Overview on the Pharmacological Functions of Polysaccharides from *Lycium Barbarum*

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**Abstract:** In the last decades, the bioactivity of natural products and health benefits has drawn much attention. *Lycium barbarum* has long been deemed as anti-inflammatory, antipyretic, and anti-ageing Chinese herbal medicine and nutritious supplements. The major constituents of *Lycium barbarum* are polysaccharides named *Lycium barbarum* polysaccharides (LBPs) that have plenty of biological effects such as antioxidant activity, anti-tumor, anti-inflammatory and neuroprotective effect, etc. In recent years, LBPs tend to be a new research focus. Here, we summarized the pharmacological activities of LBPs, aiming to provide a reference for further research as well as application of LBPs in food and pharmaceutical industry.

**Keywords:** *Lycium barbarum* polysaccharides; pharmacological activities; neuroprotective; antioxidant

1. **INTRODUCTION**

Traditional Chinese herb *Lycium barbarum* (also called Goji berries, wolfberry), popular for its biological and pharmacological functions, is widely grown in the dry or semidry regions of China (such as Gansu province, Ningxia province, etc.), Korea, Japan, as well as Europe. High soil and air temperature, low latitude, strong light intensity, and moderate soil moisture are favorable geographical and climatic conditions for the production of nutrient-rich Goji berries [1]. It was estimated that there were eighty species of *Lycium barbarum*, of which seven species were found in China [2]. *Lycium barbarum* has long been used as medicine in China that could be traced back to the Tang Dynasty. According to Chinese traditional medicine, *Lycium barbarum* berries were considered to have the ability of improving the function of eyes, the activity of liver and kidneys, as well as enhancing the endurance/physical energy [3]. Moreover, its novel applications were explored such as *Lycium barbarum* was cultivated and consumed as nutritious supplements. Particularly, adding juice concentrate or extract of *Lycium barbarum* fruit to beverages could effectively improve liver function and reduce oxidative stress [4]. Due to the potential health benefits, ingredients from *Lycium barbarum* were extensively identified and analyzed, including but not limited to polysaccharides, flavonoids, carotenoids and polyphenols, of which *Lycium barbarum* polysaccharides (LBPs) were among the most bioactive ingredients. LBPs were composed of a bunch of water-soluble monosaccharides and glycoconjugates [5], including arabinose (Ara), rhamnose (Rha), glucose (Glc), xylose (Xyl), fucose (Fuc), glucuronic acid (GlcA), etc [6].

LBPs were supposed to have a variety of biological effects, including antioxidant, anti-tumor effects,
blood glucose and lipids metabolism regulation, anti-ageing, immune regulation, anti-radiation, etc [7-12]. Further, we summarized and updated pharmacological functions of LBPs according to recent studies, to provide theoretical basis for extensive comprehension and making full use of LBPs.

2. PHARMACOLOGICAL ACTIVITIES AND POTENTIAL HEALTH BENEFITS OF LBPS

In line with other polysaccharides, LBPs have a variety of biological activities. At present, the biological functions of LBPs has covered anti-oxidation, neuroprotection, anti-tumor, anti-inflammation, anti-apoptotic effects, etc (as shown in Figure 1).

2.1 The neuroprotective effect of LBPs

According to former studies, LBPs exhibited great neuroprotective effects on in vivo and in vitro models of neurological diseases such as Alzheimer’s disease (AD), Parkinson’s disease (PD), stroke, and so on [13-15].

AD, a neurodegenerative disease with characteristics of gradual memory loss and cognitive disorders, is the most common cause of dementia [16]. The neuropathological features of AD contained progressive hippocampal and cortical atrophy, the presence of neurofibrillary tangles and the aggregation of β-amyloid (Aβ) in extracellular senile plaques [17]. Evidence from genetics and biochemical studies proved that excessive production of cytotoxic Aβ generated via amyloid precursor protein (APP) hydrolysis was responsible for the development and progression of AD [18]. The proteolytic processing of APP was comprised of amyloidogenic and non-amyloidogenic ways, where the former was mediated by β- and γ-secretase resulting in the generation of Aβ, while the latter was mediated by α- and γ-secretase leading to the production of a non-Aβ fragment termed p3 [19, 20]. One prospective strategy for AD prevention is to suppress the generation or assembly of Aβ [21]. Some study demonstrated that LBP1C-2 could reduce the production of Aβ42 by decreasing the expression of APP cleavage enzyme 1 (BACE1) and upregulating the expression of ADAM10 [22-24].

