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Review

Agaricomycetes mushrooms (Basidiomycota) as potential neuroprotectants

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Abstract
The edible and medicinal agaricoid and polyporoid mushrooms (phylum Basidiomycota, order Agaricomycetes) have long been known by humans as valuable food and medicines. They are producers of different groups of high- and low-molecular weight bioactive compounds (alkaloids, phenolics, polysaccharides, proteins, terpenoids, vitamins etc.) with around 130 therapeutic effects, including neuroprotective. Mushroom-derived biotech products are reported as effective neuroprotectants, however their potential to prevent or mitigate several neurodegenerative pathologies, such as Alzheimer and Parkinson diseases, epilepsy, depression and others has not been fully explored. This review discusses the neuroprotective potential of Agaricomycetes fungi and possibilities for their application as natural neuroprotectants.

Keywords
Agaricomycetes, antioxidant, anti-inflammatory, bioactive compounds, neurodegenerative, neuroprotective

Introduction
Neurodegeneration is incurable pathological process of progressive loss of structure and function of nerve cells, which lead to their death. In recent years age-related neurodegenerative diseases (NDD), such as Alzheimer's, Parkinson's and Meniere's diseases, multiple sclerosis affecting more than 35 million people worldwide. Available scientific data support the theory that the oxidative stress-derived neuro-inflammation in the neuron-glia system, as well as mitochondrial dysfunction are early pathological conditions and key points in the pathogenesis of NDD (Lin and Beal, 2006; Kozarski et al., 2015; Chen et al., 2016b; Trovato Salinaro et al., 2018). The functional role of mitochondria and reactive oxygen species (ROS) formation are positively implicated in cellular stress response mechanisms and highly regulated process controlled by different intracellular signalling pathways, including vitagenes (Cornelius et al., 2013). The strategy to prevent the development of NDD is a stress-free lifestyle, physical activity, and healthy diet, enriched with different natural products, including mushroom supplements (Brandalise et al., 2017; Rossi et al., 2018; Bai et al., 2019; Fan et al., 2019).

Despite the advancement of pharmacological treatment of age-related NDD, their management remains largely ineffective. Moreover, available drugs have always been associated with several side effects, while natural products have gained recognition to prevent development of patho-neurological

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symptoms. Therefore, it is urgent to explore neuroprotectants with natural, including plant and mushroom origin.

Agaricomycetes mushrooms (phylum Basidiomycota) are widely distributed worldwide and have been appreciated in traditional medicine for thousands of years for nutritional and medicinal properties, as well as a part of human culture and religious attribute (Hobbs, 2004; Chang and Miles, 2004; Badalyan, 2012; Chang and Wasser, 2017; Badalyan and Zambonelli, 2019; Badalyan et al., 2019).

According to a large number of chemical and myco-pharmacological studies, mushrooms are producer of different bioactive compounds (BAC) with neuroprotective effect (NPE) (Friedman, 2015; Chen et al., 2018a,b; Gupta et al., 2018; Badalyan et al., 2019; Lee et al., 2019; Yadav et al., 2020; Badalyan and Rapior, 2021). Although the mechanism of neuroprotective action of mushroom-derived BAC has not been thoroughly investigated, recent literature and research reviews reveal their potential to prevent the development and mitigate the symptoms of NDD (Sabaratnam and Phan, 2018; Yadav et al., 2020; Badalyan and Rapior, 2021). Several mushroom-derived biotech products (pharmaceuticals, nutraceuticals and nutriceuticals) currently available in the market have been demonstrated to be effective as neuroprotectants (Wang et al., 2014; Friedman, 2015; Bandara et al., 2015; Phan et al., 2015; Thangthaeng et al., 2015; Brandalise et al., 2017; Rathore et al., 2017; Rossi et al., 2018; Yin et al., 2018; Ho et al., 2020).

The review discusses recent advances in research on the neuroprotective potential of Agaricomycetes mushrooms belonging to different ecological and taxonomic groups and perspectives of their biomedical application as neuroprotectants.

Neuroprotective potential of Agaricomycetes mushrooms

Agaricomycetes mushrooms have been used by humans from ancient times as food and medicine (Chang and Miles, 2004; Hobbs, 2004; Badalyan, 2012; Chang and Wasser, 2017; Badalyan and Zambonelli, 2019; Badalyan et al., 2019; Badalyan and Rapior, 2021). They are a source of different BAC (β-glucans, lectins, phenolics, terpenoids, vitamins, etc.) possessing around 130 therapeutic effects (i.e., antitumor, anti-inflammatory, anti-oxidant, anti-microbial, hypocholesterolemic, hypoglycemic, etc.) (Badalyan, 2012; Gargano et al., 2017; Gupta et al., 2018; Morel et al., 2018; Badalyan et al., 2019; Hyde et al., 2019). Scientific data are documented the NPE of several mushrooms [i.e. *Agaricus bisporus* (J.E. Lange) Imbach*, Ganoderma lucidum* (Curtis) P. Karst.*, Hericium erinaceus* (Bull.) Pers.*, Pleurotus ostreatus* (Jacq.) P. Kumm., etc.] which could be highly efficient in complementary therapy of neurological disorders (Park et al., 2012; Phan et al., 2017; Sabaratnam and Phan, 2018; Chen et al., 2018a,b; Cui and Zhang, 2019; Lew et al., 2020; Badalyan and Rapior, 2021). However, further myco-pharmacological studies, pre-clinical and clinical trials are still required for the comprehensive evaluation of NPE of mushroom-derived products in the form of approved clinical drugs (Badalyan et al., 2019; Lucius, 2020).

