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Nutritional values, bioactive compounds and health benefits of purslane (*Portulaca oleracea* L.): a comprehensive review

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ABSTRACT

Portulaca oleracea L., commonly known as purslane, is a worldwide weed species belonging to the family Portulacaceae and has been known as "Global Panacea". As one of the most widely consumed green vegetables and medicinal plants around the world, it has recently been re-evaluated as a potential "new crop" due to the properties that differentiate it as one of the best vegetable sources of omega-3 fatty acid (α-linolenic acid), as well as a variety of nutrients and phytochemicals. Accordingly, emerging research has found that purslane exhibits health-promoting properties like anti-inflammatory, anti-hyperglycemic, antioxidant, neuroprotective, and immunomodulatory. These findings suggest that this species possesses a potential using as a dietary supplement beyond potherb and traditional medicine. This review systematically summarizes the up-to-date research carried out on purslane, including the nutritional compositions, bioactive compounds, and health benefits it exerts as well as limitations, challenges, and future directions of research. Finally, we hope that this review would provide purslane with a comprehensive reference and future scope as functional and health-promoting food for disease prevention and treatment.

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1. Introduction

Purslane (*Portulaca oleracea* L.) is a succulent annual herb of the family Portulacaceae, widely distributed in temperate and tropical regions throughout the world. It is considered a very invasive species and used to be ranked as the 8 most common weed worldwide. Furthermore, being ubiquitously used as a potherb in the Mediterranean, central European, and Asian countries, purslane is also known as "Global Panacea"[1]. Purslane has smooth, reddish, mostly prostrate stems, and alternate leaves clustered at stem joints and ends, which resembles horse tooth; the yellow flowers have 5 regular parts and are up to 6 mm wide in sessile terminal heads; seeds are small and dark brown with small warty convex. Purslane has a taproot with fibrous secondary roots and is endowed with the ability of tolerating poor, compacted soils as well as drought. As a cosmopolitan green vegetable, fresh purslane is commonly consumed as a green salad or potherb, while the seeds can be crushed into a powder and blended in cereals for use in bread, gruels, and hotcakes[2]. Purslane possesses high nutritional value mainly benefits from its constituents such as omega-3 fatty acids, carotenoids, vitamins, minerals, etc. There is a growing interest towards functional foods, which can be defined as foods that, besides providing nutrients and energy, affect beneficially one or more target functions in the body and thus promoting health[3]. Being characterized by superior nutritional functions to normal green leafy vegetables[4], purslane is becoming a promising nutritional supplement for human health and attracting more and more focus in recent years.

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Besides nutritional value, the medicinal value of purslane should not be underestimated. Purslane is listed as one of the most widely used medicinal plants in the world by the World Health Organization. As a homology of medicine and food in China, the dry aerial parts of purslane can be used as traditional Chinese medicine to treat eczema, erysipelas, snake bites, metrorrhagia, and metrostaxis[5], while the ethnopharmacological uses in other countries vary slightly. For example, the leaves and seeds of purslane are utilized to cure cardiovascular complaints and circulatory diseases in Nepal[1]. Accordingly, there have been reports of purslane exerting biological functions such as anti-inflammatory, anti-hyperglycemic, antioxidant, immunomodulatory[6-9], etc. It has been identified that purslane contained polysaccharides, alkaloids, flavonoids, and other phytochemicals, these chemical compositions were closely related to the biological activities reported.

Previous reviews mainly focused on the phytochemical and pharmacological properties of purslane and they were not comprehensive enough to provide an overview of the current research progress on purslane[1,10-13]. With an aim to support the current trend of purslane becoming a functional food, this review comprehensively provides a basis for better understanding of the phytochemical profiles and healthy benefits on purslane, facilitating the development of potential food and medicinal applications. In this review, a database of the nutritional compounds in purslane was compiled, the latest reports about bioactive phytochemicals and health benefits of purslane have been summarized. Finally, conclusions and prospects of research on purslane are proposed.

2. Nutritional value

As a rich source of nutritional composition, purslane has earned the nickname "longevity vegetable" in China. Water is the major constituent of fresh purslane, covering 88.5%−94.78% fresh weight (FW)[2,14-17]. The ash and carbohydrate content are 1.37%−11.18% FW and 3.39%−5.20% FW, respectively, while the protein content reaches 5.2% FW[2,14-15,17]. In the following part, the composition along with nutritional functions of fatty acids (FAs), amino acids, carotenoids, vitamins, and minerals of purslane are introduced in detail.

2.1 FAs

FAs are carboxylic acids with long aliphatic chains which might be straight or branched, saturated or unsaturated. Human body can't synthesize omega-3 fatty acids, the major classes of polyunsaturated fatty acids (PUFAs), which means that they must be obtained from dietary sources. Omega-3 fatty acids, increasingly recognized as necessity for healthy growth and development, are playing an indispensable role in preventing and treating of cancer, coronary artery disease, hypertension, diabetes, arthritis, and other inflammatory and autoimmune diseases[18]. Current studies indicate that purslane contains the higher amount of omega-3 fatty acids, especially α-linolenic acid (ALA) than any green leafy vegetable[19-20]. A study compared the content of omega-3 fatty acids and antioxidants in edible wild plants including spinach, buttercrunch lettuce, red leaf lettuce and mustard greens, the results showed that purslane is the richest source of omega-3 fatty acids among the green leafy vegetables examined[20]. The FAs profile of purslane involving 27 FAs[21]. Among them, the most abundant were reported to be linoleic acid (25.09%−32.90%), palmitic acid (23.43%−26.89%), linolenic acid (17.91%−28.40%), and oleic acid (9.70%−15.09%)[22].

The FAs profile in purslane differed among the plant parts, harvesting stages, genotypes, and growth conditions. A previous study examined total FAs concentrations at three stages of harvest (6-, 10-, and 14-true-leaf stages) of purslane and found that purslane leaves harvested at the 14-true-leaf stage had similar PUFAs concentrations with those at the 6-true-leaf stage, but they showed higher omega-6/omega-3 ratio as compared with the leaves harvested at the 6-true-leaf stage[23]. Low omega-6/omega-3 ratio (< 2) is important for a proper equilibrium between these two FAs in human body, thus playing an indispensable role in the effective functioning of the cardiovascular system[24]. Nemzer and co-workers reported the total FAs content in purslane was highest in the leaves (332.49 mg/100 g, dry weight for wild purslane)[19]. Liu et al.[25] also found that the total FAs (linolenic acid and omega-3 acid) accounted for 58.0%–62.5% in the leaves and 9.6%–24.0% in the stems.

2.2 Amino acids

Besides FAs, purslane also contains a wide variety of amino acids. It was found that cultivated purslane contains higher amounts of amino acids than wild[19]. Essential amino acids like leucine ((1 463.00 ± 5.77) mg/100 g dry weight (DW)), valine ((976.00 ± 9.85) mg/100 g DW), lysine ((978.00 ± 13.50) mg/100 g DW), phenylalanine ((853.00 ± 7.51) mg/100 g DW), isoleucine ((801.00 ± 9.17) mg/100 g DW), threonine ((759.00 ± 5.51) mg/100 g DW), histidine ((346.00 ± 3.21) mg/100 g DW), and methionine ((316.00 ± 27.68) mg/100 g DW) have been detected in cultivated purslane. Additionally, the non-essential amino acids with a relative higher amount are glutamic acid ((2 187.0 ± 11.6) mg/100 g DW), aspartic acid ((1 640 ± 0) mg/100 g DW), alanine ((1 213.00 ± 15.28) mg/100 g DW), and arginine ((957.00 ± 2.00) mg/100 g DW)[19].

2.3 Carotenoids

Apart from the pronounced content in FAs, other extremely important nutrients, such as carotenoids are also present in purslane. Carotenoids are pigments that are found in plants, a wide range of animals (in feathers, beaks, exoskeletons, and fish skin), algae, fungi, and bacteria. In addition to providing color to these organisms, carotenoids are also engaged in photosynthesis and act as antioxidant defenses[26]. Several types of carotenoids were detected and quantified in purslane including α-carotene (0.009 mg/100 g FW), β-carotene (3.5 mg/100 g FW), lutein (5.4 mg/100 g FW), and zeaxanthin (0.19 mg/100 g FW)[27]. Another study also found that neoxanthin and violaxanthin presented in purslane, with content of 0.73 and 11.47 mg/100 g DW, respectively[28].

2.4 Vitamins

Vitamins, known as a micronutrient, which is required in small quantities. Vitamins are usually regarded as natural antioxidants. Purslane is rich in vitamins, such as vitamin C, vitamin E, vitamin K, and B-complex vitamins like riboflavin, niacin, and pyridoxine. Nemzer et al. compared the nutrient compositions of cultivated and wild

purslane and found that cultivated purslane contained greater amounts of vitamins than that of wild one[19]. Specifically, the highest vitamins presenting in cultivated purslane is vitamin C (152 mg/100 g DW) in comparison with the wild purslane (140 mg/100 g DW), followed by vitamin E (11 967 μg/100 g DW *vs.* 7 793 μg/100 g DW), vitamin K (1 383 μg/100 g DW *vs.* 907 μg /100 g DW).

2.5 Minerals

Both macroelements and microelements in purslane have been reported. Among them, K ((6 400.00 ± 141.07) mg/100 g DW), Mg ((1 266.67 ± 20.82) mg/100 g DW), and Ca ((914.33 ± 17.95) mg/100 g DW) are relatively abundant in cultivated purslane, whereas P ((281.67 ± 3.21) mg/100 g, DW), Na ((35.07 ± 1.72) mg/100 g DW), Mn ((6.77 ± 0.12) mg/100 g DW), Cu ((1.18 ± 0.02) mg/100 g DW), Fe ((41.73 ± 0.67) mg/100 g DW), Zn ((6.62 ± 0.18) mg/100 g DW), and Se ((6.63 ± 0.20) μg/100 g DW) exist in relative lower amount[19].

3. Bioactive compounds

Bioactive compounds are non-nutrient ingredients found in foods, being capable of modulating physiological processes and resulting in the promotion of better health[29]. Natural bioactive compounds are drawing increasing attention because of their diverse medicinal properties and extensive applications in various commercial sectors such as food, cosmetic, and pharmaceutical industries. However, the component index of purslane has not been specified and it remains unclear which ingredient contributes most to purslane's healthy benefits. For example, in the *Pharmacopoeia of the People's Republic of China* (2020 edition)[5], only the criteria for identifying authenticity of purslane were specified, the markers or component index for quality control of purslane are absent. Thus, exploring the phytochemical profiles of purslane has been the subject of intense investigation over the last few decades, yet advances are still constantly occurring. Therefore, in this section, major classes of bioactive compounds isolated from purslane such as polysaccharides, alkaloids (**1**–**79**), flavonoids (**80**–**91**), and other phytochemicals (**92**–**109**) were compiled and discussed.

3.1 Polysaccharides

As an emerging type of natural product with high added value, plant polysaccharides exhibit low toxicity and various biological activities[30], such as immunomodulatory, antibacterial, antidiabetic, and prebiotic activity[31-34]. Ginseng polysaccharides and Astragalus polysaccharides have been successfully applied in clinical practice, while bottlenecks arose in determining the structure of bioactive polysaccharides[35]. All of these confer both prospects and challenges for exploiting bioactive polysaccharides in biomedical applications.

It is reported that carbohydrate content of purslane reaches about 5.20% FW. As a major active component isolated from purslane, polysaccharide has been studied extensively. Previous studies revealed that purslane polysaccharides (PPs) exhibited anti-cancer, antioxidant, anti-diabetes, and other biological activities[36-39]. Hot water extraction along with alcohol precipitation method is the primary method for extracting PPs. Further purification is performed either by DEAE-cellulose chromatography based on ion exchange or Sephadex/Sephacryl chromatography based on size exclusion, or a combination of both. Accumulating evidences suggest that PPs are mainly composed of acidic polysaccharides[40-42]. The earliest reported PPs was a mucilage isolated from fresh leaves of purslane and consists of esterified galacturonic acid residues joined by *α*-(1→4)-linkages, named homogalacturonan (HG), which is the most abundant pectic polysaccharide, constituting 65% of total pectin[43]. In one recent study, a linear non-esterified homogalacturonan (POPW-HG) (around 41.2 kDa) was purified from the aerial parts of purslane (Fig. 1). Further bioactivity evaluation preliminarily indicated that POWP-HG could increase an antibody response, Th1 and Th2 immune response[42]. It is a common phenomenon that acetylation and methyl-esterification of specific carbons (C2, C3 and C6, respectively) occur on the galacturonic acid moiety in pectin. Previous study found pectin esterification is affected by its development stage, source, and extraction conditions[44]. Another reported acidic PP (POWP-H) was rhamnogalacturonan I (RG-I) composed of Rha (15.7%), Ara (31.7%), Gal (42.5%), and GalA (10.1%), whose weight-average molecular weight (M_w) is 1.2 × 10^6 g/mol. The chemical structural of POWP-H was deduced by its degraded product POWP-H-H (Fig. 1), which had the RG-I backbone with short side chain of *β*-Gal*p*-(1→4)-*β*-Gal*p*-(1→ attached at the *O*-4 position of →2,4)-*α*-Rha*p*-(1→. Combining methylation analysis and nuclear magnetic resonance (NMR) analysis, POWP-H might be a highly branched and acetylated RG-I backbone surrounded by abundant *α*-Ara*f*-(1→ as terminal ends, and numerous →3,6)-*β*-Gal*p*-(1→ as well as minor →2,3,5)-*α*-Ara*f*-(1→, →3,4,6)-*β*-Gal*p*-(1→, →3,4)-*β*-Gal*p*-(1→, →4,6)-*β*-Gal*p*-(1→ as branching points. The polydispersity index (PDI = M_w/M_n) of POWP-H was 1.6, and solution conformation analysis revealed that POWP-H was highly branched and adopted a flexible conformation[45].