Several studies indicated that crude LBPs could significantly attenuate cytotoxicity triggered by Aβ in vitro, and their sulfated derivatives were proved to possess anti-angiogenic activity [22, 23, 25]. LBPs pretreatment could markedly protect neurons from Aß-mediated cellular apoptosis possibly via depressing the activity of caspase-2 and -3, underlining the potential beneficial role of LBPs in AD [26].

One of the vital clinical features and standards for AD diagnosis is cognitive dysfunction [27]. In APP/PS1 double-transgenic mice, LBPs drastically improved the cognitive functions as determined by novel object recognition test and Morris water maze (MWM), as well as enhanced neurogenesis and proliferation, restored hippocampal synaptic plasticity. Moreover, LBPs decreased Aβ levels, amyloid plaque burden in vivo [28]. Similarly, LBPs treatment could significantly enhance cognitive and memory ability according to MWM and NORT, and prevent the decrease of cell proliferation and differentiation in scopolamine-treated rats [29].

PD is also known as dyskinesia, with the prevalence secondary to AD among neurodegenerative diseases. The protective effect of LBPs on pathological alterations and neurobehavioral defects was confirmed in a PD mouse model mediated by methyl-4-phenyl-1,2,3,6- tetrahydropyridine (MPTP). LBPs could enhance the expression of SOD2, GSH-Px, CAT as well as repress MPTP-mediated aberrant α-synuclein aggregation. Moreover, phosphorylation of AKT and mTOR could also be upregulated by LBPs treatment, indicating the protective effect of LBPs on attenuating MPTP-induced nigrostriatal degeneration was probably due to the activation of PTEN/AKT/mTOR
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signaling pathway [30]. Besides, LBPs could dose-dependently decrease cell apoptosis, impede amassing of ROS and NO, as well as suppress the expression of NF-κB and iNOS mediated by 6-hydroxydopamine exposure, and the mechanism was found to be associated with the regulatory effect of LBPs on ROS-NO pathway [31].

The protective effect of LBPs on neurobehavioral defects mediated by cerebral ischemia was also sufficiently studied. A study reported that LBPs pretreatment could significantly ameliorate regional cortical blood flow, enhance motor coordination ability and memory, and repress microglia and astrocytes activation after perfusion in middle cerebral artery occlusion (MCAO) mice. The results further implied that LBPs could inhibit MCAO-mediated stimulation of NF-κB and p38 pathway, as well as decrease the expression of proinflammatory mediators in the hippocampus [32]. LBPs could also protect primary cultured hippocampal neurons from cerebral ischemia/ reperfusion injury possibly due to the activation of PI3K/Akt/mTOR signaling pathway [33]. Similarly, Wu et al. conducted a study on investigating the potential effect of LBPs on MCAO mice, where LBPs were administered prophylactically to MCAO mice by intragastric administration for 7 days, followed by cerebral ischemia for 2 hours and reperfusion for 24 hours. Consequent results suggested that neuronal morphological damage and neuronal apoptosis were markedly reduced, and caspase-3 activity and Bax protein expression was significantly decreased while Bcl-2 expression was increased with LBPs pretreatment [34].

LBPs pretreatment could also effectively protect retinal nerves and photoreceptor cells from light-induced retinal damage [35]. Li et al. reported that LBP could obviously retard the secondary degeneration of retinal ganglion cells, ameliorate the polarization of microglia/ macrophages, as well as decrease the autophagy level upon partial optic nerves injury [36]. Similarly, in an electric stimulation-induced microglial injury system, pretreatment with LBPs dramatically restored the appearance of cells, as well as attenuated inflammatory response, oxidative damage, and cell apoptosis possibly due to the modulation on endogenous autophagy and MAPK signaling pathway [37]. Another study demonstrated that LBPs could dose-dependently reduce the expression of Bax and Caspase-3 in hippocampal neurons exposed to sevoflurane, as well as promote the phosphorylation of ERK1/2 and the expression of Bcl-2 [38]. Furthermore, LBPs treatment could also exert neuroprotective effects against hypoxia, as manifested by reduced brain apoptosis, improved performance in MWM test in CoCl2-exposed rats [39]. Similarly, Deng et al. obtained Lycium ruthenicum polysaccharide 3 (LRP3) from crude polysaccharide through using ion exchange and gel permeation chromatography approaches. They found that LRP3 also exhibited neuroprotective effect on rat primary cortical neurons against oxygen-glucose deprivation/reoxygenation (OGD/R)-induced neuronal damage [40].

