119. Wu H, Liu Z, Lu P, Barrow C, Dunshea FR, Suleria HAR. Bioaccessibility and bioactivities of phenolic compounds from roasted coffee beans during in vitro digestion and colonic fermentation. Food Chem. 2022;386:132794. https://doi.org/10.1016/j.foodchem.2022.132794

120. Mechi D, Baccouri B, Martín-Vertedor D, Abaza L. Bioavailability of Phenolic Compounds in Californian-Style Table Olives with Tunisian Aqueous Olive Leaf Extracts. Molecules. 2023;28:707. https://doi.org/10.3390/molecules28020707

121. Li CX, Wang FR, Zhang B, Deng ZY, Li HY. Stability and antioxidant activity of phenolic compounds during in vitro digestion. J Food Sci. 2023;88:696–716. https://doi.org/10.1111/1750-3841.16440

122. Ribnicky DM, Roopchand DE, Oren A, Grace M, Poulev A, Lila MA, et al. Effects of a high fat meal matrix and protein complexation on the bioaccessibility of blueberry anthocyanins using the TNO gastrointestinal model (TIM-1). Food Chem. 2014;142:349–57. https://doi.org/10.1016/j.foodchem.2013.07.073

123. Mandalari G, Vardakou M, Faulks R, Bisignano C, Martorana M, Smeriglio A, et al. Food Matrix Effects of Polyphenol Bioaccessibility from Almond Skin during Simulated Human Digestion. Nutrients. 2016;8:568. https://doi.org/10.3390/nu8090568

124. Liu H, Wang Y, Wang Y, Wang J, Hu H, Zhong X, et al. Effective Identification of Variety and Origin of Chenpi Using Hyperspectral Imaging Assisted with Chemometric Models. Foods. 2025;14:1979. https://doi.org/10.3390/foods14111979

125. Cirrincione F, Ferranti P, Ferrara A, Romano A. A critical evaluation on the valorization strategies to reduce and reuse orange waste in bakery industry. Food Research International. 2024;187:114422. https://doi.org/10.1016/j.foodres.2024.114422

126. Mohamed MFS, Yu Y-L, Wang L-H, Lin M-K, Chao J. Advances in phytochemistry, pharmacology, and sustainable utilization of orange peels. Int J Food Prop. 2026;29. https://doi.org/10.1080/10942912.2026.2637277

127. Danciu C-A, Mag A-G, Stanciu C, Vidu L, Stanciu M. Valorization of Plant-Based Food By-Products Through Green Extraction of Bioactive Compounds for Functional Food. Molecules. 2026;31:646. https://doi.org/10.3390/molecules31040646

128. Yadav S, Malik K, Moore JM, Kamboj BR, Malik S, Malik VK, et al. Valorisation of Agri-Food Waste for Bioactive Compounds: Recent Trends and Future Sustainable Challenges. Molecules. 2024;29:2055. https://doi.org/10.3390/molecules29092055

129. Zheng S, Huang Z, Dong L, Li D, Hu X, Chen F, et al. Sustainable Extraction Technology of Fruit and Vegetable Residues as Novel Food Ingredients. Foods. 2025;14:331. https://doi.org/10.3390/foods14020331

130. Bhadange YA, Carpenter J, Saharan VK. A Comprehensive Review on Advanced

View Article Online
DOI: 10.1039/D6FB00080K

Extraction Techniques for Retrieving Bioactive Components from Natural Sources. ACS Omega. 2024;9:31274–97. https://doi.org/10.1021/acsomega.4c02718

131. Angioletti Decker BL, Fonteles TV, Fernandes FAN, Rodrigues S. Green extraction technologies for valorising Brazilian agri-food waste. Sustainable Food Technology. 2026;4:62–88. https://doi.org/10.1039/D5FB00323G

132. Laureati M, De Boni A, Saba A, Lamy E, Minervini F, Delgado AM, et al. Determinants of Consumers' Acceptance and Adoption of Novel Food in View of More Resilient and Sustainable Food Systems in the EU: A Systematic Literature Review. Foods. 2024;13:1534. https://doi.org/10.3390/foods13101534