Nowadays, dozens of mushroom species from different ecological (saprotrophs, xylotrophs, mycorrhizal) and taxonomic (agaricoid, polyporoid, russuloid, hymenochaetoid, and others) groups are biotechnologically cultivated and used as medicine however genetic mechanisms of their bioactivity and medicinal effect have not been fully exploited, yet (Kües and Badalyan, 2017). The recent advances in study of nutritional and medicinal values of Agaricomycetes, biotechnological production of mycelial biomass and mushrooms have been reported, innovative biological, biochemical and genetic approaches to produce health-enhancing mushroom-derived biotech products have been developed (Chang and Wasser, 2017; Gargano et al., 2017; Gupta et al., 2018; Badalyan and Zambonelli, 2019; Badalyan et al., 2019; Hyde et al., 2019; Badalyan and Rapior, 2021).

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Study of Agaricomycetes biodiversity, assessment of bioresources and creation of specialized culture collections will have an incredible impact on fundamental and applied myco-pharmacological and biotechnological research to develop novel mushrooms-derived products, including neuroprotectants (Badalyan and Gharibyan, 2016, 2017, 2020; Badalyan and Borhani, 2019a,b; Badalyan and Zambonelli, 2019; Badalyan, 2020).

Neuroprotective compounds of Agaricomycetes mushrooms

Agaricomycetes, particularly agaricoid (order Agaricales) and polyporoid (order Polyporales) species [*Flammulina velutipes* (Curtis) Singer*, Lentinula edodes* (Berk.) Pegler*, Pleurotus* (Fr.) P. Kumm., *Ganoderma* P. Karst., and *Trametes* Fr. species, etc.], as well as russuloid (order Russulales) species *Hericium erinaceus* (Bull.) Pers. are recognized as rich source of neuroprotective compounds, such as polysaccharides, terpenoids, phenolics, steroids, alkaloids, etc. (Badalyan, 2012; Phan et al., 2012; Zhang et al., 2016b; Chen et al., 2018a,b; Ćilerdžić et al., 2018, 2019; Lemieszek et al., 2018; Sabaratnam and Phan, 2018; Badalyan et al., 2019; Wang et al., 2019b; Badalyan and Rapior, 2021).

Polysaccharides or β-glucans are one of the major BAC in mushrooms. Except immunomodulating and antitumor activities they also possess significant antioxidant, anti-inflammatory, and neuroprotective activities allowing to use them as potential neuroprotectants (Wasser and Didukh, 2005; Khan et al., 2014; Kozarski et al., 2015; He et al., 2017; Wang et al., 2019a; Badalyan et al., 2019; Wu et al., 2019). The NPE of polysaccharides isolated from polyporoid chaga mushroom *Inonotus obliquus* (Fr.) Pilát (Ning et al., 2014), and agaricoid [*Agaricus bisporus*, *Coprinus comatus* (O. F. Müll.) Pers., *Coprinellus truncorum* (Scop.) Redhead, Vilgalys & Moncalvo and *Pleurotus eryngii* (DC.) Quél.] and cantharelloid (*Cantharellus cibarius* Fr.) species have also been reported (Mahmoud et al., 2014; Lemieszek et al., 2018; Pejin et al., 2019; Zhang et al., 2020). The NPE of bioactive polysaccharides from well-known edible medicinal mushroom *H. erinaceus* and new prospects for their usage as neuroprotectant is proposed (Friedman, 2015; Cheng et al., 2016; He et al., 2017; Wang et al., 2019a).

Agaricomycetes are also source of bioactive terpenoids, steroids, and sterols with neurotrophic and anti-neuroinflammatory activity. Hericenones, hericipins and erinacines have been isolated from *H. erinaceus* (Rupcic et al., 2018; Lee et al., 2020), cyathane diterpenes with from *Cyathus africanus* H.J. Brodie and *C. hookeri* Berk. (Tang et al., 2019; Yin et al., 2019), lanostane triterpenes, ganoderic acid, lucidone A, and aromatic meroterpenoids from *G. lucidum* (Wang et al., 2019b) and other *Ganoderma* species [*G. applanatum* (Pers.) Pat*., G. leucocontextum* T. H. Li, W. Q. Deng, Sheng H. Wu, Dong M. Wang & H. P. Hu*, G. microsporum* R. S. Hseu*, G. resinaceum* Boud.] (Chen et al., 2018a; Ćilerdžić et al., 2018; Lai et al., 2019; Zhao et al., 2019). Anti-neuroinflammatory polyoxygenated lanostanoids from Chaga mushroom *I. obliquus* were recently reported (Kou et al., 2021).

Phenolics, such as hispidin and derivatives were isolated from *G. applanatum, Phellinus baumii* Pilát*, Trametes versicolor* (L.) Lloyd, and *T. gibbosa* (Pers.) Fr. They possess diverse pharmacological effects, including anti-inflammatory, antioxidant and neuroprotective (Palacios et al., 2011; Khatua et al., 2013; Kozarski et al., 2015; Pop et al., 2018; Jiang et al., 2020).