2.2 The antioxidant property of LBPs

Former reports suggest that LBPs and related glycoconjugates could effectively scavenge superoxide anions, 1,1-diphenyl-2-picrylhydrazyl (DPPH)-, hydroxyl-, and ABTS radicals, as well as improve the level of antioxidant enzymes [41-44]. Free radicals could be dose-dependently eliminated by LBPs, and the clearance rate reached a plateau as the concentration of LBPs increased [44].

LBPs could exert antioxidant effects by increasing enzymatic activity and expression of anti-oxidative enzymes including glutathione peroxidase (GSH-Px), superoxide dismutase (SOD) and catalase (CAT) and decreasing malondialdehyde (MDA) in vivo and in vitro [45, 46]. LBPs could also repress hydrogen peroxide-induced embryonic stem cell death, MDA and caspase-3 expression, as well as improve Bcl-2 expression [47]. Similarly, Li et al. proposed that LBPs inhibited hydrogen...
peroxide-induced oxidative stress by lowering reactive oxygen species (ROS) and lactate dehydrogenase (LDH) levels while increasing SOD activity in trophoblast HTR8/SV5 cells [48]. Moreover, LBPs could effectively ameliorate cellular damage, cell apoptosis as well as autophagy induced by hydrogen peroxide via down-regulating miR-194 in PC-12 cells [49]. Chen et al. fed weaned piglets with different concentrations of LBPs and found that LBPs could effectively promote antioxidant properties through improving antioxidant enzyme activities including CAT, SOD, and GSH-Px, etc., as well as decreasing the MDA content in serum and liver of piglets [50]. Tang et al. extracted LBPs to obtain LBP-1 and LBP-2, where LBP-2 was acquired by deproteinating LBP-1 using Sevag method. Consequent supplementation of Drosophila melanogaster with dietary LBP-1 or LBP-2 resulted in increased SOD and CAT activities but reduced MDA levels [51].

Nuclear factor E2-related factor 2 (Nrf2) played a significant role in the endogenous antioxidant system. Nrf2 could bind to antioxidant response element (ARE) thus upregulate downstream genes with antioxidant activities, such as heme oxygenase1 (HO-1), SOD and GSP-Px [52, 53]. LBPs were supposed to inhibit hydrogen peroxide-induced Nrf2 and HO-1 decrease and facilitate the binding of Nrf2 to HO-1 promoter [39]. Similar research implied that LBPs could decrease the level of ROS and lipid peroxide, while increase cell viability, SOD and GSP-Px levels mediated by silencing Nrf2 gene in fibroblastic HSF cells [12]. In vivo and in vitro studies indicated that LBPs could markedly attenuated high fat-mediated insulin resistance, manifested by improved expression of antioxidant and detoxifying enzymes, upregulated phosphorylation of Nrf2 and GSK3β, whereas ROS levels as well as phospho-JNK levels were decreased possibly due to the activation of PI3K/AKT/Nrf2 signaling pathway. Besides, LBPs dramatically attenuated expression of glycolytic and gluconeogenic genes by activating Nrf2 [54]. Similarly, Tang et al. proposed that LBPs pretreatment could markedly protect photoreceptor cells from light-mediated injury possibly via enhancing the expression of Nrf2 and TrxR1, eliminating oxygen free radicals, and decreasing resultant oxidative stress [35].

Antioxidants strongly related to ageing, and LBPs were identified as efficient antioxidants and anti-ageing agents according to former studies [55]. The expression of antioxidant enzymes including SOD, GSH-Px and CAT was markedly upregulated in senile mice treated with LBPs intragastrically (200, 350 and 500 mg/kg respectively), whereas the formation of MDA (metabolite of lipid peroxidation products) was significantly decreased [56]. Another study showed that hydrogen peroxide-induced apoptosis, ROS and MDA production, as well as loss of Δψm were markedly attenuated in the human lens epithelial cells upon LBPs treatment. Further, LBPs also upregulated the expression of Bcl-2, downregulated the expression of Bax, attenuated cellular senescence, as well as improved the enzyme activity of SOD and GSH in human lens epithelial cells [57].