133. Lima Nascimento LG, Odelli D, Fernandes de Carvalho A, Martins E, Delaplace G, Peres de sá Peixoto Júnior P, et al. Combination of Milk and Plant Proteins to Develop Novel Food Systems: What Are the Limits? Foods. 2023;12:2385. https://doi.org/10.3390/foods12122385

134. Núñez-Pérez J, Burbano-García JL, Espín-Valladares R, Lara-Fiallos M V., DelaVega-Quintero JC, Cevallos-Vallejos M, et al. Cascade Valorisation of Lemon Processing Residues (Part II): Integrated Biorefinery Design, Circular Economy, and Techno-Economic Feasibility. Foods. 2026;15:1041. https://doi.org/10.3390/foods15061041

135. Lan Z, Zhang X, Cai X, Pan W, Li W, Sun Y, et al. Metabolite profiling and 'dryness'-like effect analysis of 'Chenpi' plant tea (Citri Reticulatae Pericarpium peel) with and without steaming peocessing. Food Research International. 2025;206:116089. https://doi.org/10.1016/j.foodres.2025.116089

136. Liu Y, Wen H, Kong J, Hu Z, Hu Y, Zeng J, et al. Flavor characterization of Citri Reticulatae Pericarpium (Citrus reticulata 'Chachiensis') with different aging years via sensory and metabolomic approaches. Food Chem. 2024;443:138616. https://doi.org/10.1016/j.foodchem.2024.138616

137. Yang D, Wu X, Shi H, Zhang J, Wang C. Essential aroma substances and release pattern of Xinhui Chenpi. Beverage Plant Research. 2022;2:1–8. https://doi.org/10.48130/BPR-2022-0022

Figure 1. *Citrus reticulata* fruit and its dried pericarp (Chenpi).

(a) (b)

Figure 2. Chenpi-based products.

Table 1. Most common volatile compounds in Chenpi, including content, the aroma description, and odour activity value (OAV).

Number	Volatile compounds	Content (mg/kg)	Odour activity value (OAV)	Aroma description	References
1	α-Pinene	43.78 - 1550	273 – 3127.014	Fresh, camphor, earthy woody odour, pine-like, and herbal	[28,135,136]
2	β-Pinene	170 - 1160	26 - 36	Woody-green pine-like smell, herbal, and pungent	[28,136]
3	β-Myrcene	31.782 - 1930	3427 - 21188.2	Ethereal, resinous, soapy, spicy odour, woody, and pungent	[28,135]
4	α-Terpinene	3.47 - 250	1.45 – 2.38	Woody, lemon-flavored, and orange	[28,135,137]
5	d-Limonene	3291.64 - 78360	11720 - 24026.58	Citrus, ethereal, fruity	[28,135–137]

				odour, and spicy	
6	γ-Terpinene	130.53 - 13280	6.54 – 130.53	Pine-like smell, woody, lemon-flavoured, sweet, and floral	[28,135–137]
7	Terpinolene	110 - 700		Citrus flavor	[28]
8	Linalool	20 – 561.39	368 - 20049.61	Aniseed, citrus, floral, terpene (pleasant scent), and sweet	[28,136,137]
9	Citronellal	20 - 80	-	Japanese pepper tree, floral, and lemon scent	[28]
10	(+)-4-terpineol	40 – 370.81	57.94	Camphoraceous, earthy, musty odour (pleasant), and woody	[28,137]

11	(S)-(−)-Perillaldehyde	20 – 70	-	Minty and herbal	[28]
12	Thymol	20 - 70	381.80	Herbal, pleasant aromatic odour, and medicine	[28,137]
13	Carvacrol	30 – 40	3 - 5	Spicy and citrusy	[28,136]
14	Dimethyl anthranilate	30 - 740	23917 - 28563	Floral, pepper, spicy, and citrus	[28,136]
15	(−)-β-caryophyllene	10 - 110	-	Spicy	[28]
16	2-Methoxy-4-vinylphenol	253.67	13351.10	Pungent and floral	[137]
17	Geraniol	16.99	1699.27	Rose	[137]
18	Octanal	78.71	342.23	Orange flavour	[137]
19	α-terpineol	4.92 - 250.54	15.66 - 291.32	Floral and woody	[137]
20	β-Ionone	1.94	231.49	Woody	[137]
21	Cymenol	29.62	164.56	Pungent and refreshing	[137]