Agaricomycetes mushrooms as neuroprotectants

Medicinal Agaricomycetes species with protective effects against oxidation and inflammation can be used as neuroprotectants in treatment of various life-style and age-related chronic diseases, including NDD (Palacios et al., 2011; Thangthaeng et al., 2015; Phan et al., 2015, 2017; Badalyan et al. 2019; Yadav et al., 2020; Badalyan and Rapior, 2021). It was reported that mushroom-based daily diets can improve the cognitive abilities in ageing people and prevent the neurodegeneration (Rathore et al.,

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2017; Rossi et al., 2018; Sabaratnam and Phan, 2018; Yin et al., 2018; El Sayed and Ghoneum, 2020). However, scientific validation and further clinical trials are required to understand the molecular and biochemical mechanisms involved in the stimulation of neurite outgrowth and consider mushrooms as neuroprotectants (Badalyan et al., 2019; Cui and Zhang, 2019; Lucius, 2020; Badalyan and Rapior, 2021).

Several agaricoid, polyporoid, russuloid, cantharelloid and other groups of agaricomycetous mushrooms, such as *A. bisporus* (Kozarski et al., 2020), *Agaricus brasiliensis* Fr. (Qin and Han, 2014), *Auricularia polytricha* (Mont.) Sacc. (Bennett et al., 2013), *Amanita caesarea* (Scop.) Pers. (Li et al., 2017), *Cantharellus cibarius* (Lemieszek et al., 2018), *Laetiporus sulphureus* (Bull.) Murrill, and *P. ostreatus* (Ćilerdžić et al., 2018, 2019), *Fomitopsis betulina* (Bull.) B. K. Cui, M. L. Han & Y. C. Dai, and *Fomitopsis officinalis* (Vill.) Bondartsev & Singer (Pleszczyńska et al., 2017; Muszyńska et al., 2020), *G. lucidum* (Rahman et al., 2020), *H. erinaceus* (Ma et al., 2010), *Lignosus rhinocerotis* [= *L. rhinocerus* (Cooke) Ryvarden] (Farha et al., 2019), *Phellinus linteus* (Berk. & M. A. Curtis) Teng (Chen et al., 2016a), *Trametes* (= *Coriolus*) species (Knežević et al., 2018; Scuto et al., 2020), as well as *Flammulina velutipes* (Phan et al., 2017; Sabaratnam and Phan, 2018), *Grifola frondosa* (Dicks.) Gray (Fan et al., 2019), *Lentinus edodes* (Berg.) Singer (Diallo et al., 2020) and *Pleurotus giganteus* (Berk.) Karun. & K. D. Hyde (Phan et al., 2012, 2014) have been used in traditional medicine as neuroprotective and antidepressant agents against ageing-related NDD (Fig. 1). Among these, *H. erinaceus, G. lucidum, L. edodes* and *Polyporus umbellatus* (Pers.) Fr. are widely used as bio-ingredients in the formulation of cholesterol-free natural food products (Chang and Buswell, 1996; Ma et al., 2010; Bandara et al., 2015; Rossi et al., 2018; Sabaratnam and Phan, 2018; Yin et al., 2018; Ho et al., 2020).

Currently, around 80 different BAC from over 20 brain-improving culinary and medicinal mushrooms have been reported, molecular mechanisms of neuroprotection and possible clinical trials are discussed (Phan et al., 2015; Badalyan and Rapior, 2021). Nevertheless, before the clinical application of mushroom-derived neuroprotectants as preventive and therapeutic drugs the synergistic effects of isolated biocompounds and stabilization for their administration needs to be appropriately evaluated (Badalyan et al., 2019; Gründemann et al., 2020; Lucius, 2020; Badalyan and Rapior, 2021).

One of the major etiological factors of Alzheimer's disease is oxidative stress, which accelerates β - amyloid peptide plaque accumulation in the brain. Edible medicinal agaricoid oyster mushrooms (*P. eryngii, P. giganteus, P.* ostreatus) contain a high level of antioxidants, including ergothioneine, adenosine, and polyphenol, which reduce the age-related oxidative stress (Badalyan, 2012; Phan et al., 2014; Ćilerdžić et al., 2019; Liang et al., 2020; Zhang et al., 2020).

Several white-rot polyporoid fungi, such as *Trametes* (= *Coriolus*) species, have been used for centuries in the traditional medicine, however only *T. versicolor* has been comprehensively studied (Knežević et al., 2018; Pop et al., 2018; Kıvrak et al., 2020). The mycelial extract of *T. versicolor* was the most effective inhibitor of acetylcholinesterase activity, while extract of *T. gibbosa* significantly inhibited tyrosinase activity. The chemical screening revealed strong synergistic action of content of BAC produced by studied *Trametes* species (Knežević et al., 2018). According to research data the role of the inflammasome and the importance of *Coriolus* (= *Trametes*) and *Hericium* derived nutra- and nutriceuticals in neuroprotection have been considered (Trovato Salinaro et al., 2018).