2.3 The immunomodulatory effect of LBPs

Previous studies indicated that inflammatory reactions were involved in numerous diseases. The nuclear factor κB (NF-κB) plays an important role in cell survival and inflammation, where abnormally elevated NF-κB level was deemed as a key indicator of inflammatory or autoimmune diseases. NF-κB pathway could be stimulated by translocation of NF-κB to nucleus in response to various irritative substances including IL-1β, TNF-α, growth factors, TLR4, etc [58, 59]. Ni et al. established an in vitro cartilage inflammation injury model by exposing ATDC5 cells to IL-1β. Subsequent results suggested that either COX-2 elevation or the activation of NF-κB signaling pathway mediated by IL-1β was significantly suppressed by LBPs treatment [60]. Another study indicated that LBPs treatment could suppress hepatotoxicity, mitigate immune organ injury, improve immune indexes, as well as increase the generation or secretion of cytokines including IL-1β, IL-2,
TNF-α, IL-6, and IFN-γ in cyclophosphamide-mediated mice [61]. Moreover, LBP s significantly repressed the increase of IL-1β, IL-6, IL-8, NF-κB and TNF-α mediated by lipopolysaccharide (LPS) exposure in a dose-dependent manner, as well as upregulated the mRNA levels of HO-1, NQO1 and Nrf2 but downregulated the expression of NF-κB and Keap1 [62]. Peng et al. purified LRGP3 from L. ruthenicum Murr. using hot water extraction method followed by Savage method for purification. Subsequent results showed that LRGP3 could significantly decrease NO production, prevent IκBα from degradation, as well as repressed pro-inflammatory cytokines like IL-1α, TNF-α, IL-6 in mouse macrophage cells exposed to LPS. Meanwhile, LRGP3 could also decrease the expression of Toll-like receptor 4 (TLR4) and the phosphorylation of NF-κB p65, suggesting the anti-inflammatory effect of LRGP3 might be relevant to TLR4/NF-κB signaling pathway [63]. Similarly, Zhang et al. purified a fraction named LBPF4-OL from LBP s by hot water extraction and Savage method. They stated that LBPF4-OL could significantly facilitate the expression of TLR4/MD2 and phospho-p38 MAPK though depressing the expression of phospho-JNK and phospho-ERK1/2, suggesting a potential role of LBPF4-OL as an inducer or activator in TLR4/MD2/MAPK signal pathway [64]. Analogously, LBP s markedly decreased the expression of IL-1β and TNF-α, and restored the lung morphology in hyperoxia-mediated mice, possibly due to the inhibitory effect of LBP s on SIRT1-mediated stimulation of NLRP3 inflammasome [65]. Furthermore, LBP s could facilitate the activation and multiplication of immune cells including B cells, T cells, macrophagocytes, NK cells and dendritic cells [66-69]. Studies indicated that LBP s could stimulate the maturation of dendritic cells both phenotypically and functionally, as manifested by enhanced expression of CD40, -80, -86, decreased ingestion of Ag, up-regulated allostimulatory effect, as well as improved Th1/Th2 response, implying the potential role of LBP s as an adjuvant for dendritic cells associated vaccines [70].

2.4 The anti-apoptotic activity of LBP s

Apoptosis is automatically controlled to maintain a stable internal environment [71]. LBP s were deemed to have bidirectional regulation effects, i.e. promoting apoptosis of tumor cells or tumor volume shrinkage, as well as repressing apoptosis in normal cells or tissues. Hydrogen peroxide was frequently used in establishing oxidative damage cell models, while oxidative stress could lead to apoptosis [72, 73]. One study demonstrated that LBP s repressed ΔΨm decrease and cell apoptosis mediated by hydrogen peroxide via enhancing the expression of Bcl-2, survivin, and HIF1-α, but inhibiting the expression of Bax [48]. The accumulation of excessive ROS could exacerbate damage of retinal tissue, since free radicals trigger lipid peroxidation, protein damage and DNA breakage. LBP s could also protect retinal ganglion cells from CoCl₂-induced apoptosis by increasing ΔΨm and decreasing ROS [74]. Moreover, LBP s significantly protected human retinal pigment epithelial cells from hydrogen peroxide-induced cell apoptosis as manifested by increased expression of Bcl-2 and decreased expression of Bax [75].