In addition to acidic PPs whose structures were elucidated, neutral PPs also present in purslane. However, the neutral PPs composition varied considerably among different research results. In one study, the neutral faction obtained from purslane composed of 41% of arabinose (Ara) and 43% of galactose (Gal) residues, besides traces of rhamnose (Rha) residues[43], while another study reported a neutral PP consisted of glucose (Glc), mannose (Man), and Ara with small amounts of Gal, presuming it might be an arabino glucomannan[46]. Zhao et al.[36] reported a slightly different water-soluble neutral PP (named POL-P3b), analysis of monosaccharides showed that glucose and galactose were the major constituent of POL-P3b, and the molar ratio was 0.75:1.00. Though, the chemical structure of POL-P3b has not been thoroughly described, the related pharmacological activities were reported successively. POL-P3b possessed inhibitory activity on cervical cancer cell growth *in vitro* and *in vivo*, and its antitumor mechanism involves inhibition of toll-like receptor 4 (TLR4)/nuclear factor-κB (NF-κB) signaling pathway, which decreased the release of cytokine/chemokine and vascular endothelial growth factor (VEGF) and induced apoptosis in HeLa cell[36-47].

Although the pharmacological activity of PPs have been continuously verified, the objects involved in pharmacological research were crude polysaccharides or polysaccharides whose structure has not been fully characterized. Challenges in the characterization of the PPs will undoubtedly limit the further study such as structure-activity relationship elucidation and structural modification. Partial hydrolysis is an effective method

for characterizing polysaccharides with complex structure because structural information of degraded products will assist the characterization of polysaccharides. Besides, chemical methods such as methylation, periodate oxidation, and controlled Smith degradation combined with advanced high-resolution NMR, matrix-assisted laser desorption/ionization time of flight mass spectrometry (MALDI-TOF-MS) as well as size exclusion chromatography with multi-angle laser light scattering (SEC-MALLS) technologies make it possible to finely characterize structure of PPs in the future[48].

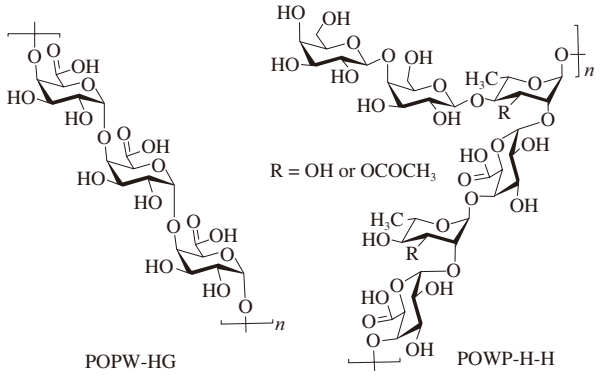


Fig. 1 Chemical structures of characteristic polysaccharides present in purslane.

3.2 Alkaloids

Alkaloids are structurally diverse compounds that are generally classified according to the basic character of the molecule (from Latin *alkali*) and a presence of at least one nitrogen atom, preferably in a heterocycle[49]. With a variety of biological effects on humans and other animals, alkaloids are widely applied as drugs in modern medicine such as morphine, quinine, ephedrine, and nicotine[50]. Phytochemical investigations of purslane reveal that it contains common alkaloids including *N-trans*-feruloyltyramine, dopa, dopamine (**34**), noradrenaline, thymine, and uracil[10]. It was found that the amount of dopamine in purslane leaves is as high as 0.69%, DW. In comparison, norepinephrine is only 0.074%, DW[51]. Liang et al.[52] developed a microwave extraction (MWE)-ultra performance liquid chromatography (UPLC)-(+/−)-multiple reaction monitor (MRM) method to extract and quantify 8 alkaloids from ten different natural sources of purslane. The results showed the contents of these alkaloids in purslane from different sources varied considerably. The final level of bioactive compounds can be affected by environmental factors, culture conditions, harvesting time, different extraction solvents and approaches[53-54]. Therefore, the endeavor needs to be made to establish a robust quality assessment system for the purslane.

Table 1
Bioactive alkaloids in purslane and their contribution to biological potential.

Compounds	Potential activity	Testing subjects	Results	Positive control	Reference
Oleracein A (**1**)	Anti-oxidant	DPPH radical quenching	EC_{50} = (8.96 ± 0.19) μmol/L	Vitamin C EC_{50} = (11.70 ± 0.22) μmol/L	[58]
Oleracein B (**2**)			EC_{50} = (5.56 ± 0.11) μmol/L		
(*S*)-(−)-Oleracein E (**48**)			EC_{50} = (9.87 ± 0.08) μmol/L	Caffeic acid EC_{50} = (4.97 ± 0.09) μmol/L	
Oleracein F (**3**)			EC_{50} = (21.00 ± 0.10) μmol/L	Butylated hydroxyanisole EC_{50} = (15.26 ± 0.72) μmol/L	[59]
Oleracein G (**4**)			EC_{50} = (37.69 ± 0.75) μmol/L	Vitamin C EC_{50} = (16.44 ± 0.44) μmol/L	
Oleracein C (**5**)			EC_{50} = 38.28 μmol/L	Vitamin C EC_{50} = 30.15 μmol/L	[56]
Oleracein D (**6**)			EC_{50} = 34.55 μmol/L		
Oleracein K (**7**)			EC_{50} = 15.30 μmol/L		
Oleracein L (**8**)			EC_{50} = 16.13 μmol/L		
Oleracein N (**9**)			EC_{50} = 29.05 μmol/L		
Oleracein O (**10**)			EC_{50} = 27.64 μmol/L		
Oleracein R (**11**)			EC_{50} = 31.58 μmol/L		
Oleracein S (**12**)			EC_{50} = 35.41 μmol/L		
Oleraindole A (**18**)			IC_{50} = (16.20 ± 0.11) μmol/L	Butylated hydroxyanisole (BHA) EC_{50} = (53.13 ± 0.36) μmol/L	[60]
Oleraindole B (**19**)			IC_{50} = (13.88 ± 0.06) μmol/L		
Oleraciamide E (**22**)			IC_{50} = (24.64 ± 0.33) μmol/L	BHA, EC_{50} = (56.39 ± 0.53) μmol/L	[61]
Iseluxine (**41**)			EC_{50} = 9.98 μmol/L	Vitamin C EC_{50} = 20.72 μmol/L	[62]
Portulacatone (**63**)			EC_{50} = 14.36 μmol/L		
Betacyanin (**21**)	Cognitive improvement	*D*-Gal-induced neurotoxicity mice	Increase the activities of SOD nearly to 76.5% of the control group (50 mg/kg body weight)	Vitamin C improves the SOD activities to 70% of the control group (50 mg/kg body weight)	[63]
(7′*R*)-*N*-Feruloyl normetanephrine (**23**)		Human lung cancer cell lines A549	IC_{50} = 24.54 μmol/L	Adriamycin IC_{50} = 1.22 μmol/L	[64]
N-trans-Feruloyl tyramine (**24**)			IC_{50} = 37.20 μmol/L		
(3*R*)-3,5-Bis(3-methoxy-4-hydroxy-phenyl)-2,3-dihydro-2(1*H*)-pyridinone (**66**)			IC_{50} = 28.80 μmol/L		
1,5-Dimethyl-6-phenyl-1,2-dihydro-1,2,4-triazin-3(2*H*)-one (**76**)			IC_{50} = 21.76 μmol/L		
Oleraciamide D (**67**)	Cytotoxic	Human neuroblastoma cell lines SH-SY5Y	Show cytotoxicity against SH-SY5Y cells when treat with 50 μmol/L	/	[65]

Table 1 (*Continued*)

Compounds	Potential activity	Testing subjects	Results	Positive control	Reference
6,9,11-Trihydroxybenzo[1,3] dioxolo[4,5-c]phenanthridin-5(4*H*)-one (**68**)		Human lung cancer cell lines A549	IC_{50} = 11.62 μmol/L	Doxorubicin IC_{50} = 4.33 μmol/L	
6,11-Dihydroxy-8,9-dimethoxybenzo[1,3]-dioxolo[4,5-c] phenanthridin-5(4*H*)-one (**69**)		Human breast adenocarcinoma cell lines MCF-7	IC_{50} = 17.86 μmol/L	Doxorubicin IC_{50} = 15.53 μmol/L	[66]
Lycoricidine (**71**)			IC_{50} = 19.50 μmol/L		
Oxynorchelerythrine (**70**)		Human colorectal cancer cell lines HCT116	IC_{50} = 18.49 μmol/L	Doxorubicin IC_{50} = 12.91 μmol/L	
Oleraindole A (**18**)			IC_{50} = (55.12 ± 0.20) μmol/L	Eserine IC_{50} = (33.53 ± 0.15) μmol/L	[60]
Oleraindole B (**19**)			IC_{50} = (46.76 ± 0.08) μmol/L		
Oleraindole D (**20**)			IC_{50} = (58.78 ± 0.36) μmol/L	Eserine IC_{50} = (31.92 ± 0.11) μmol/L	[67]
Oleraciamide G (**42**)			IC_{50} = (65.71 ± 0.15) μmol/L		
Oleraciamide E (**22**)			IC_{50} = (52.43 ± 0.33) μmol/L	Eserine IC_{50} = (32.11 ± 0.10) μmol/L	[61]
Benzamide (**31**)			IC_{50} = (113.65 ± 1.30) μmol/L		
(*E*)-*p*-Coumaramide (**32**)			IC_{50} = (117.52 ± 1.12) μmol/L		
(*E*)-Ferulamide (**33**)			IC_{50} = (121.77 ± 0.72) μmol/L		
β-Carboline-3-carboxylic acid (**55**)			IC_{50} = (67.65 ± 0.87) μmol/L		
2,3,4,9-Tetrahydro-1*H*-pyrido[3,4-*b*] indole-3-carboxylic acid (**57**)	Anticholinesterase	Acetylcholinesterase	IC_{50} = (63.71 ± 0.83) μmol/L	Eserine IC_{50} = (29.74 ± 0.14) μmol/L	[68]
(1*S*,3*S*)-1-Methyl-1,2,3,4-tetrahydro-*β*-carboline-3-carboxylic acid (**58**)			IC_{50} = (65.41 ± 0.90) μmol/L		
soyalkaloid A (**59**)			IC_{50} = (62.22 ± 1.02) μmol/L		
Oleraurea (**79**)			IC_{50} = (65.69 ± 0.86) μmol/L		
Portulacatone B (**61**)			IC_{50} = (50.49 ± 0.17) μmol/L		
Portulacatal (**62**)			IC_{50} = (58.37 ± 0.30) μmol/L	Eserine IC_{50} = (38.31 ± 0.13) μmol/L	[69]
Oleracone L (**65**)			IC_{50} = (46.00 ± 0.22) μmol/L		
Oleraisoindole A (**73**)			IC_{50} = (60.40 ± 0.82) μmol/L	Eserine IC_{50} = (34.47 ± 0.50) μmol/L	[70]
Oleracrylimide A (**28**)			Inhibit the release of IL-1β at 10 μmol/L and TNF-α at 5 μmol/L		
Oleracrylimide B (**29**)			Inhibit the release of IL-1β at 10 μmol/L and TNF-α at 5 μmol/L	Dexamethasone inhibits the release of IL-1β and TNF-α at 10 μmol/L	[71]
Oleracrylimide C (**30**)			Inhibit the release of IL-1β at 20 μmol/L and TNF-α at 10 μmol/L		
Oleracein X (**13**)			NO inhibition = 38.9% IL-6 inhibition = 82.4% (treat with 10 μmol/L)		
Oleracein Y (**14**)			NO inhibition = 38.8% IL-6 inhibition = 74.2% (treat with 10 μmol/L)		
Oleracein Z (**15**)			NO inhibition = 34.7% IL-6 inhibition = 81.0% (treat with 10 μmol/L)		
Oleracein ZA (**16**)			NO inhibition = 45.7% IL-6 inhibition = 75.6% (treat with 10 μmol/L)		
Oleracein ZB (**17**)			NO inhibition = 22.4% IL-6 inhibition = 63.2% (treat with 10 μmol/L)		
(*E*)-*N*-[4-(*β*-*D*-Glucopyranosyloxy)-phenethyl]-3-(4-hydroxyphenyl) acrylamide (**25**)			NO inhibition = 40.0% IL-6 inhibition = 76.2% (treat with 10 μmol/L)		
(*E*)-*N*-[3-Hydroxy-4-(*β*-*D*-glucopyranosyloxy)phenethyl]-3-(4-hydroxyphenyl)acrylamide (**26**)			NO inhibition = 34.5% IL-6 inhibition = 74.7% (treat with 10 μmol/L)	Quercetin NO inhibition =54.6% IL-6 inhibition = 74.9%	
(*E*)-3-[4-(*β*-*D*-Glucopyranosyloxy)-3-methyoxyphenyl]-*N*-[2-(4-hydro-xy-3,5-dimet-hoxyphenyl)ethyl]-2-propenamide (**27**)			NO inhibition = 24.3% IL-6 inhibition = 54.6% (treat with 10 μmol/L)		[72]