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Legend

Fig. 1. Agaricoid and polyporoid mushrooms with neuroprotectant potential: (**a**) *Flammulina velutipes* (Photo Courtesy of PM Marty); (**b**) *Laetiporus sulphureus* (Photo Courtesy of PM Marty; (**c**) *Auricularia polytricha* (Photo Courtesy of JC Malaval); (**d**) *Ganoderma lucidum* (Photo Courtesy of JC Malaval); (**e**) *Trametes versicolor* (Photo Courtesy of JC Malaval); (**f**) *Clitocybe geotropa* (Photo Courtesy of JC Malaval); (**g**) *Lentinus edodes* (Photo Courtesy of AR Bandara, (**h**) *Cantharellus cibarius* (Photo Courtesy of AR Bandara; (**i**) *Pleurotus ostreatus* (Photo Courtesy of C Angelini); (**j**) *Grifola frondosa* (Photo Courtesy of C Angelini); (**k**) *Amanita caesarea* (Photo Courtesy of JC Malaval) and (**l**) russuloid species *Hericium erinaceus* (Photo Courtesy of AR Bandara).

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Well-known maitake mushroom, *G. frondosa,* contains a high amount of health-enhancing BAC and possesses nutritional and medicinal values (Badalyan and Zambonelli, 2019; Badalyan et al., 2019; Bai et al., 2019; Fan et al., 2019). It has been reported that proteoglucan from *G. frondosa* (PGM) can improve learning and memory; decrease the loss of neurons and histopathological abnormalities in mice. Moreover, PGM treatment could activate microglia, astrocytes, promote microglial recruitment to the β-amyloid plaques and enhance their phagocytosis, thereby alleviating pathological changes in the cortex and hippocampus. The administration of PGM as a dietary supplement may provide potential benefits on brain age-related memory dysfunction (Bai et al., 2019; Fan et al., 2019).

Several other Agaricomycetes species [*Antrodia cinnamomea* T. T. Chang & W. N. Chou*, Armillaria mellea* (Vahl.) P. Kumm.*, Calocybe indica* Purkay. & A. Chandra*, Clitocybe geotropa* (Bull.) Quél.*, Dictyophora indusiata* (Vent.) Desv.*, Hygrophorus eburneus* (Bull.) Fr.*, Paxillus panuoides* (Fr.) Fr., *Polyporus umbellatus*, *Poria cocos* F. A. Wolf, *Tremella fuciformis* Berk.*,* etc.] have also been reported as potential neuroprotectants (Lee et al., 2003; Park et al., 2012; Hsieh et al., 2013; Lu et al., 2013; Bandara et al., 2015, 2019; Zhang et al., 2016b; Rathore et al., 2017; Lee et al., 2019, 2020; Wu et al., 2019; Huang et al., 2020; Kosanić et al., 2020a,b; Badalyan and Rapior, 2021) (Fig. 1**).**

Further studies of biomedical potential of Agaricomycetes mushrooms will assist development and formulation of novel mushrooms-derived neuroprotectants.

Conclusion

Presently, human age-related neurodegenerative and psychotropic diseases are affecting the adult population worldwide. Therefore, discovering new resources of natural medicines, including plant- and mushrooms-derived biotech products is topical. This review discusses the current state of knowledge and the findings of recent studies on the neuroprotective potential of Agaricomycetes mushrooms. However, the list of studied species is far from being completed.

Future interdisciplinary research involving physicians, biologists, chemists, pharmacologists and mycologists collaborating with social scientists is required to create a scientific framework that incorporates traditional and clinical knowledge and experience to assist in the use of mushroom resources for human welfare.

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References

Badalyan SM (2012) Medicinal aspects of edible ectomycorrhizal mushrooms. In: Zambonelli A, Bonito G (eds) Edible ectomycorrhizal mushrooms, current knowledge and future prospects, vol 34. Springer, Berlin/Heidelberg, pp 317–334. https://doi.org/10.1007/978-3-642-33823-6_18

https://doi.org/10.6092/issn.2531-7342/12542

Badalyan SM (2020) Medicinal coprinoid mushrooms (Agaricomycetes) distributed in Armenia (Review). International Journal of Medicinal Mushrooms 22(3):257–267. https://doi.org/10.1615/intjmedmushrooms.2020033981

Badalyan SM, Gharibyan NG (2016) Diversity of polypore bracket mushrooms, Polyporales (Agaricomycetes) recorded in Armenia and their medicinal properties. International Journal of Medicinal Mushrooms 18(4):347–354. https://doi.org/10.1615/intjmedmushrooms.v18.i4.80

Badalyan SM, Gharibyan NG (2017) Characteristics of mycelial structures of different fungal collections. Yerevan: YSU Press. 174p.

Badalyan SM, Borhani A (2019a) The diversity and distribution of edible and medicinal mushrooms from Mazandaran province of northern Iran. Proceedings YSU Chemistry and Biology 53(1):33–41.

