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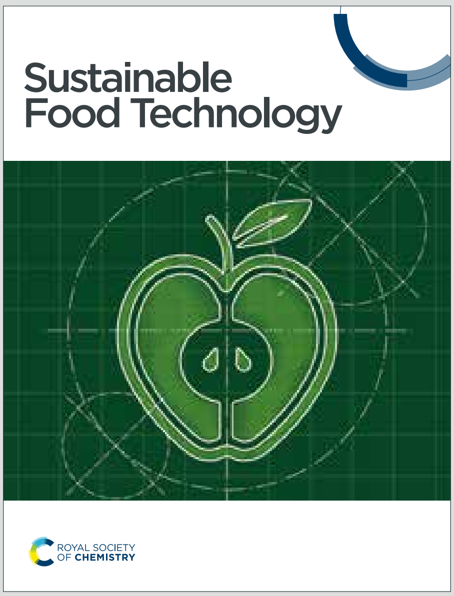

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Sustainability spotlight

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.

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

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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

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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

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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

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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’-

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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

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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

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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

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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

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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

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[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%

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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

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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%),

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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*,

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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

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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

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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

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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

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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

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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.

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Competing interests

The authors declare that they have no competing or interests.

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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.

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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]

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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.