22	1-Octanol	3.32	144.30	Oily and fruity	[137]
23	(-)-Carvone	6.18	92.26	Mint and spicy	[137]
24	Furfural	274.80	91.60	Nut	[137]
25	Nonanal	6.45	64.50 - 364	Oily, sweet, and orange	[136,137]
26	n-Decanoic acid	7.17	55.19	Floral	[137]
27	1-Nonanol	10.10	10.10	Orange scent	[137]
28	Copaene	3.36	1.61	-	[135]
29	Decanal	-	573 - 669	Fresh and spicy	[136]
30	α-Phellandrene	-	7 - 8	Cream and fruity	[136]

Table 2. Extraction of polysaccharides from Chenpi.

Extraction method	Environment impact	Key findings	References
Hot water extraction	Low-medium	The yield of 8.9% Molecular weight of 55.4 kDa.	[80]
Hot water extraction	Low-medium	The yield ranges from 17% to 18.6%, and the yield decreased with increasing the storage time (from 5 – 20 years).	[81]
Hot water extraction	Low-medium	The yield of 4.28%. The monosaccharide composition (mol %): Arabinose (49.68%), galacturonic acid (26.02%), galactose (10.70%), rhamnose (5.25%), glucose (4.34%), mannose (3.26%), and xylose (0.73%). In an animal model (male Balb/c mice), treatment with extracted pectin (50 mg/kg and 250 mg/kg) alleviated gastric lesions, decreased oxidative stress, and suppressed inflammatory responses in alcohol-induced mice.	[83]
Hot water extraction	Low-medium	The monosaccharide composition (mol %): galacturonic acid (64.7%), arabinose (16.8%), galactose (13.7%), rhamnose (2.9%), and glucose (1.9%). In a high-fat diet-induced Casper zebrafish model of non-alcoholic fatty	[82]

		liver disease, incorporation of extracted polysaccharides into zebrafish feed (10 µg/mL and 40 µg/mL) ameliorated hepatic steatosis, and this effect was enhanced with increasing treatment time and dosage.	
Acid extraction (using HCl)	High	The yield reached 25.77% under the optimised extraction conditions, namely, the liquid-to-solid ratio at 25:1 (v/w), temperature of 80 °C, pH of 0.5, and extraction time of 90 min. The molecular weight of extracted polysaccharides obtained from different storage time (0, 1, 5, 10, and 15 years) ranged from 10 – 16 kDa, whereas the longest-aged Chenpi obtained the lowest molecular weight of polysaccharide (10.57 kDa). The degree of esterification ranged from 54.68% - 72.40%.	[38]
Fermentation (*Bacillus licheniformis*)	Low	The molecular weight of 3.72 kDa. The solubility of 189.85 mg/mL. The monosaccharide molar ratio of arabinose (31.75%), galactose (24.77%), galacturonic acid (20.94%), fucose (7.83%), rhamnose (7.53%), glucose (4.08%), mannose (1.93%), and glucuronic acid (1.15%).	[93]

		In vitro fermentation, the extracted polysaccharides increased the relative abundances of *Bacteroides*, *Parabacteroides*, *Phascolarctobacterium*, and *Lachnospira*, and decreased the relative abundances of *Shigella*, *Megamonas*, and *Haemophilus*	
Ultrasound-assisted extraction	Low	The yield of 7.0% was under optimised extraction conditions, namely a liquid-to-solid ratio of 30:1 (v/w), pH of 4.4, temperature of 90 °C, powder of 250 W, and extraction time of 20 min. The molecular weight of 122.0 kDa. The monosaccharide ratio (mol %): galacturonic acid (51.17%), arabinose (25.63%), galactose (12.25%), and glucose (5.46%). In an animal model, the addition of extracted polysaccharides (60 mg/kg/d) to the feed of male mice (high fat diet, 45% fat, 16.8 kcal/g diet) for 4 weeks reduced body weight and adipose tissue accumulation. The extracted polysaccharides stimulated the growth of *Lactobacillus johnsonii*.	[88]

View Article Online
DOI: 10.1039/D6FB00080K

Data Availability Statement

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.