Badalyan SM, Borhani A (2019b) Medicinal, nutritional and cosmetic values of macrofungi distributed in Mazandaran province of northern Iran (review). International Journal of Medicinal Mushrooms 21(11):1099–1106. https://doi.org/10.1615/IntJMedMushrooms.2019032743

Badalyan SM, Zambonelli A (2019) Biotechnological exploitation of macrofungi for the production of food, pharmaceuticals and cosmeceuticals. In: Sridhar KR, Deshmukh SK (eds.) Advances in macrofungi: diversity, ecology and biotechnology. CRC Press, pp 199–230. https://doi.org/10.1201/9780429504075

Badalyan SM, Gharibyan NG (2020) Pharmacological properties and resource value of Hymenochaetoid fungi (Agaricomycetes) distributed in Armenia: Review. International Journal of Medicinal Mushrooms 22(12):1135–1146. https://doi.org/10.1615/IntJMedMushrooms.2020037092

Badalyan SM, Rapior S (2021) The Neuroprotective Potential of Macrofungi. In: Medicinal Herbs and Fungi – Neurotoxicity vs. Neuroprotection. Eds. D. Agrawal & M. Dhanasekaran. Springer Nature Singapore, pp. 37–77. https://doi.org/10.1007/978-981-33-4141-8_2

Badalyan SM, Barkhudaryan A, Rapior S (2019) Recent progress in research on the pharmacological potential of mushrooms and prospects for their clinical application. In: Agrawal DC, Dhanasekaran M (eds) Medicinal mushrooms: recent progress in research and development. Springer Nature, Singapore, pp 1–70. https://doi.org/10.1007/978-981-13-6382-5_1

Bai Y, Chen L, Chen Y (2019) A Maitake (*Grifola frondosa*) polysaccharide ameliorates Alzheimer's disease-like pathology and cognitive impairments by enhancing microglial amyloid-β clearance. RSC Advances 9(64):37127–37135. https://doi.org/10.1039/C9RA08245J

Bandara AR, Rapior S, Bhat DJ, Kakumyan P, Chamyuang S, Xu J, Hyde KD (2015) *Polyporus umbellatus*, an edible-medicinal cultivated mushroom with multiple developed health-care products as food, medicine and cosmetics: a review. Cryptogamie Mycologie 36(1):3–42. https://doi.org/10.7872/crym.v36.iss1.2015.3

Bandara AR, Rapior S, Mortimer PE, Kakumyan P, Hyde KD, Xu J (2019) A review of the polysaccharide, protein and selected nutrient content of *Auricularia,* and their potential pharmacological value. Mycosphere 10(1):579–607. https://doi.org/10.5943/mycosphere/10/1/10

Bennett L, Sheean P, Zabaras D, Head R (2013) Heat-stable components of wood ear mushroom, *Auricularia polytricha* (higher basidiomycetes), inhibit in vitro activity of beta secretase (BACE1). International Journal of Medicinal Mushrooms 15(3):233–249. https://doi.org/10.1615/intjmedmushr.v15.i3.20

Brandalise F, Cesaroni V, Gregori A, Repetti M, Romano C, Orrù G, Botta B, Girometta C, Guglielminetti ML, Savino E et al. (2017) Dietary supplementation of *Hericium erinaceus* increases mossy fiber-CA3 hippocampal neurotransmission and recognition memory in wild-

type mice. Evidence Based Complementary and Alternative Medicine 2017:3864340.

Chang ST, Buswell JA (1996) Mushroom nutriceuticals. World Journalof Microbiology and Biotechnology 12(5):473–476. https://doi.org/10.1007/BF00419460

Chang ST, Miles PG (2004) Mushrooms: cultivation, nutritional value, medicinal effect, and environmental impact. 2nd ed. CRC Press, Boca Raton. https://doi.org/10.1021/np058221b

Chang ST, Wasser SP (2017) The cultivation and environmental impact of mushrooms. In: Oxford research encyclopaedia. Environmental science - agriculture and the environment, Oxford University press USA, 2016, pp 1–39. https://doi.org/10.1093/acrefore/9780199389414.013.231

Chen H, Tian T, Miao H, Zhao YY (2016a) Traditional uses, fermentation, phytochemistry and pharmacology of *Phellinus linteus*: a review. Fitoterapia 113:6–26. https://doi.org/10.1016/j.fitote.2016.06.009

Chen H, Zhang J, Ren J, Wang W, Xiong W, Zhang Y, Bao L, Liu H (2018a) Triterpenes and meroterpenes with neuroprotective effects from *Ganoderma leucocontextum*. Chemistry & Biodiversity 15(5):e1700567. https://doi.org/10.1002/cbdv.201700567

Chen WW, Zhang X, Huang WJ (2016b) Role of neuroinflammation in neurodegenerative diseases (Review). Molecular Medicine Reports 13(4):3391–3396. https://doi.org/10.3892/mmr.2016.4948

Chen WY, Chang CY, Li JR, Wang JD, Wu CC, Kuan YH, Liao SL, Wang WY, Chen CJ (2018b) Anti-inflammatory and neuroprotective effects of fungal immunomodulatory protein involving microglial inhibition. International Journal of Molecular Sciences 19(11):3678. https://doi.org/10.3390/ijms19113678

Cheng JH, Tsai CL, Lien YY, Lee MS, Sheu SC (2016) High molecular weight of polysaccharides from *Hericium erinaceus* against amyloid beta-induced neurotoxicity. BMC Complementary and Alternative Medicine 16:170. https://doi.org/10.1186/s12906-016-1154-5

Ćilerdžić J, Galić M, Vukojević J, Stajic M (2019) *Pleurotus ostreatus* and *Laetiporus sulphureus* (Agaricomycetes): possible agents against Alzheimer and Parkinson diseases. International Journal of Medicinal Mushrooms 21(3):275–289. https://doi.org/10.1615/IntJMedMushrooms.2019030136