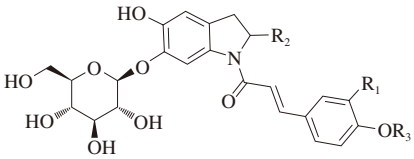
Table 1 (*Continued*)

Compounds	Potential activity	Testing subjects	Results	Positive control	Reference
(−)-(*S*)-3-Hydroxy-1-(3,4-dihydroxy-phenethyl) pyrrolidine-2,5-dione (**36**)	Anti-inflammation	RAW 264.7 cells	NO inhibition = 30.0% IL-6 inhibition = 78.0% (treat with 10 μmol/L)	Quercetin NO inhibition = 51.9% IL-6 inhibition = 77.4%	[73]
4-Carboxy-6,7-dihydro-9,10-dihydroxy-benzo-[*a*]quinolizinium carboxylate inner salt (**53**)			NO inhibition = 40.6% IL-6 inhibition = 81.1% (treat with 10 μmol/L)		
6,7-Dihydro-1,10,11-trihydroxy-benzo[*a*]-quinolizinium hydroxide inner salt (**54**)			NO inhibition = 27.0% IL-6 inhibition = 79.0% (treat with 10 μmol/L)		
(2*R*,3*S*,3′*S*,5*S*,6*R*)-2-Ethoxy-5-hydroxy-6-(hydroxymethyl)-2′,3′,4′,5,6,9′-hexahydro-2*H*,4*H*-spiro[pyran-3,1′-pyrido[3,4-*b*] indole]-3′-carboxylic acid (**60**)			NO inhibition = 46.9% IL-6 inhibition = 76.8% (treat with 10 μmol/L)		
(−)-(*S*,*Z*)-5-(3,4-Dihydroxybutylidene) imidazolidi-ne-2,4-dione (**74**)			NO inhibition = 29.9% IL-6 inhibition = 72.5% (treat with 10 μmol/L)		
(+)-(*S*)-2-[1-(4-Hydroxyphenethyl)-3-hydroxy-2,5-dioxopyrrolidin-3-yl] acetic acid (**37**)			NO inhibition = 34.8% IL-6 inhibition = 73.3% (treat with 10 μmol/L)		
(−)-(*R*)-2-[1-(4-Hydroxyphenethyl)-3-hydroxy-2,5-dioxopyrrolidin-3-yl] acetic acid (**38**)			NO inhibition = 23.0% IL-6 inhibition = 69.1% (treat with 10 μmol/L)		
(+)-(*S*)-2-[1-(3,4-Dihydroxyphenethyl)-3-hydroxy-2,5-dioxopyrrolidin-3-yl]acetic acid (**39**)			NO inhibition = 55.8% IL-6 inhibition = 76.3% (treat with 10 μmol/L)		
(−)-(*R*)2-[1-(3,4-Dihydroxyphenethyl)-3-hydroxy-2,5-dioxopyrrolidin-3-yl]acetic acid (**40**)			NO inhibition = 41.6% IL-6 inhibition = 71.2% (treat with 10 μmol/L)		
Dopamine (**34**)			EC_{50} = 18.0 μmol/L	3,4-Dihydroxybenzohydroxamic acid EC_{50} = 82.4 μmol/L	
2-Sulfonic acid dopamine (**35**)			EC_{50} = 309.9 μmol/L		
(*S*)-(−)-Salsolinol (**43**)			EC_{50} = 58.7 μmol/L		
6,7-Dihydroxy-1-methyl-3,4-dihydroisoquinoline (**44**)			EC_{50} = 209.2 μmol/L		
6,7-Dihydroxy-3,4-dihydroisoquinoline (**45**)			EC_{50} = 247.6 μmol/L		
(*R*)-(+)-1-Isobutyl-6,7-dihydroxy-1,2,3,4-tetrahydroisoquinoline (**46**)			EC_{50} = 497.7 μmol/L		
(*R*)-(+)-1-Benzyl-6,7-dihydroxy-1,2,3,4-tetrahydroisoquinoline (**47**)			EC_{50} = 106.9 μmol/L		
(*S*)-(−)-Oleracein E (**48**)			EC_{50} = 35.4 μmol/L		
1-(5′-Hydroxylmethylfuran-2-yl)-6,7-dihydrox-y-3,4-dihydroisoquinoline (**49**)			EC_{50} = 203.4 μmol/L		
1-(Furan-2-yl)-6,7-dihydroxy-3,4-dihydroisoquinoline (**50**)			EC_{50} = 18.1 μmol/L		

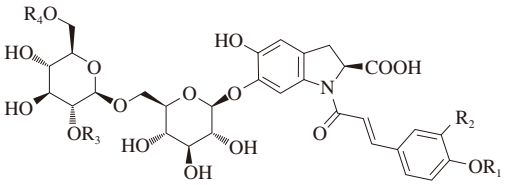
Purslane alkaloids (**1**–**79**) with a wide range of bioactivity are summarized in Fig. 2 and Table 1. Among them, betacyanin (**21**), a water-soluble pigments betalains with neuroprotective effects was found. Similar to betalains, a type of water-soluble indoline amide glycosides (**1**–**20**) was firstly isolated from purslane in 2005[55]. As the characteristic chemical markers of purslane, indoline amide glycosides contain 5,6-dihydroxyindoline-2-carboxylic acid moieties and are acylated with *p*-coumaric or ferulic acid[56]. The content of two major indoline amides oleracein A (**1**) and oleracein B (**2**) were determined to be (2.49 ± 0.11) and (2.35 ± 0.09) mg/g, respectively. Total indoline amides were (9.76 ± 0.57) mg/g (calculated by oleracein A) or (15.12 ± 0.88) mg/g (calculated by oleracein B) using HPLC-UV method[57].

3.3 Flavonoids

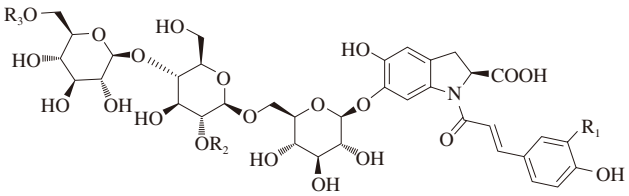
Being widely distributed in plants, flavonoids are another representative bioactive component found in purslane. The flavonoid content of fresh purslane was 0.3 mg quercetin/100 g FW[74]. While Spina et al.[75] reported that wild and cultivated purslane had 0.46–0.54 mg quercetin/100 g DW. Siriamornpun et al.[76] determined the phytochemicals from different morphological parts of purslane and found the flavonoid content were leaf > flower > stem. A variation of the major type of flavonoid present in different parts also be observed. Specifically, rutin is the major flavonoid found in leaf, while myricetin is the highest in flower and stem. The relevant biological potential exerted by flavonoids characterizing purslane are summarized in Fig. 3 and Table 2.



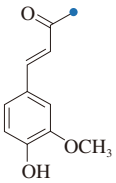
1	R_1 = H	R_2 = COOH	R_3 = H
2	R_1 = OCH_3	R_2 = COOH	R_3 = H
3	R_1 = OCH_3	R_2 = β-$COOCH_3$	R_3 = H
4	R_1 = H	R_2 = β-$COOCH_3$	R_3 = H
5	R_1 = H	R_2 = β-COOH	R_3 = Glucose
6	R_1 = OCH_3	R_2 = β-COOH	R_3 = Glucose



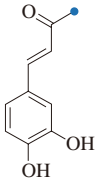
7	R_1 = H	R_2 = H	R_3 = Caffeoyl	R_4 = H
8	R_1 = H	R_2 = OCH_3	R_3 = Caffeoyl	R_4 = H
9	R_1 = H	R_2 = H	R_3 = Feruloyl	R_4 = H
10	R_1 = H	R_2 = OCH_3	R_3 = Feruloyl	R_4 = H
11	R_1 = Glucose	R_2 = H	R_3 = Feruloyl	R_4 = H
12	R_1 = H	R_2 = H	R_3 = H	R_4 = Feruloyl
13	R_1 = H	R_2 = OCH_3	R_3 = Sinapoly	R_4 = H



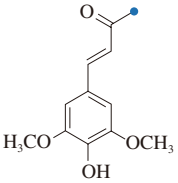
14	R_1 = H	R_2 = R_3 = Caffeoyl	
15	R_1 = H	R_2 = Caffeoyl	R_3 = Feruloyl
16	R_1 = OCH_3	R_2 = Feruloyl	R_3 = H
17	R_1 = OCH_3	R_2 = Feruloyl	R_3 = Sinapoyl



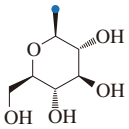
Feruloyl



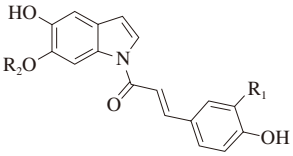
Caffeoyl



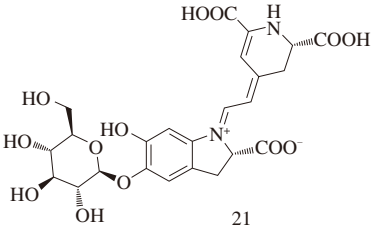
Sinapoyl



Glucose



18	R_1 = H	R_2 = H
19	R_1 = OCH_3	R_2 = H
20	R_1 = H	R_2 = Glucose



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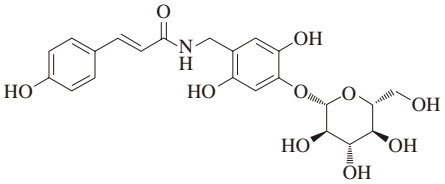

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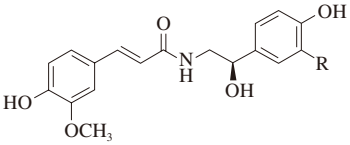
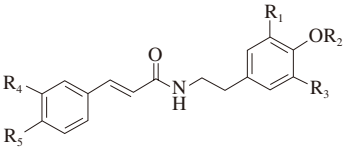
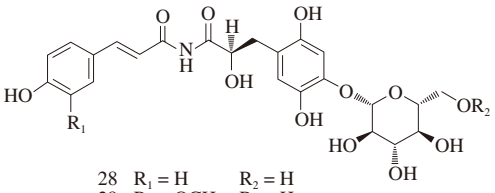


23 R = OCH_3
24 R = H

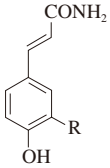


25	R_1 = R_3 = R_4 = H	R_2 = Glucose	R_5 = OH
26	R_1 = R_4 = H	R_2 = Glucose	R_3 = R_5 = OH
27	R_1 = R_3 = R_4 = OCH_3	R_2 = H	R_5 = *O*-Glucose

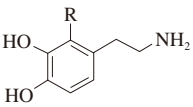


28	R_1 = H	R_2 = H
29	R_1 = OCH_3	R_2 = H
30	R_1 = OCH_3	R_2 = Glucose

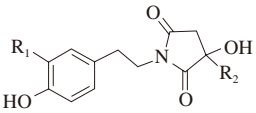
31



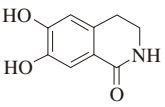
32 R = H
33 R = OCH_3



34 R = H
35 R = HSO_3



36	R_1 = OH	R_2 = α-H
37	R_1 = H	R_2 = β-CH_2COOH
38	R_1 = H	R_2 = α-CH_2COOH
39	R_1 = OH	R_2 = β-CH_2COOH
40	R_1 = OH	R_2 = α-CH_2COOH



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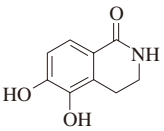

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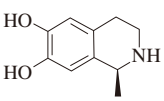

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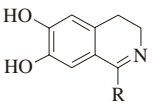
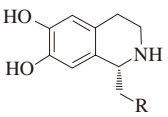
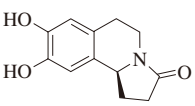


44 R = CH_3
45 R = H



46 R = Isopropyl
47 R = Phenyl



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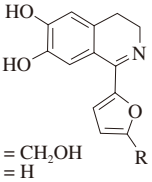
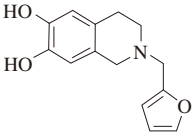


49 R = CH_2OH
50 R = H



51

Fig. 2 Chemical structures of bioactive alkaloids (**1-79**) present in purslane.