Excessive apoptosis is increasingly associated with ageing and ageing-related diseases [76]. One study carried out in a zebrafish model implied the protective effect of LBP s against ageing and cell apoptosis, with the level of ageing-related genes including p53, p21 as well as Bax was downregulated, while the expression of anti-ageing genes like Mdm2 and TERT was upregulated upon LBP s treatment [77]. Chen et al. reported that LBP s could significantly reduce cell death induced by LPS and repress the activation of caspase-3 in vitro [78]. LBP s could also dose-dependently suppress osteoblast apoptosis mediated by palmitate (PA), which was relevant to the inhibition of endoplasmic reticulum stress (ERS)-mediated JNK phosphorylation [79]. Similarly, Yang et al. reported that LBP s could inhibit cisplatin-mediated cell apoptosis in MLTC-1 cells through downregulating the expression of caspase-3, -7 and -12 [80]. Another study showed that LBP s...
treatment could greatly downregulate the expression of pro-caspase and cleaved caspase, while upregulate the expression of PARP as well as cleaved PARP in photoreceptor cells exposed to N-methyl-N-nitrosourea [81].

2.5 The anti-cancer effect of LBPs

Apoptosis played an indispensable role in preventing canceration by eliminating damaged cells or abnormally excessive cells. A series of studies suggested that LBPs had favorable anti-tumor activity and stimulated apoptosis of cancer cells [82]. One study demonstrated that LBPs could inhibit proliferation and mediate apoptosis in human hepatoma cells [83]. Deng et al. separated four water-soluble LBPs fractions (i.e. LBP-2, LBP-3, LBP-4, and LBP-5) with different MW. In vitro experiments suggested that all of the LBPs fractions exhibited great inhibitory effect on murine hepatoma H22 cell line viability, but cell apoptosis, S-phase arrest and mitochondrial dysfunction were only observed in cells treated with LBP-3 [84]. Furthermore, LBP-3 repressed transplanted tumor growth by 37.97% as well as prolonged survival time in tumor-bearing mice. Similar studies reported that LBPF5 obtained from purification of LBPs with ion-exchange chromatography could notably suppress the multiplication and migration of B16/F10 cells originated from bladder cancer [85] via downregulating PI3K/AKT pathway [86]. Similarly, studies on primary human hemangioma endothelial cells (HemEC) indicated that LBPs could effectively inhibit the proliferation of HemECs and induce apoptosis of HemECs through PI3K/AKT signaling pathway [87]. Shen and Du demonstrated that LBPs could dose-dependently stimulate Erk1/2 activity and S phase cell cycle arrest in MCF-7 cells [88]. Analogously, combined usage of LBPs and recombinant interferon (IFN-α2b) significantly promoted cell cycle arrest, facilitated cell apoptosis, as well as repressed cell multiplication in mouse Renca cells. Further, tumor volume and the ratio of myeloid-derived suppressor cells were significantly decreased in mice with transplanted tumor upon LBPs and IFN-α2b combined treatment [89].

2.6 The Hypoglycemic activity of LBPs

A significant decrease in serum glucose and increase in proinsulin indexes was uncovered after 3 months oral administration of LBPs at a dose of 300 mg/day according to a clinical trial on 67 patients with type II diabetes. Moreover, high-density lipoprotein levels in diabetic patients were increased upon LBPs treatment, suggesting the potential role of LBPs as therapeutic adjuvants for type II diabetes [90]. Tang et al. obtained crude LBPs using hot water extraction method at the optimum temperature of 30°C and working pressure of 0.25 MPa, and further purified and obtained four components named LBP1, LBP2, LBP3 and LBP4 respectively. Two components LBP3a and LBP3b were purified from LBP3 using Sephadex G-150 columns (2.5 cm × 60 cm), and the hypoglycemic activity of LBP3b was studied. LBP3b repressed the uptake of glucose in a dose-dependent manner in vitro, possibly due to the combination of LBP3b with bit points of glucose absorption, thus delayed the absorption of glucose, and finally decreased postprandial blood glucose [91]. Li also proposed that oral administration of LBPs could effectively improve oxidative indexes of blood, kidney and liver in streptozotocin-induced diabetic rats [92]. Moreover, LBPs were always used in treating certain diabetic complications, such as diabetic peripheral neuropathy, testicular dysfunction, vascular disease, and diabetic retinopathy, etc [93-95]. LBPs were found to slightly reduce blood glucose, partly relieve hyperalgesia, and greatly ameliorate nerve fiber myelin structural damage in diabetic rats, suggesting the protective effect of LBPs against diabetic peripheral neuropathy [96]. Besides, LBPs played a protective role by increasing cell proliferation, inhibiting apoptosis, regulating the expression of sirtuin 1 (SIRT1) and hypoxia-inducible factor 1-alpha (HIF-1α) in diabetic rats [97]. Testicular
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dysfunction was regarded as a serious secondary complication to diabetes. Shi et al. reported that LBPs could inhibit excessive testicular autophagy via activating PI3K/AKT signaling pathway, thereby protect diabetic mice against testicular dysfunction [98].