Ćilerdžić JL, Sofrenić IV, Tešević VV, Brčeski ID , Duletić-Laušević SN, Vukojević JB, Stajić MM (2018) Neuroprotective potential and chemical profile of alternatively cultivated *Ganoderma lucidum* basidiocarps. Chemistry & Biodiversity 15(5):e1800036. https://doi.org/10.1002/cbdv.201800036

Cornelius C, Perrotta R, Graziano A, Calabrese EJ, Calabrese V (2013) Stress responses, vitagenes and hormesis as critical determinants in aging and longevity: Mitochondria as a "chi". Immunity and Ageing 10(1):15. https://doi.org/10.1186/1742-4933-10-15

Cui X, Zhang Y-H (2019) Neuropharmacological effect and clinical applications of *Ganoderma* (Lingzhi). In: Lin Z, Yang B (eds) *Ganoderma* and health. Advances in experimental medicine and biology book series 1182. Springer Nature Singapore Pte Ltd., pp 143–157. https://doi.org/10.1007/978-981-32-9421-9_5

Diallo I, Boudard F, Morel S, Vitou M, Guzman C, Saint N, Michel A, Rapior S, Traoré L, Poucheret P et al. (2020) Antioxidant and anti-inflammatory potential of Shiitake culinary-medicinal mushroom, *Lentinus edodes* (Agaricomycetes), sporophores from various culture conditions. International Journal of Medicinal Mushrooms 22(6):535–546. https://doi.org/10.1615/IntJMedMushrooms.2020034864

https://doi.org/10.6092/issn.2531-7342/12542

El Sayed NS, Ghoneum MH (2020) Antia, a natural antioxidant product, attenuates cognitive dysfunction in streptozotocin-induced mouse model of sporadic Alzheimer's disease by targeting the amyloidogenic, inflammatory, autophagy, and oxidative stress pathways. Oxidative Medicine and Cellular Longevity 2020:4386562. https://doi.org/10.1155/2020/4386562

Fan L, Chen L, Liang Z, Bao H, Wang D, Dong Y, Zheng S, Xiao C, Du J, Li H (2019) A polysaccharide extract from Maitake culinary-medicinal mushroom, *Grifola frondosa* (Agaricomycetes) ameliorates learning and memory function in aluminum chloride-induced amnesia in mice. International Journal of Medicinal Mushrooms 21(11):1065–1074. https://doi.org/10.1615/IntJMedMushrooms.2019032914

Farha M, Parkianathan L, Abdul Amir NAI, Sabaratnam V, Wong KH (2019) Functional recovery enhancement by tiger milk mushroom, *Lignosus rhinocerotis,* in a sciatic nerve crush injury model and morphological study of its neurotoxicity. Journal Animal and Plant Sciences 29(4):930–942.

Friedman M (2015) Chemistry, nutrition, and health-promoting properties of *Hericium erinaceus* (lion's mane) mushroom fruiting bodies and mycelia and their bioactive compounds. Journal of Agricultural and Food Chemistry 63(32):7108–7123. https://doi.org/10.1021/acs.jafc.5b02914

Gargano ML, van Greisen LJLD, Isikhuemhen OS, Lindequist U, Venturella G, Wasser SP, Zervakis GI (2017) Medicinal mushrooms: valuable biological resources of high exploitation potential. Plant Biosystems 151(3):548–565. https://doi.org/10.1080/11263504.2017.1301590

Gründemann C, Reinhardt JK, Lindequist U (2020) European medicinal mushrooms: Do they have potential for modern medicine? – An update. Phytomedicine 66:153131. https://doi.org/10.1016/j.phymed.2019.153131

Gupta S, Summuna B, Gupta M, Annepu SK (2018) Edible mushrooms: cultivation, bioactive molecules, and health benefits. In: Mérillon JM, Ramawat KG (eds) Bioactive molecules in food, reference series in Phytochemistry. Springer, pp 1–33. https://doi.org/10.1007/978-3-319-54528-8_86-1

He X, Wang X, Fang J, Chang Y, Ning N, Guo H, Huang L, Huang X, Zhao Z (2017) Structures, biological activities, and industrial applications of the polysaccharides from *Hericium erinaceus* (Lion's mane) mushroom: a review. International Journal of Biological Macromolecules 97:228–237. https://doi.org/10.1016/j.ijbiomac.2017.01.040

Ho LH, Zulkifli NA, Tan TC (2020) Edible mushroom: Nutritional properties, potential nutraceutical values, and its utilisation in food product development. In: An introduction to mushroom. IntechOpen. https://doi.org/10.5772/intechopen.91827

Hobbs C (2004) Medicinal value of Turkey tail fungus *Trametes versicolor* (L.:Fr.) Pilát (Aphyllophoromycetideae). International Journal of Medicinal Mushrooms 6:195–218. https://doi.org/10.1615/IntJMedMushrooms.v7.i3.100

Hsieh PW, Wu JB, Wu YC (2013) Chemistry and biology of *Phellinus linteus*. BioMedicine 3(3):106–113. https://doi.org/10.1016/j.biomed.2013.01.002