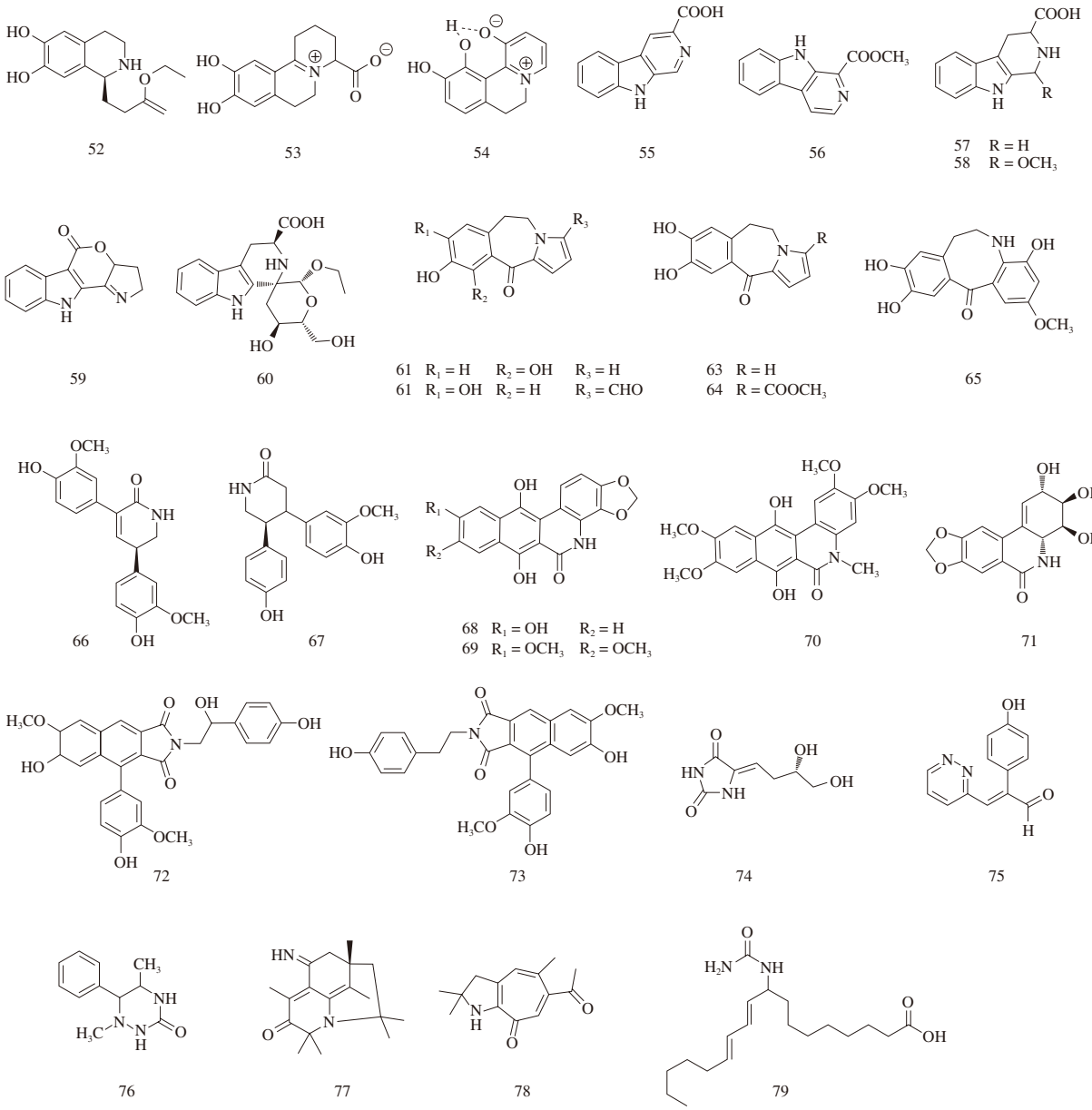


Fig. 2 (*Continued*)

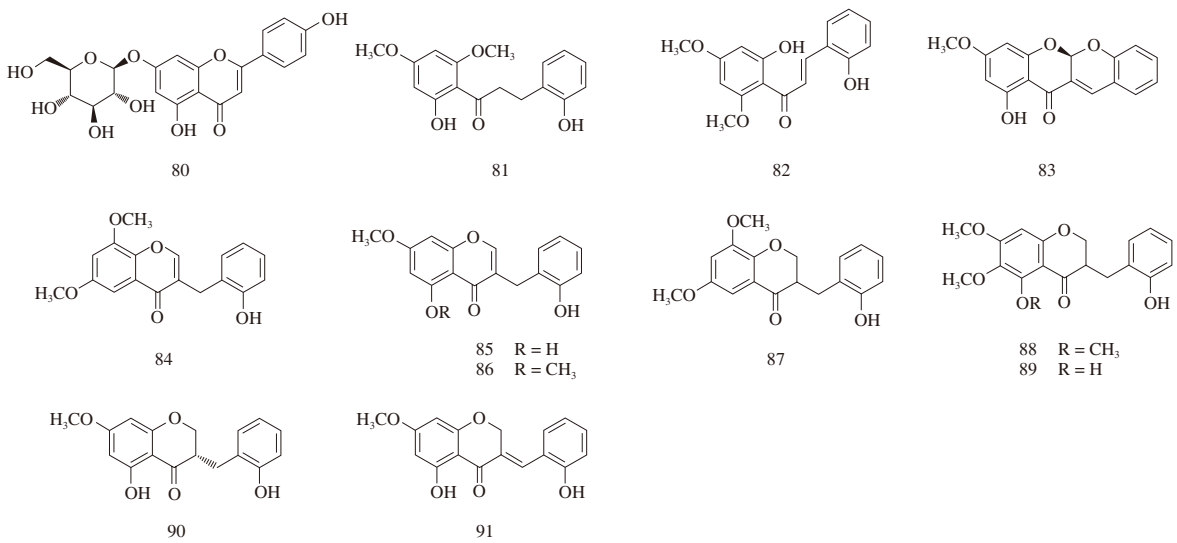


Fig. 3 Chemical structures of bioactive flavonoids (**80–91**) present in purslane.

Table 2
Bioactive flavonoids in purslane and their contribution to biological potential.

Compounds	Potential activity	Testing subjects	Results	Positive control	Reference
Apigenin (**80**)	Antibacterial	*Pseudomonas aeruginosa*, *Salmonella typhimurium*, *Proteus mirabilis*, *Klebsiella pneumoniae*, *Enterobacter aerogenes*	MIC > 4 mg/mL	/	[77]
Oleracone E (**81**)	Anti-oxidant	DPPH radical quenching	IC_{50} = (13.72 ± 0.07) μmol/L	Butylated hydroxyanisole IC_{50} = (59.14 ± 0.04) μmol/L	[78]
	Anticholinesterase	Acetylcholinesterase	IC_{50} = (78.85 ± 0.16) μmol/L	Eserine IC_{50} = (31.13 ± 0.02) μmol/L	
Oleracone D (**85**)	Anti-oxidant	DPPH radical quenching	IC_{50} = (12.02 ± 0.02) μmol/L	Butylated hydroxyanisole IC_{50} = (59.14 ± 0.04) μmol/L	
	Anticholinesterase	Acetylcholinesterase	IC_{50} = (59.56 ± 0.50) μmol/L	Eserine IC_{50} = (31.13 ± 0.02) μmol/L	
Oleracone C (**90**)	Anti-oxidant	DPPH radical quenching	IC_{50} = (23.53 ± 0.03) μmol/L	Butylated hydroxyanisole IC_{50} = (59.14 ± 0.04) μmol/L	
	Anticholinesterase	Acetylcholinesterase	IC_{50} = (68.87 ± 0.09) μmol/L	Eserine IC_{50} = (31.13 ± 0.02) μmol/L	
2,2′-Dihydroxy-4′,6′-dimethoxychalcone (**82**)	Cytotoxic	SGC-7901 cell line	IC_{50} = 1.6 μg/mL	Cisplatin IC_{50} = 1.6 μg/mL	[79]
		K-562 cell line	IC_{50} = 24.6 μg/mL		
Portulacanone B (**88**)		SGC-7901 cell line	IC_{50} = 16.2 μg/mL		
		NCI-H460 cell line	IC_{50} = 17.8 μg/mL		
			IC_{50} = 20.1 μg/mL		
Portulacanone C (**89**)	Anti-adipogenic	Mouse 3T3-L1 adipocytes	Reduce the expression levels of *FABP4*, *FATP1*, *ACS1* (treat with 10 μmol/L)	/	[80]
Oleracone F (**86**)	Anti-oxidant	DPPH radical quenching	IC_{50} = 17.78 μmol/L	Butylated hydroxyanisole IC_{50} = (56.96 ± 1.20) μmol/L	[81]
(*E*)-5-Hydroxy-7-methoxy-3-(2-hydroxyben-zyl)-4-chromanone (**91**)	Anti-diabetic	Mouse 3T3-L1 adipocytes	Increase glucose uptake by 1.8-fold (treat with 5 μmol/L)	/	[82]
		Rat skeletal muscle cell lines	Increase the glucose uptake by 1.27-fold (treat with 1 μmol/L)	/	[83]
		Palmitate-induced insulin resistance L6 skeletal muscle cells	Increase glucose uptake by (0.93 ± 0.05)-fold; increase glycogen synthesis by (79.57 ± 5.90)% (treat with 50 μmol/L)		[84]
		INS-1 pancreatic β cells	Increase insulin secretion to 9.61 ng/h (treat with 1 μmol/L)	/	[85]
	Anti-inflammation	RAW 264.7 cell lines	Decrease the expression of pro-inflammatory cytokines (TNF-α, IL-1β, IL-6) (treat with 10 μmol/L)	/	[86]
	Anti-adipogenesis	3T3-L1 adipocytes	Decrease the triglyceride levels by 45% and increase glycerol release by 192% (treat with 30 μmol/L)	Hydroxy citric acid reduces the triglyceride levels by 42% and increases glycerol release by 196% (treat with 50 μmol/L)	[87]
Oleracone G (**83**)	Anti-inflammation	RAW 264.7 cell lines	Decrease the secretion of IL-1β (treat with 10 μmol/L)	/	[88]
Oleracone J (**84**)	Anti-oxidant	DPPH radical quenching	IC_{50} = 27.57 μmol/L	Butylated hydroxyanisole IC_{50} = (56.08 ± 0.03) μmol/L	[89]
			IC_{50} = 18.34 μmol/L	Butylated hydroxyanisole IC_{50} = 57.41 μmol/L	
	Anticholinesterase	Acetylcholinesterase	IC_{50} = 59.08 μmol/L	Eserine IC_{50} = (33.26 ± 0.03) μmol/L	
Oleracone K (**87**)	Anti-oxidant	DPPH radical quenching	IC_{50} = 23.92 μmol/L	Butylated hydroxyanisole IC_{50} = 57.41μmol/L	
	Anticholinesterase	Acetylcholinesterase	IC_{50} = 67.89 μmol/L	Eserine IC_{50} = (33.26 ± 0.03) μmol/L	

Among them, HM-chromanones (homoisoflavones) (**80**–**91**) are the major type. However, as the key compounds accountable for the antioxidant activity of the purslane, a positive correlation between antioxidant activity and the total flavonoid content of purslane has not been verified yet.

3.4 Others

Additionally, lignans and aromatics are also present in purslane, as well as esters. Their structures (Fig. 4) have been investigated and scientific evidences have been produced regarding relevant biological and pharmacological activities (Table 3), among which phenylpropanoids **102** and **103** possess rare halogen chlorine and nitro substitutions.

4. Health benefits

As a medicinal and edible plant, purslane is considered as functional sources for human health promoting. Multiple studies have highlighted the wide range of pharmacological activities of different purslane-derived constituents, whose unequivocal benefits have been well documented, both through *in vitro* and *in vivo* studies (Fig. 5). In this section, purslane extracts, fractions, and pure compounds with biological properties will be recapitulated and discussed in details (Tables 4 and 5).