2.7 Other Biological Activities

In addition to above mentioned bioactivities, LBPs were reported to have the ability of radioresistance [99], anti-fatigue [100], intestinal microbiota regulation [101, 102], cardioprotection [103], protecting male reproductive organs [104, 105] as well as kidney and liver from damage [106-110]. As bioactive ingredients, LBPs exhibited versatile biological activities as well as benefits for human health.

Figure 1. Summary of biological effects of polysaccharides from Lycium barbarum (LBPs). LBPs exerted a remarkable protective effect on in vitro and in vivo models. LBPs treatment increased the activity of SOD, CAT and GSH-Px but decrease the expression level of ROS and MDA via PI3K/AKT/Nrf2 pathway, and reduced apoptosis by inhibiting the generation of oxidative stress. LBPs decreased the expression of genes related to aging like p53, p21, and decreased the expression of apoptosis-related protein caspase 3, caspase 7 and caspase 12. Moreover, LBPs exerted neuroprotective effects via inhibiting the production of Aβ by reducing the expression of β-APP cleavage enzyme 1 (BACE1) and up-regulating the expression of ADAM10. Besides, LBPs also enhanced neuroprotective function by inhibiting the generation of oxidative stress. LBPs could also down-regulated the expression of proinflammatory mediators and chemokines like IL-2, 8 IL-6, IL-1β, TNF-α and IFN-γ via NF-κB pathway.

3. PERSPECTIVES

In conclusion, Lycium barbarum has been explored both medically and nutritionally so far. Particularly, it has been used to improve the function of liver, kidney and lung as Chinese traditional medicine for a long time. Lycium barbarum berries were edible either fresh or dried, or could be processed into jam, juice, wine and tea. At present, Lycium barbarum berries were widely used in food supplements and Chinese herbal medicine, such as Goji Yishen Capsule, Goji Cream Formula, Compound Goji Granules, and Wolfberry pulp, etc. What’s more, Lycium barbarum has a variety of physiological activities, which is highly related to its abundant content of polysaccharides i.e. LBPs. Studies suggest that LBPs possessed plenty of biological functions, including anti-oxidation, neuroprotective effect, anti-tumor, immunomodulation, anti-apoptosis, anti-inflammation,
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hypoglycemic effect, etc, though the mechanism involved in biological activities of LBPs was yet to be clarified. Thus, further studies using systematic pharmacology approaches such as proteomic and metabolomic analysis are required to uncover the molecular target networks of LBPs. Besides, researchers acquired good effect by using LBPs in clinical trials for patients with type II diabetes, though clinical safety data on LBPs are still lacking. Moreover, the safe and effective use of herbal medicines like LBPs requires a full understanding of their side effects and mechanism of action. Therefore, it is necessary to establish a relationship between dose response and dose toxicity of LBP in animal and human studies to provide effective evidence for further development of LBPs-related health products. Last but not least, the relation between LBPs bioactivities and chemical structures was not properly established. Accordingly, further study on relationship between structure and bioactivity, could be one of the research priorities on LBPs.

AUTHOR CONTRIBUTIONS

X.Z. wrote the first draft of this manuscript and drew Tables 1, 2 and Figures 1. S.L., X.G., Z.G., Y.S., Z.G. and X.D. revised the manuscript. X.D. designed this review and checked the draft as the final version before submission.

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