Huang YJ, Hsu NY, Lu KH, Lin YE, Lin SH, Lu YS, Liu WT, Chen MH, Sheen LY (2020) *Poria cocos* water extract ameliorates the behavioural deficits induced by unpredictable chronic mild stress in rats by down-regulating inflammation. Journal of Ethnopharmacology 258:112566. https://doi.org/10.1016/j.jep.2020.112566

Hyde KD, Xu J, Rapior S, Jeewon R, Lumyong S, Niego AGT, Abeywickrama PD, Aluthmuhandiram JVS, Brahamanage RS, Brooks S et al (2019) The amazing potential of fungi: 50 ways we can exploit fungi industrially. Fungal Diversity 97:1–136. https://doi.org/10.1007/s13225-019-00430-9

Jiang F, Zhang HN, Zhang L, Feng J, Wang WH, Zhang Z, Musa A, Wu D, Yang Y (2020) Antioxidant and neuroprotector influence of endo-polyphenol extract from magnesium acetate multi-stage addition in the oak bracket medicinal mushroom, *Phellinus baumii* (Agaricomycetes). International Journal of Medicinal Mushrooms 22(2):183–195. https://doi.org/10.1615/IntJMedMushrooms.2020033699

Khan MS, Zhang X, You L (2014) Structure and bioactivities of fungal polysaccharides. In: Ramawat K, Mérillon JM (eds) Polysaccharides – bioactivity and biotechnology. Springer, Cham, pp 1851–1866. https://doi.org/10.1007/978-3-319-03751-6_28-1

Khatua S, Paul S, Acharya K (2013) Mushroom as the potential source of new generation of antioxidant– a review. Research Journal of Pharmacy and Technology 6(5):496–505

Kıvrak I, Kıvrak S, Karababa E (2020) Assessment of bioactive compounds and antioxidant activity of Turkey tail medicinal mushroom *Trametes versicolor* (Agaricomycetes). International Journal of Medicinal Mushrooms 22(6):559–571. https://doi.org/10.1615/IntJMedMushrooms.2020035027

Knežević A, Stajić M, Sofrenić I, Stanojković T, Milovanović I, Tešević V, Vukojević J (2018) Antioxidative, antifungal, cytotoxic and anti-neurodegenerative activity of selected *Trametes* species from Serbia. PLoS One 13(8):e0203064. https://doi.org/10.1371/journal.pone.0203064

Kosanić M, Petrović N, Stanojković T (2020a) Bioactive properties of *Clitocybe geotropa* and *Clitocybe nebularis*. Journal of Food Measurement and Characterization 14(2):1046–1053. https://doi.org/10.1007/s11694-019-00354-7

Kosanić MM, Šeklic DS, Jovanovic MM, Petrovic NN, Markovic SD (2020b) *Hygrophorus eburneus*, edible mushroom, a promising natural bioactive agent. EXCLI Journal 19:442–457. https://doi.org/10.17179/excli2019-2056

Kou RW, Han R, Gao YQ, Li, D, Yin X, Gao JM (2021) Anti-neuroinflammatory polyoxygenated lanostanoids from Chaga mushroom *Inonotus obliquus*. Phytochemistry 184: 112647. https://doi.org/10.1016/j.phytochem.2020.112647

Kozarski M, Klaus A, Jakovljevic D, Todorovic N, Vunduk J, Petrović P, Niksic M, Vrvic MM, van Griensven L (2015) Antioxidants of edible mushrooms. Molecules 20:19489–19525. https://doi.org/10.3390/molecules201019489

Kozarski M, Klaus A, Vunduk JD, Jakovljević DM, Jadranin MB, Nikšić MP (2020) Health impact of the commercially cultivated mushroom *Agaricus bisporus* and the wild-growing mushroom *Ganoderma resinaceum* – A comparative overview. Journal of the Serbian Chemical Society 85(6):721–735. https://doi.org/10.2298/JSC190930129K

Kües U, Badalyan SM (2017) Making use of genomic information to explore the biotechnological potential of medicinal mushrooms. In: Agrawal DC, Tsay HS, Shyur LF, Wu YC, Wang SY (eds) Medicinal plants and fungi: recent advances in research and development, medicinal and aromatic plants of the world, vol 4. Springer, New York, pp 397–458. https://doi.org/10.1007/978-981-10-5978-0_13

Lai G, Guo Y, Chen D, Tang X, Shuai O, Yong T, Wang D, Xiao C, Zhou G, Xie Y et al. (2019) Alcohol extracts from *Ganoderma lucidum* delay the progress of Alzheimer's disease by regulating DNA methylation in rodents. Frontier of Pharmacology 10:272. https://doi.org/10.3389/fphar.2019.00272

Lee KF, Tung SY, Teng CC, Shen CH, Hsieh MC, Huang CY, Lee KC, Lee LY, Chen WP, Chen CC et al. (2020) Post-treatment with erinacine A, a derived diterpenoid of *H. erinaceus*, attenuates neurotoxicity in MPTP model of Parkinson's disease. Antioxidants 9(2):E137. https://doi.org/10.3390/antiox9020137

Lee W, Fujihashi A, Govindarajulu M, Ramesh S, Deruiter J, Majrashi M, Almaghrabi M, Nadar RM, Moore T, Agrawal DC et al. (2019) Role of mushrooms in neurodegenerative diseases. In: Agrawal DC & Dhanasekaran M (eds) Medicinal mushrooms: recent progress in research and development. Springer Nature, Singapore, pp 223–249. https://doi.org/10.1007/978-981-13-6382-5_8