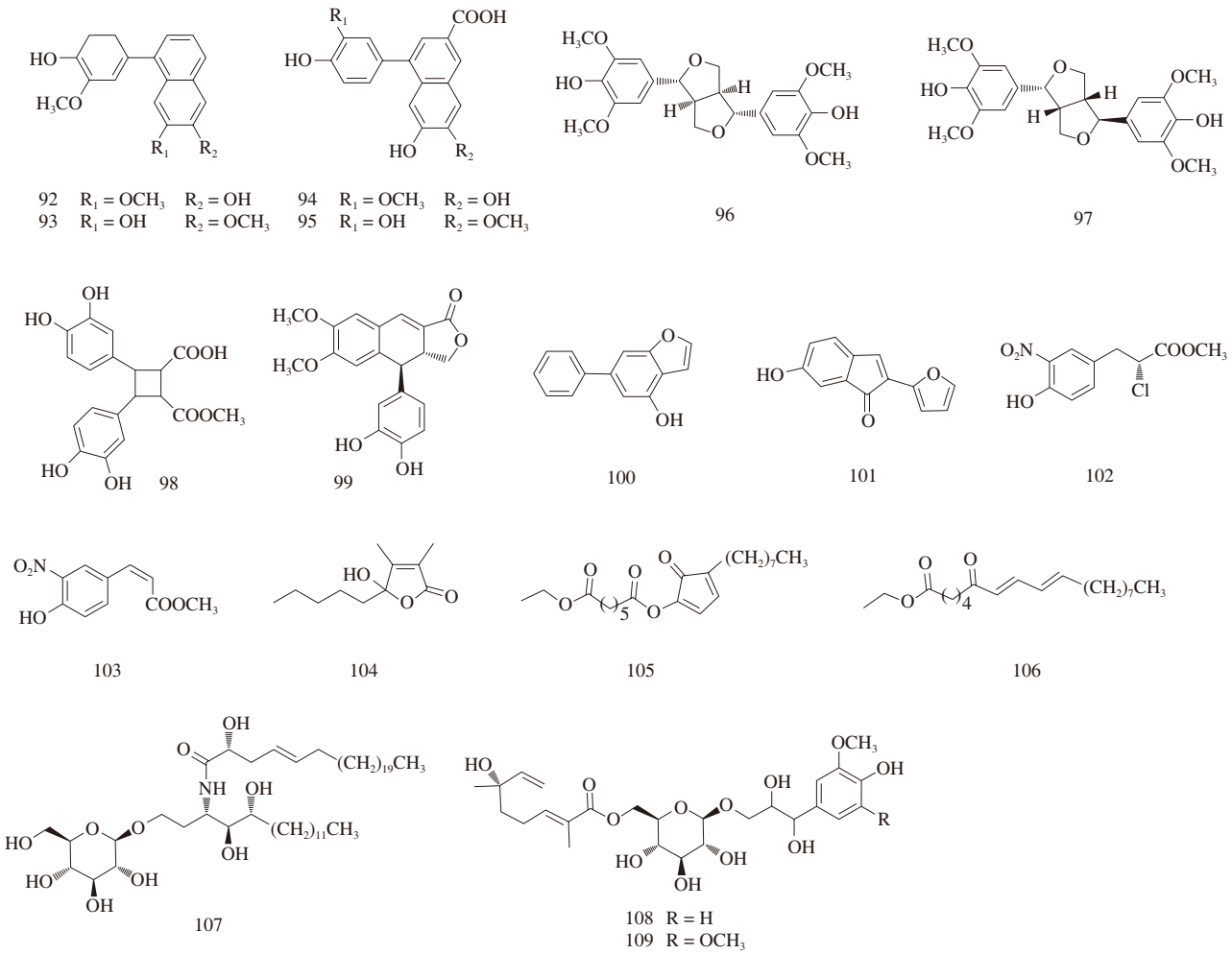


Fig. 4 Chemical structures of other bioactive (**92–109**) phytochemicals present in purslane.

Table 3
Other bioactive phytochemicals in purslane and their contribution to biological potential.

Chemical class	Compounds	Potential activity	Testing subjects	Results	Positive control	Reference
Lignans	Oleralignan (**92**)	Anti-oxidant	DPPH radical quenching	IC_{50} = 20.64 μmol/L	Butylated hydroxyanisole IC_{50} = (33.85 ± 0.24) μmol/L	[90]
	(+)-Syringaresinol (**96**)			IC_{50} = 17.34 μmol/L		
	(+)-Lirioresinol A (**97**)			IC_{50} = 16.46 μmol/L		
	Monomethyl-3,3′,4,4′-tetrahydroxy-*δ*-truxinate (**98**)			IC_{50} = 8.00 μmol/L		
	Oleralignan C (**94**)			IC_{50} = (21.02 ± 0.05) μmol/L	Butylated hydroxylanisole IC_{50} = (58.33 ± 0.03) μmol/L	[91]
	Oleralignan D (**95**)			IC_{50} = (20.81 ± 0.02) μmol/L		
	Oleralignan B (**93**)			IC_{50} = 20.12 μmol/L	Butylated hydroxyanisole IC_{50} = (56.08 ± 0.03) μmol/L	[88]
		Anti-inflammation	RAW 264.7 cell lines	Decrease the secretion of IL-1β (treat with 20 μmol/L)	/	
	Oleralignan A (**99**)	Anticholinesterase	Acetylcholinesterase	IC_{50} = (58.31 ± 0.23) μmol/L	Eserine IC_{50} = (33.05 ± 0.13) μmol/L	[92]
Aromatics	Olerabenzofuran (**100**)	Anti-inflammation	RAW 264.7 cells	Inhibit IL-1β production at 10 μmol/L	Dexamethasone inhibits IL-1β production at 10 μmol/L	[93]
	Oleraindenone (**101**)			Inhibit IL-1β production at 20 μmol/L		
	(2*R*)-(+)-2-Chloro-3-(3-nitro-4-hydroxyphenyl)-methyl propionate (**102**)	Antimicrobial	*Candida albicans* ATCC 90028	MIC = 256 μg/mL	Amphotericin B MIC = 0.125 μg/mL	[94]
	cis-3-(3-Nitro-4-hydroxyphenyl)-methyl acrylate (**103**)	Anti-inflammation	RAW 264.7 cells	EC_{50} = 18.0 μmol/L	/	

Table 3 (*Continued*)

Chemical class	Compounds	Potential activity	Testing subjects	Results	Positive control	Reference
Esters	Hydroxydihydrobovolide (**104**)	Cytotoxicity	SH-SY5Y cell lines	Inhibit cell growth when treat with 50 μmol/L	/	[95]
	1-Ethyl 7-(4-octyl-5-oxocyclopenta-1,3-dien-1-yl) heptanedioate (**105**)	Anticholinesterase	Acetylcholinesterase	IC_{50} = (63.87 ± 0.54) μmol/L	Eserine IC_{50} = (33.98 ± 0.23) μmol/L	[96]
	Ethyl (7*E*,9*E*)-6-oxooctadeca-7,9-dienoate (**106**)			IC_{50} = (64.71 ± 0.25) μmol/L		
	Portulacerebroside A (**107**)	Cytotoxicity	Human liver cancer HCCLM3 cells	Suppress adhesion rate of the cells at 0.5 h by (58.1 ± 1.3)% when treat with 10 μg/mL	/	[97]
	9-(6-*O*-[(2*E*,6*S*)-2,6-Dimethyl-6-hy-droxy-2,7-octadienoyl]-*β*-*D*-glucop-yranosyloxy)-guaiacylglycerol (**108**)	Anti-oxidant	DPPH radical quenching	IC_{50} = (11.6 ± 0.6) μmol/L	Tocopherol IC_{50} = (14.8 ± 0.8) μmol/L	[98]
	9-(6-*O*-[(2*E*,6*S*)-2,6-Dimethyl-6-hy-droxy-2,7-octadienoyl]-*β*-*D*-glucop-yranosyloxy)-syringoylglycerol (**109**)			IC_{50} = (36.7 ± 5.7) μmol/L		

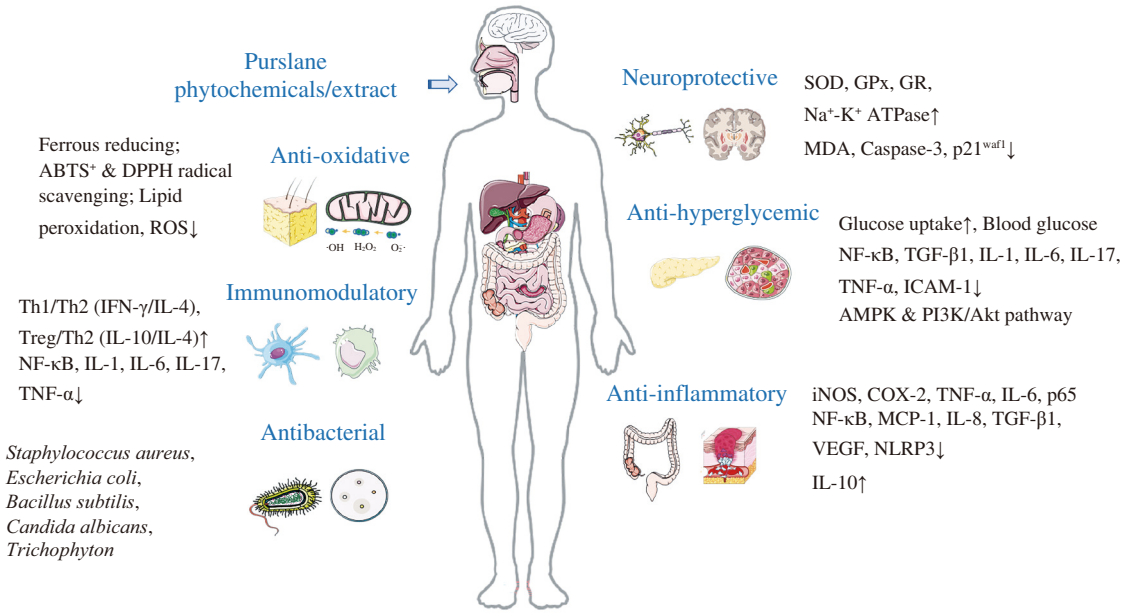


Fig. 5 Bioactivities of purslane and their underlying mechanisms/targets.

4.1 Anti-inflammatory effects

Inflammation is an essential response provided by the immune systems that ensures the survival during infection and tissue injury. Health conditions including cancer, heart disease, diabetes, arthritis, and depression, are among those linked to chronic inflammation, which contribute to more than half of deaths worldwide[99]. Thus, the discovery of phytoconstituents capable of interfering with inflammatory pathways and reducing protracted inflammation could be beneficial to human health. Purslane has significant advantages in anti-inflammatory function, which have been recognized after *in vivo* and *in vitro* studies. Lee et al.[100] reported that the aqueous extract of purslane prevented the tumor necrosis factor alpha (TNF-α)-induced vascular inflammatory process in the human umbilical vein endothelial cell (HUVEC) by inhibiting of intracellular reactive oxygen species (ROS) production and activating nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB) as well as reducing the expression of adhesion molecule. According to the study carried out in 2018[73], isoquinoline alkaloids (**43**–**52**) isolated from purslane exhibited anti-inflammatory activities by inhibiting NO production in lipopolysaccharide (LPS)-induced murine macrophage RAW 264.7 cells (EC_{50} = 18.1−497.7 μmol/L). Among these isoquinoline alkaloids, compounds **43**, **48**, **50**, and **52** were more potent than positive control 3,4-dihydroxybenzohydroxamic acid (EC_{50} = 82.4 μmol/L), with EC_{50} values of 58.7, 35.4, 18.1, and 36.3 μmol/L, respectively. It must be mentioned that dopamine, a catecholamines alkaloid obtained showed the most potential anti-inflammatory activity (EC_{50} = 18.0 μmol/L). Previous study has revealed that dopamine inhibits NLRP3 inflammasome activation via dopamine D1 receptor[101]. Indeed, almost half of the alkaloids isolated from purslane showed certain anti-inflammatory activity as shown in Table 2. These results might be a hint that various types of alkaloids in purslane contribute to the potential anti-inflammatory purslane exhibits.

In another study, the anti-inflammatory effect and potential mechanisms of purslane extract rich in flavonoids on LPS-stimulated RAW 264.7 cells were evaluated[6]. This study suggested that the mechanism of anti-inflammatory effects might be attributed to the inhibition to the protein expression of inducible nitric oxide synthase (iNOS), cyclooxygenase-2 (COX-2), and partial suppression on

Table 4
Potential bioactivity of purslane based on *in vitro* studies.

Materials tested	Functions	Potential mechanisms/targets	Results	Reference
50% Ethanolic extract	Anti-inflammatory	Reduce LPS-induced synthesis of NO and the expression levels of iNOS and COX-2; In the higher dose of 400 μg/mL, reduce the productions of TNF-α and IL-6, inhibit the expression levels of P65, p-P65, pMEK and p-IκB-α	Inhibit NO release and IL-6 production by 46.16%, 48.97%, respectively (treat with 400 μg/mL)	[6]
Aqueous extract		Inhibit the translocation of p65 NF-κB to the nucleus; Reduce the mRNA expressions of monocyte chemoattractant protein 1 and IL-8; Inhibit the intracellular ROS production	/	[100]
Polysaccharide POPs		Down-regulate the pro-inflammatory cytokine levels (IL-1β, IL- 6, TNF-α); Up-regulate cytoplasmic NF-κB p65 and down-regulate the intranuclear NF-κB p65	/	[145]
80% Ethanolic extract	Anti-hyperglycemic	Enhance glucose uptake by stimulating GLUT4 translocation to the plasma membrane through activating the PI3K and AMPK pathway	Glucose uptake increase 1.45-fold (treat with 50 μg/mL)	[7]
Polysaccharide POP		Protect INS-1 cells and enhance the insulin synthesis in INS-1 cells by partially inhibiting on I_{Na} channel	Increase insulin contents by (165.22 ± 20.74)% compared control (treat with 0.5 mg/ mL)	[146]
Polysaccharide POP		Regulate insulin secretion in INS-1 cells through voltage-gated Na^+ channel	POP at 0.05–1.00 mg/mL increased insulin secretion; 0.1 mg/mL POP downregulate the expression levels of $Na_{V1.3}$	[41]
70% Ethanolic extract	Immunomodulatory	Promote Th1/Th2 (IFN-γ/IL-4) and Treg/Th2 (IL-10/IL-4) balances	/	[126]
Aqueous extract	Anti-influenza A viruses (IAV)	Suppress the production of circulating H1N1 and H3N2 and inhibit the binding of virus to cells	EC_{50} = 220.1 μg/mL (A/WSN/1933 (H1N1)) EC_{50} = 121.6 μg/mL (A/California/07/2009 (H1N1)) EC_{50} = 112.4 μg/mL (A/Perth/16/2009 (H3N2)) EC_{50} = 191.2 μg/mL (A/Brisbane/10/2007 (H3N2))	[147]
Subcritical carbon dioxide extract	Antimicrobial	Inhibit the growth of *Staphylococcus aureus*, *Escherichia coli*, *Bacillus subtilis*, and *Candida albicans*	Growth suppression zones are 20.0, 18.0, 21.0, 15.0 mm, respectively	[135]
Ethyl acetate fraction		Against dermatophytes of the genera *Trichophyton*	Static antifungal activity (SAFA) = 64% for *T. mentagrophytes* EV861 SAFA = 70% for *T. mentagrophytes* HIC8185(treat with 100 μg/mL)	[133]
95% Ethanolic		Inhibit *Candida albicans* growth	MIC = (10.0 ± 0.2) μg/mL	[134]
85% Ethanolic extract		Against *Staphylococcus aureus*	MIC = (10.0 ± 0.1) mg/mL	[148]
Ethanolic extract	Modulate the activity of osteoclast	Suppress receptor activator of nuclear factor-κB ligand (RANKL)-induced Ca^{2+} oscillations by inhibiting Ca^{2+} release from internal Ca^{2+} stores	/	[149]
Methanolic extract & Ethyl acetate fraction	Anti-Hepatitis C virus (anti-HCV)	Inhibit the NS3 mRNA and protein level	Reduce the NS3 gene expression by 80% (methanolic extract) and 85% (ethyl acetate fraction)	[150]
Ethanol fraction	Anti-photoaging	Suppress matrix metalloproteinases and type I procollagen degradation	/	[140]
Extract		Protect human fibroblast and keratinocytes cells from UVB-induced damage	/	[141]
70% Ethanolic extract	Anti-melanogenic	Alleviate tyrosinase, tyrosinase-related protein 1 (TRP-1), TRP-2, and microphthalmia-associated transcription factor expression levels as well as melanin content	Treat with 50 μg/mL reduce cellular tyrosinase activity and extracellular melanin content than arbutin (10 mmol/L)	[151]
Methanolic extract	Anti-oxidant	$ABTS^+$ and DPPH radical scavenging ability	$ABTS^+$ and DPPH assays of the extract are 390 μmol trolox equivalent (TE)/g dried extract (DE) and 260 μmol TE/g DE	[8]
Fraction rich in phenolics		Lipid peroxidation inhibiting capacity	IC_{50} = (154.1 ± 2.5) (μg/mL); TEAC = (1.9 ± 0.3) mmol/L TE	[107]
Polysaccharides POP II and POP III		Radical scavenging ability; ferrous reducing ability; suppress ROS generation	DPPH radical scavenging activities of POP II & POP III were 35.24%, and 17.21%; POP II & POP III decreased ROS levels by 43% and 49%	[38]
Polysaccharide POL-P3b	Antitumor	Upregulate the expression of CD80, CD86, CD83, major histocompatibility complex class II molecules; Increase TLR-4 expression; stimulate cytokine production (IL-12, TNF-α)	POL-P3b (treat with 250 mg/mL) show the same effect as positive control LPS (treat with 100 ng/mL)	[130]
Polysaccharide POL-P3b		Decrease the release of cytokine/chemokine, VEGF and induced apoptosis in HeLa cells by inhibiting TLR4/NF-κB signaling pathway	/	[47]

Table 5
Potential bioactivity of purslane based on *in vivo* studies.

Materials tested	Functions	Potential mechanisms/targets	Experimental models	Reference
Petroleum ether fraction (seeds)	Anti-hyperlipidemic	Lower serum triglycerides and cholesterol level	STZ-induced mice	[137]
Aqueous extract		Reduce triglyceridemia, cholesterolemia, and improve reverse cholesterol transport	Enriched-cholesterol diet rats	[136]
Aqueous extract		Upregulate the expression of genes involve in cholesterol efflux and bile acids' synthesis; Downregulate farnesoid X receptor; Modulate AMPK activation and miR-33/34a expression in the liver	High-cholesterol diet rats	[152]
96% Ethanolic extract	Anti-inflammatory	Improve memory deficits	LPS-induced neuroinflammation rats	[24]
80% Ethanolic extract		Inhibit oxidative stress; inhibit NLR family pyrin domain containing 3 (NLRP3) inflammasome related genes (NLRP3, ASC, pro-caspase-1 and IL-1β); Modulate inflammatory cytokines and the activation of NF-κB	Zymosan-induced joint inflammation mice	[153]
80% Ethanolic extract		Increase the colon length; inhibit oxidative stress response; Reduce the mRNA expressions of pro-inflammatory cytokines (*TNF-α*, *IL-1β*, and *IL-6*)	DSS-induced ulcerative colitis C57BL/6 male mice	[102]
70% Ethanolic extract		Lower the inflammatory cytokines (IL-1β, IL-6, TNF-α); increase the anti-inflammatory cytokine IL-10; Suppress TGF-β1 and vascular endothelial growth factor (VEGF); Lower malondialdehyde level and enhance glutathione level	Surgical-induced peritoneal adhesion rats	[104]
Aqueous extract		Regulate inflammatory cytokines (TNF-α, IL-6, IL-1β), transcription factors (NF-κB and PPAR-γ), and apoptosis	DSS-induced colitis mice	[103]
Aqueous extract	Anti-oxidant	Reduce levels of blood and liver lipid peroxidation; Increase the activity of blood and liver antioxidant enzymes	High-fat diet induced mice	[108]
80% Ethanolic extract	Hepatoprotective	Decrease the serum aminotransferase level and reduce the liver histological damage	CCl_4-induced liver injury male C57 mice	[154]
80% Ethanolic extract		Preserve the histological integrity of liver cells; Improve antioxidant activity of SOD	CCl_4-induced hepatic toxicity male Wistar rats	[155]
75% Ethanolic extract		Increase the antioxidant capacity and relieve the inflammatory injury of the liver cells	50% Ethanol induced alcoholic liver injury rats	[156]
Phenolic extract	Cognition-improvement	Attenuate oxidative stress; Improve survival rate and enhance cognitive function	*D*-gal/$NaNO_2$-induced senile mice	[57]
90% Ethanolic extract	Neuroprotective	Reduce the mercury concentration and protect cerebellum and cortex against neurotoxicity	Methylmercury-induced cognitive dysfunction rats	[124]
80% Ethanolic extract		Decrease the serum neuron specific enolase level and the activity of caspase-3 in neuron; Increase the neuron viability and attenuate the pathological damages	Hypoxia exposure ICR mice	[157]
Aqueous extract		Reduce the expression of $p21^{waf1}$ mRNA and prolong telomere length; Increase the SOD activity and decrease the MDA level	*D*-gal-induced neurotoxicity mice	[158]
Fresh juice		Up-regulate glutathione peroxidase transcription; increase Na^+-K^+-ATPase activity; Increase protein carbonyl content;	Rotenone-induced neurodegeneration rats	[121]
		Decrease the number of apoptotic cells; Decrease the ROS production; Down-regulate the expression of the *caspase-3* gene	Rotenone-induced neurotoxicity rats	[122]
Polysaccharides POP		Alleviate the cognitive impairment and reverse the Pb-induced spine loss in CA1 and DG area of brain	Pb-induced cognitive dysfunction rats	[159]
Fresh plant material	Wound healing	Accelerate the wound healing process by decreasing the surface area of the wound and increasing the tensile strength	Male albino Swiss mice with wound creation	[160]
Ethanolic extract	Anti-hyperglycemic	Improve insulin levels and relieved chronic inflammation through the Rho–NF-κB pathway	STZ-induced mice	[115]
80% Ethanolic extract		Improve insulin resistance through the PI3k/Akt and AMPK pathways	C57BL/Ksj-*db/db* mice	[112]
50% Ethanolic extract		Decrease blood glucose levels and increase body weights	STZ-induced rats	[116]
Aqueous extract		Suppress hyperglycemia and diabetic vascular inflammation; Prevent the development of diabetic endothelial dysfunction and vascular complications	C57BL/KsJ-*db/db* mice	[114]
		Prevent renal fibrosis by reducing TGF-β1 through inhibition of the advanced glycation end production; Inhibit NF-κB activation and reduce intercellular adhesion molecule-1 expression	C57BL/KsJ-*db/db* mice	[161]
Seeds powder		Lower the fasting blood glucose and glycated hemoglobin levels	STZ-induced mice	[117]
Polysaccharides CPP		Decrease fasting blood glucose, total cholesterol and triglyceride; Increase high-density lipoprotein cholesterol serum insulin level	Alloxan-induced diabetic mice	[162]
Seed polysaccharide fraction PPFt		Reduce fasting blood glucose and TBARS level; Increase the activity of SOD and catalase (CAT)	STZ-induced mice	[163]
Polysaccharides CPOP		Improve the glucose tolerance; Reduce TNF-α and IL-6 levels; Reduce MDA and SOD activities	STZ-induced mice	[39]
Ethyl acetate fraction	Immunomodulatory	Ameliorate the nonspecific immune response	Cyclophosphamide -treated ICR mice	[127]
70% Ethanolic extract		Modulate body weight and colon length; Decrease NF-κB activity; Reduce the accumulation of leukocytes and downregulate proinflammatory mediators (IL-1, IL-6, IL-17, TNF-α)	Acetic acid-induced ulcerative colitis mice	[9]
Aqueous extract		Decrease the blood lymphocytes, eosinophils, basophils, and serum immunoglobulin E (IgE); Downregulate mRNA expression levels of interferon-γ (*IFNγ*), *TNF-α*, thymic stromal lymphopoietin and *IL-4*	2,4-Dinitrochlorobenzene-induced atopic dermatitis mice	[164]
Dried purslane powder	Antagonistic-Cd	Inhibit inflammation and accumulation of Cd; Enhance the activity of antioxidant enzymes; Promote the synthesis of hepatic bile acid and regulate the intestinal microbiota	Cd-treated C57BL/6 male mice	[165]
Polysaccharide POL-P3b	Antitumor	Increase apoptotic tumor cells and lower the tumor weight	U14-bearing mice	[36]
Polysaccharide POP		Increase the ratio of $CD4^+/CD8^+$ T lymphocyte; Increase the peripheral WBC count and decrease the serum AST, ALT, BUN and creatinine levels	S180-bearing mice	[37]
Polysaccharide PPs		Increase the body weight, peripheral WBC count, thymus and spleen indexes and promote splenocytes proliferation; enhance SOD, CAT, GSH-Px activities and serum cytokines (IL-2, IL-4, TNF-α)	*N*-methyl-*N*-nitro-*N*-nitrosoguanidine (MNNG)-induced gastric cancer rats	[166]

NF-κB and mitogen-activated protein kinase (MAPK) activation. Apart from this, flavonoids like luteolin, kaempferol, and quercitrin were detected from purslane extract using UPLC-MS analysis. However, whether the anti-inflammatory effect is mediated by these compounds remains unclear. Furthermore, it has been observed that the administration of purslane extract can prevent memory and TNF-α deterioration in male Wistar rats induced with LPS, thus exhibiting anti-neuroinflammation and cognitive improvement activity[24].

There are several records on the traditional use of purslane in inflammatory bowel disease symptoms such as bloody stools, diarrhea, and abdominal pain and purslane had been confirmed to be a potential agent in recent studies. In dextran sulphate sodium (DSS)-induced ulcerative colitis (UC) mice, the ethanolic extract of purslane showed protective effects by suppressing the oxidative stress and inflammatory activities. Compared to the untreated group, orally administrated with purslane extract (100 mg/kg) significantly reversed and improved weight loss, diarrhea, and colonic shortening. Moreover, it has been found that the administration of purslane extract can lead to reduced mRNA expressions of pro-inflammatory cytokines such as *TNF-α*, interleukin-1 (*IL-1β*), and interleukin-6 (*IL-6*), as well as reduced protein expressions of TNF-α and NF-κB p65[102]. Consistently, it had been observed that extract of purslane was capable of attenuating development of UC in DSS model equivalent to the treatment of mesalazine. Further exploration for potential mechanisms suggested purslane extract in the alleviation of inflammatory bowel disease could be related to its regulation of inflammatory cytokines (TNF-α, IL-6, and IL-1β), transcription factors like NF-κB, peroxisome proliferator-activated receptor-γ (PPAR-γ), and apoptosis[103]. The anti-inflammatory properties of purslane make it a therapeutic advantage for inflammation-related diseases. A study reported the therapeutic effects of the hydroethanolic extract of purslane on surgical-induced peritoneal adhesion (PA). Specifically, the extract (100 and 300 mg/kg) notably reduced inflammatory cytokines (IL-1β, IL-6, and TNF-α), fibrosis (TGF-β1), angiogenesis (VEGF), and oxidative (MDA) factors, while increased anti-inflammatory cytokine IL-10, antioxidant factor glutathione (GSH), compared to the control group[104].

From these findings, it might be inferred that the anti-inflammatory mechanisms of purslane (Fig. 6) mainly involving in inhibiting NF-κB pathway and the production of pro-inflammatory cytokines, as well as stimulating antioxidant factors.

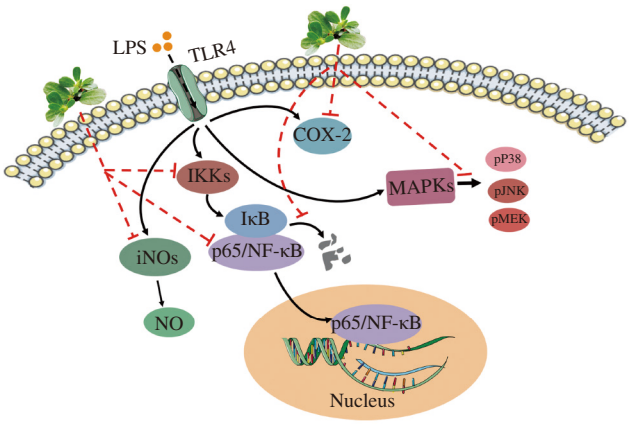


Fig. 6 Schematic representation of the potential target/mechanism of anti-inflammation activities of purslane.

4.2 Anti-oxidant effects

Studies have proved that purslane serves as a rich source of antioxidants, related to the unsaturated FAs, vitamins, and polyphenolics present in this vegetable. Lim et al.[105] compared the antioxidant properties of different purslane cultivars and found that the ornamental cultivars have higher total phenol content (TPC) ((478 ± 45) mg GAE/100 g) and antioxidant activities than the common purslane ((127 ± 13) mg GAE/100 g), which were assessed by the 1,1-diphenyl-2-picrylhydrazyl (DPPH), ferric-reducing antioxidant power (FRAP), and *β*-carotene bleaching (BCB) assays. The results also suggested that the TPC correlates well with the antioxidant activities as measured by the DPPH and FRAP assays but does not correlate with BCB activity. However, the ascorbic acid content (ACC) has no correlation with the antioxidant activities. Other than variation of antioxidant capacity among genotypes, the differences of antioxidant capacity of purslane also varied at different growth stages. The higher TPC level and antioxidant activities of mature purslane than immature one was observed via the DPPH test and the FRAP assay[106]. Another study demonstrated that TPC was the major contributors towards antioxidant activity in purslane[107]. Fraction rich in quantified phenolics (Fraction 3) was separated from the crude extract of purslane, Fraction 3 appeared to have the lowest IC_{50} in DPPH assay and the highest trolox equivalent antioxidant capacity (TEAC) valuesas well as the most potent activity in thiobarbituric acid reactive substances (TBARS) assay. Consistently, the free phenolic acids like chlorogenic, caffeic, *p*-coumaric, ferulic, rosmarinic acids, and the free flavonoids like quercetin and kaempferol were detected using standard reference compounds in this Fraction 3.

The antioxidant capacity of polysaccharide fractions (POP II and POP III) purified from purslane were evaluated. It was found that both of them possessed strong antioxidant activities both in cell-free radical generating systems and in cell-mediated radical generating systems. With regards to cell-free radical generating systems, the DPPH radical scavenging activities of POP II and POP III were 35.24% and 17.21% at 1.0 mg/mL, respectively, both POP II and POP III inhibited lipid peroxidation in a dose-dependent manner. Both POP II and POP III suppressed alloxan-induced ROS production and protect HIT-T15 cells from alloxan-induced ROS stress, contributing to anti-cytotoxic actions in cell-mediated radical generating systems[38]. Apart from *in vitro* studies, research on antioxidant potential of purslane *in vivo* had also emerged. In the high-fat-diet-induced oxidative injury mice model, the significant increase in blood and liver lipid peroxidation levels was observed, whereas the decrease of antioxidant enzymes activity was detected compared to normal control mice[108]. However, administration of purslane extract inhibited oxidative injury in a dose-dependent manner via enhancing blood and liver antioxidant enzyme activities, modulating leptin/*β*-actin (B), and liver PPARα/*β*-actin, decreasing liver, spleen FAS mRNA, p-PERK and p-PERK/PERK protein expression levels in mice.

Apart from the extract of purslane, antioxidant activity of compounds isolated has been also extensively studied. A class of characteristic ingredients are indoline amide glucosides, which exert excellent DPPH radical scavenging activity with EC_{50} values range from 15.30 to 43.52 μmol/L. Among them, the DPPH radical scavenging activity of oleracein K (**9**) and oleracein L (**10**) were

twice of vitamin C (EC_{50} = 30.15 μmol/L), and the EC_{50} were 15.30 and 16.13 μmol/L, respectively[56]. The antioxidant activity of this type ingredients was also verified by pharmacological experiments *in vivo*. The phenolic extract from purslane contained indoline amides glucosides attenuated oxidative stress, improved survival rate, and enhanced cognitive function in *D*-gal/$NaNO_2$-induced senile mice[57]. Antioxidant activity of purslane has been mainly expressed in DPPH radical scavenging capacity by researchers. For example, flavonoids obtained in purslane such as oleracone D (**85**), oleracone E (**81**) and oleracone F (**86**) exhibited tremendous potency in DPPH radical quenching with IC_{50} values range from 11.73 μmol/L to 17.78 μmol/L[78,81]. Purslane lignans like (+)-syringaresinol (**96**), (+)-lirioresinol A (**97**) and monomethyl-3,3',4,4'-tetrahydroxy-*δ*-truxinate (**98**) showed two times higher of free radical scavenging capacity than positive control butylated hydroxyanisole (IC_{50} = (33.85 ± 0.24) μmol/L)[90]. Further study is worth being conducted to explore whether polysaccharides, flavonoids, lignans, and indoline amide glycosides play a synergistic role on exerting antioxidant activity.

4.3 Anti-hyperglycemic effects

Diabetes mellitus (DM), defined as a disorder of carbohydrate metabolism characterized by impaired ability of the body to produce or respond to insulin and thereby failing to maintain proper levels of sugar (glucose) in the blood, is an emerging epidemic with a miserable impact on almost every country, age group, and economy globally. There are two types of DM, type 1 diabetes, also known as insulin-dependent diabetes mellitus (IDDM) or juvenile-onset diabetes, typically develops in childhood. Type 2 diabetes, formerly referred to as non-insulin-dependent diabetes mellitus or adult-onset diabetes, normally develops after the age of 40 and grows more common with age[109]. Glucagon-like peptide-1 (GLP-1), a target for treating diabetes, is a glucose-sensitive insulin secretagogue that can improve peripheral insulin action, prevent gastric emptying, inhibit glucagon secretion[110]. In one recent study, Cho et al.[111] evaluated the effect of 6 Korean plants on GLP-1 release and demonstrated that the purslane extract showed the highest activity in inducing GLP-1 secretion. The possible mechanism might be relevant to satiety increase and appetite suppression. Purslane has been found to exert anti-hyperglycemic properties in many investigations with a variety of biological mechanisms. One of these mechanisms involves the phosphatidylinositol 3-kinase (PI3K) and 5′-AMP-activated kinase (AMPK) pathway. Ethanolic extract from the purslane has resulted in the enhancement of glucose uptake, which was caused by stimulating glucose transporter type 4 (GLUT4) translocation to the plasma membrane through activating the PI3K and AMPK pathway in 3T3-L1 adipocytes (Fig. 7)[7]. Meanwhile, another study revealed that supplementation with purslane extract significantly lower the blood glucose and the glycosylated hemoglobin levels (HbA1c) in C57BL/Ksj-*db*/*db* mice than those in *db*/*db*-control group[112]. Additionally, lower homeostatic index of insulin resistance (HOMA-IR) and higher quantitative insulin sensitivity check index were found. Further investigation revealed that purslane extract reduced hyperglycemia by improving insulin resistance through the PI3k/Akt and AMPK pathways in the skeletal muscle of C57BL/Ksj-*db*/*db* mice.

Microvascular and macrovascular complications of DM like nephropathy, retinopathy, and neuropathy vary according to the severity and length of poorly controlled diabetes, especially if it is comorbid with other conditions like dyslipidemia and hypertension[113]. One of the most devastating consequences of DM is the effect on arteriosclerotic cardiovascular disease. Lee et al.[114] demonstrated that the extract obtained from purslane has an antidiabetic effect by prevention of the developed diabetic symptoms and suppression of diabetic vascular complications in type 2 diabetic *db*/*db* mice.

Chemically-induced rodent models of type 1 diabetes are typically established with an injection of streptozotocin (STZ) and alloxan, which are both β-cell toxic agents that can induce hyperglycemia within a few days of administration. In STZ-induced diabetic mice, purslane extract increased body weight and decreased food intake of liver injury mice, reduced inflammatory cytokines in serum and also inhibited the expression of Rho, ROCK1, ROCK2, p-NFκBp65, and p-IκBα in liver tissue. It can be concluded that purslane improved insulin levels and relieved chronic inflammation through the Rho-NFκB pathway, thus decreasing the concentration of blood glucose[115]. Another study also reported that the extract from purslane exhibited beneficial effects on blood glucose levels as well as other metabolic aberrations on a STZ-induced model[116].

Currently, research about purslane seeds is arising and mostly focus on its potential anti-hyperglycemic effects[117-119]. A study in 2021 showed that purslane seeds can lower blood glucose levels, potentially affect phosphoinositide-3-kinase regulatory subunit 1, TNF, PPAR-γ, and other targets associated with insulin resistance and inflammation through the actions of various chemical components including genistein, levodopa, and daidzein etc.[117].

In addition to purslane extract, pure phytochemicals isolated from purslane also showed anti-hyperglycemic activity, providing molecular basis to support the anti-hyperglycemic effects purslane exhibits. One study reported that a HM-chromanone, named (*E*)-5-hydroxy-7-methoxy-3-(2-hydroxyben-zyl)-4-chromanone (**91**), could increase glucose uptake in 3T3-L1 adipocytes through activating the PI3K/AKT and AMPK pathways (Fig. 7). An induction effect of GLUT4 translocation exerted by **91** is also found[82]. In another investigation conducted by Park et al, the protective effect of **91** for INS-1 pancreatic β cells was revealed. Exposure of INS-1 pancreatic β cells to glucose leads to apoptosis, while **91** treatment dose-dependently increased cell viability and significantly decreased the intracellular level of ROS, TBARS, and NO levels[85]. Additionally, the insulinotropic effect of polysaccharide from purslane, named as POP, had been revealed. POP possessed a cell protective effect by increasing the cell viability and enhanced the insulin synthesis function in INS-1 cells, which exerted anti-hyperglycemic activity in another mechanism. Further study suggested that POP induced-secretion/production of insulin were mediated by voltage-gated Na^+ channel through its change of function and subunits expression. These effects involved the change of intracellular Ca^{2+} releasing, ATP metabolism, cell membrane and mitochondrial membrane potential, etc.

In the referred studies, possible benefits of purslane for diabetic treatment were constantly revealed. However, studies on the anti-hyperglycemic activity of purslane are still limited due to the active ingredient remains unclear coupled with the in-depth mechanism study is scarce. In parallel with active ingredient mining, the mechanism of anti-hyperglycemic effects of purslane will also be necessary in order to discover functional components, innovative

therapeutic agents, or adjuvants for preventing or treating DM, which is a major health concern worldwide[120].

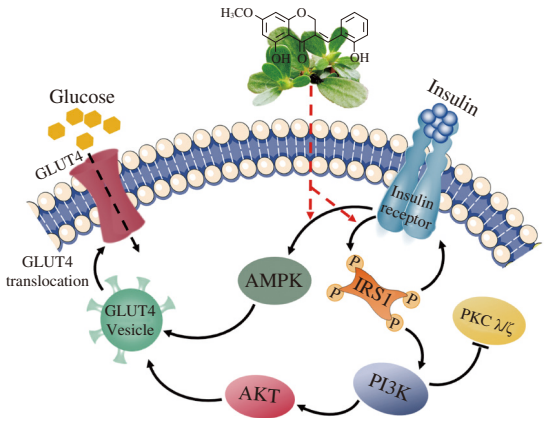


Fig. 7 Schematic representation of the potential target/mechanism of anti-hyperglycemic activities of purslane.

4.4 Neuroprotective effects

Multiple studies have highlighted the neuroprotective activity of different extracts prepared from purslane. In one of these studies, purslane juice reversed the increases in protein carbonyl and H_2O_2 that were a consequence of the oxidative stress generated by rotenone administration. Increasing evidence supports the idea that neuronal degeneration in Parkinson's disease (PD) might result from increased exposure to free radicals coupled with a deficit of antioxidant mechanisms[121]. Dietary feeding of purslane to rats has the propensity to attenuate rotenone-induced oxidative stress owing to its antioxidant nature and its ability to modulate the activities of antioxidant defenses, thus possessing promising activity against neurotoxicity. Another finding also reported the anti-apoptotic and antioxidant effects of purslane on rotenone induced brain injury in rats[122]. Purslane juice treatment significantly decreased the number of apoptotic cells and ROS production in the striatum. On the one hand, purslane contains high levels of vitamins C and E, which are powerful antioxidants that can prevent lipid peroxidation in plasma and tissue, protecting membranes, organelles, and proteins from oxidative damage. Furthermore, purslane is known to be rich in omega-3, previous finding revealed that dietary omega-3 supplementation of pregnant rats prevented hypothyroidism-induced apoptosis in the developing rat cerebellum[123]. All of these evidences imply the potential for purslane to prevent developing brain damage and neurodegenerative diseases associated with oxidative stress. Similar investigation also demonstrated that ethanolic extract of purslane had protective effect against MeHg-induced neurotoxicity *in vivo*[124]. With regard to active compounds, Wang et al.[63] once assessed the protective effect of betacyanin (**21**) isolated from purslane against the *D*-galactose-induced neurotoxicity in mice. In *D*-gal-treated mice, a decrease in antioxidant enzyme activities and an increase in the MDA level were detected, while betacyanin significantly reversed the cognitive impairments, and improved the activities of antioxidant enzymes in the mouse brain. Compared to vitamin C, betacyanin showed more pronounced effect in ameliorating cognition deficits.

4.5 Immunomodulatory effects

The immune system plays a crucial role in response to various pathogens such as allergens, bacteria, viruses, parasites, and other inflammatory stimuli, maintaining homeostasis in our body[125]. Due to the importance and complexity of the immune system, an imbalance of the immune system will consequentially induce the occurrence of various diseases including cancer, autoimmune, and infectious diseases. Thus, searching for a medication to regulate the inappropriate immune response is critical. A study involving *in vitro* assessment found that different concentrations of purslane extract promoted Th1/Th2 and Treg/Th2 balances in isolated human lymphocytes[126]. Besides, purslane extract also showed immunomodulatory activity in preventing inflammatory bowel disease. It was found that immune dysregulation plays an extremely important role in the acetic acid (AA)-induced pathogenesis of colitis, while treatment with purslane extract reduced colonic inflammation by alleviating the immune response and inhibiting the severity of colitis[9]. Ethyl acetate (EtOAc) extract of purslane conferred immunoactivity through ameliorating the immunosuppressive action of cyclophosphamide in mice, a significant increase in phagocytosis and higher proliferative response in splenic lymphocytes were observed[127].

The immunomodulatory activity of plant polysaccharides has been reported and confirmed continuously[128]. PPs also showed immunomodulatory activity and the mechanism involved inhibition of the red blood cell haemolysis, and increase of spleen, thymocyte T and B lymphocyte proliferation[129]. Another *in vivo* study reported that one of the PPs, named POP, inhibited the growth of transplantable sarcoma 180 and increased the number of white blood cells (WBC) and $CD4^+$ T-lymphocytes, as well as the ratio of $CD4^+/CD8^+$, resulting in the anti-tumor effect. Therefore, the anti-tumor effect elicited by POP could be associated with its immunomodulatory properties[37]. Another neutral PP, named POL-P3b, also showed immunomodulatory activity. POL-P3b could interact with dendritic cells (DCs) to effectively promote the maturation of DCs via the TLR4 signaling pathway and enhance the proliferation of lymphocytes[130]. Another study evaluated the potential of pre-administration of oral POL-P3b as an immunostimulatory on foot-and-mouth disease vaccines. Similarly, the results suggested that dietary POL-P3b supplementation could enhance the immune response, including humoral and cellular responses[131].

Considering these findings, the immunomodulatory activity exhibited by purslane might show the therapeutic value of this plant in disease associated with immune system disorder such as asthma or cancers.

4.6 Antibacterial activity

The rate at which new antimicrobials are being discovered is insufficient to deal with the emergence of bacteria and fungi that are resistant to the drugs available, especially in cases of drug-resistant Gram-negative bacterial infections. Given that natural products have provided the starting point for most major classes of antibiotics, including β-lactams, aminoglycosides, macrolides, tetracyclines, etc.[132], thus searching for antimicrobials from natural products has attracted much attention. EtOAc soluble fraction from purslane extract showed a specific and marked activity against dermatophytes of the

genera *Trichophyton*[133]. In another study, the anti-*Candida* activity of seven different plants was assessed, and it was found that the ethanolic extract of purslane had an antimicrobial selectivity against *Candida albicans* in its different dynamic forms of growth *in vitro* with MIC ~10 μg/mL[134]. However, which kind of component present in purslane attributed this antimicrobial power remains unclear. In one current study, the composition profile of carbon dioxide (CO_2) extract of purslane was analyzed and corresponding antimicrobial activity was explored. The results showed that this extract had the suppressed effect against clinically significant microorganisms such as *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis*, and *Candida albicans*. For the phytochemicals, triterpenoids, phytosterols, and FAs were identified from the CO_2 extract by gas chromatograph, but components that exert antibacterial activity remained unknown[135].

4.7 Other effects and uses

Other than the biological role of purslane mentioned above, beneficial effects of purslane on the improvement in hyperlipidemia[136-137], hypoxia[138], and hepatic fibrosis[139] have been reported. The anti-photoaging potency of purslane has been also proposed, with this effect being associated with the antioxidant potential of the homoisoflavonoids present in this plant[140]. Lee et al.[141] also demonstrated that purslane extract possessed the ability of protecting human fibroblast and keratinocytes cells from ultraviolet radiation B (UVB)-induced damage *in vitro*. In particular, the extract effectively reduced cell death and apoptotic DNA cleavage after UVB irradiation. These findings had provided a useful hint for the practical use of purslane in cosmetics.

Furthermore, due to the pectin-like PPs possess good stability, modifiable groups and biocompatibility, research focused on its functional modification for drug delivery has emerged recently. A study in 2018 reported the development of novel polymeric beads encapsulating the anticancer drug 5-fluorouracil, which was prepared by utilizing purslane mucilage, and this provided a new avenue for PPs application in drug discovery fields[142]. A following research designed and synthesized purslane polysaccharides-alendronate-platinum (PPS-ALN-Pt) conjugates. It revealed that cellular platinum accumulation of PPS-ALN-Pt conjugates was higher than that of cisplatin in HeLa cells, showing promising usage for preparing new chemotherapy drugs and formatting drug delivery system[143]. Natural polysaccharides can be employed to boost the therapeutic effect and improve the drug's targeting and bioavailability due to the inherent properties including nontoxicity, biocompatibility, and biodegradability[144]. PPs serves as a natural polysaccharide with good bioactivity and modifiable active groups, undoubtedly holding a promising prospect in pharmaceutical preparation industry.

5. Conclusion and future perspective

This review updates information on the possible function of purslane in various health disorders, as well as nutritional constituents and phyto-bioactive compounds. In recent years, nutraceuticals or functional foods have been raising the concerns of consumers and researchers for the reason that they provide both health benefits to reduce the risk of chronic diseases and basic nutrition. As a common weed with immense functional food potential, purslane is highly adaptable to various stress environments, this characteristic gives purslane competitive advantages over many other cultivated crops, signifying abundant reserve resource is available. Thus, further study is imperative to incorporate purslane in food industry, either as raw, minimally processed, and processed food products, or as an ingredient of food and dietary supplements and drugs.

However, throughout the research progress available yet, there are still some research dilemmas and challenges that impede us from better understanding and exploiting purslane as a source of food and non-food products. To address the current limitation we are faced with, future study should highlight and consolidate the following aspects:

1) With the upgrading of people's health consciousness, consumers attach great importance to personal health, thus varied functional foods have sprung up. Accumulating evidences suggest that purslane is an excellent source of FAs, polyphenols, dietary minerals as well as vitamins, which contribute to the application of purslane as nutraceutical ingredient. Marketed products related to purslane mainly used for health-promoting such as immunomodulatory, blood sugar regulation, and acne improvement. However, purslane was not used as the main ingredient of these products. Being known as "Global Panacea" and widely applied in coking, purslane related functional food is scarce around the market, corresponding studies are warranted to support the exploitation in nutraceutical field.

2) The aerial parts of purslane contain a high amount of antinutritional elements like oxalic acid (OA). A previous study showed the amount of oxalic acid in the wild purslane was (7 223.30 ± 17.55) mg/100 g DW[19]. High amounts of oxalic acid in diets might irritate the digestive system, especially the kidneys and stomach. Additionally, it has been closely linked to the development of kidney stones. Therefore, the presence of excessive OA has hampered commercial development of this species as an alternative vegetable crop. Palaniswamy et al have found that OA concentrations in purslane were altered by the stage of harvest and the nitrate to ammonium ratios in hydroponics[167]. Further research is warranted to systematically explore the factors that affect the content of nutrients and antinutritional components, which will guide for the optimization of purslane processing technology and pretreatment approach, maximizing nutrients and minimizing antinutritional components.

3) It is widely assumed that traditional herbal plants are harmless and free from adverse effects, especially purslane is consumed as a green vegetable, but genotoxic or systemic (liver and kidney) toxicity potentials of some beneficial herbs were also reported[168-169]. Owing to the great potential of purslane as a health food and medicine, safety profiling of purslane extract and its bioactive compounds is of utmost importance. To provide scientific basis for its widespread and secure use in food and drugs fields, toxicological evaluation is demanded in the future.

4) With regard to phytochemicals, the investigations on the active ingredients of purslane are insufficient to fulfill the current needs, failing to provide theoretical guidance for the application of purslane in medicine, health care, and cosmetics. Alkaloids and flavonoids isolated from purslane exhibit excellent activity like anti-inflammatory, antioxidant, etc., whereas these compounds are all trace amounts. Preparation technology including effective extraction and enrichment of these active ingredients, especially water-soluble components should gain increasing attention.

5) Purslane is one of the most widely used medicinal plants worldwide, effective quality control is of great significance for efficacy and safety medication. For example, though purslane has been regarding as a homology of medicine and food in China, *China Pharmacopoeia of the People's Republic of China* (2020 edition) lacks quality control items and index components of purslane[5]. Therefore, extensive and in-depth research on qualitative and quantitative analyses targeted on their physicochemical characteristics is imperative for explore index components of purslane, facilitating the establishment of quality evaluation and control system.

6) The majority of studies on purslane have focused on chemical compositions and bioactivities of small molecules. To date, a few pieces of literature concerned with purification and structural elucidation of PPs. PPs, one of the important chemical components of purslane, are characterized by high content, stable sources, and various biological activities. PPs might be the main potential active components. Therefore, future endeavor could be made to systematically elucidate the PPs structures, providing the corresponding structural basic explanation for biological activity and expediting the further interpretation of the structure-activity relationship as well as providing index ingredient for purslane quality control.

7) On the other hand, there are numerous studies on the health effects of purslane extract, but the majority of these pharmacological studies only involving a few indicators, which are limiting to reflect the underlying mechanisms of health benefits, making it impossible to make conclusive statements about its health benefits. Future pharmacological research should be conducted both *in vitro* and *in vivo*, as well as focus on bioactive compounds in purslane and the corresponding pharmacological action mechanisms they exert.

Declaration of interest statement

All authors declared that they have no conflict.

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