Lee IK, Yun BS, Kim JP, Ryoo IJ, Kim YH, Yoo ID (2003) Neuroprotective activity of p-terphenyl leucomentins from the mushroom *Paxillus panuoides*. Bioscience, Biotechnology, and Biochemistry 67(8):1813–1816. https://doi.org/10.1271/bbb.67.1813

Lemieszek MK, Nunes FM, Cardoso C, Marques G, Rzeski W (2018) Neuroprotective properties of *Cantharellus cibarius* polysaccharide fractions in different *in vitro* models of neurodegeneration. Carbohydrate Polymers 197:598–607. https://doi.org/10.1016/j.carbpol.2018.06.038

Lew SY, Teoh SL, Lim SH, Lim LW, Wong KH (2020) Discovering the potentials of medicinal mushrooms in combating depression. A review. Mini Review in Medical Chemistry 20(15):1518-1531. https://doi.org/10.2174/1389557520666200526125534

Li Z, Chen X, Lu W, Zhang S, Guan X, Li Z, Wang D (2017) Anti-oxidative stress activity is essential for *Amanita caesarea* mediated neuroprotection on glutamate-induced apoptotic HT22 cells and an Alzheimer's disease mouse model. International Journal of Molecular Sciences 18(8):E1623. https://doi.org/10.3390/ijms18081623

Liang C-H, Huang P-C, Mau J-L, Chiang SS (2020) Effect of the king oyster culinary-medicinal mushroom *Pleurotus eryngii* (Agaricomycetes) basidiocarps powder to ameliorate memory and learning deficit in ability in Aβ-induced Alzheimer's disease C57BL/6J mice model. International Journal of Medicinal Mushrooms 22(2):145–159. https://doi.org/10.1615/IntJMedMushrooms.2020033766

Lin MT, Beal MF (2006) Mitochondrial dysfunction and oxidative stress in neurodegenerative diseases. Nature 443:787–795. https://doi.org/doi:10.1038/nature05292

Lu MC, El-Shazly M, Wu TY, Du YC, Chang TT, Chen CF, Hsu YM, Lai KH, Chiu CP, Chang FR et al. (2013) Recent research and development of *Antrodia cinnamomea*. Pharmacology and Therapeutics 139(2):124–156. https://doi.org/10.1016/j.pharmthera.2013.04.001

Lucius K (2020) Medicinal mushrooms: current use in clinical practice. Alternative and Complementary Therapy 26(3):119–126. https://doi.org/10.1089/act.2020.29275.kha

Ma BJ, Shen JW, Yu HY, Du YC, Chang TT, Chen CF, Hsu YM, Lai KH, Chiu CP, Chang FR et al. (2010) Hericenones and erinacines: stimulators of nerve growth factor (NGF) biosynthesis in *Hericium erinaceus* Mycology 1(2):92–98. https://doi.org/10.1080/21501201003735556

Mahmoud MG, Ibrahim AY, Asker MM, El Sayed OH (2014) Therapeutic potential and structural elucidation of a water-soluble polysaccharide of a wild edible mushroom *Agaricus bisporus* against neurodegenerative disease, Alzheimer. World Journal of Pharmaceutical Sciences 2(10):1136–1145.

Morel S, Arnould S, Vitou M, Boudard F, Guzman C, Poucheret P, Fons F, Rapior S (2018) Antiproliferative and antioxidant activities of wild Boletales mushrooms from France. International Journal of Medicinal Mushrooms 20(1):13–29. https://doi.org/10.1615/IntJMedMushrooms.2018025329

Muszyńska B, Fijałkowska A, Sułkowska-Ziaja K, Włodarczyk A, Kaczmarczyk P, Nogaj E, Piętka J (2020) *Fomitopsis officinalis*: a species of arboreal mushroom with promising biological and medicinal properties. Chemistry and Biodiversity 17:e2000213. https://doi.org/10.1002/cbdv.202000213

https://doi.org/10.6092/issn.2531-7342/12542

Ning X, Luo Q, Li C, Ding Z, Pang J, Zhao C (2014) Inhibitory effects of a polysaccharide extract from the Chaga medicinal mushroom, *Inonotus obliquus* (higher basidiomycetes), on the proliferation of human neurogliocytoma cells. International Journal of Medicinal Mushrooms 16(1):29–36. https://doi.org/10.1615/intjmedmushr.v16.i1.30

Palacios I, Lozano M, Moro C, D'Arrigo M, Rostagno MA, Martínez JA, García-Lafuente A, Guillamón E, Villares A (2011) Antioxidant properties of phenolic compounds occurring in edible mushrooms. Food Chemistry 128:674–678. https://doi.org/10.1016/j.foodchem.2011.03.085

Park HJ, Shim HS, Ahn YH, Kim KS, Park KJ, Choi WK, Ha HC, Kang JI, Kim TS, IH Yeo et al. (2012) *Tremella fuciformis* enhances the neurite outgrowth of PC12 cells and restores trimethyltin-induced impairment of memory in rats via activation of CREB transcription and cholinergic systems. Behavioural Brain Research 229:82–90. https://doi.org/10.1016/J.BBR.2011.11.017

Pejin B, Tešanović K, Jakovljević D, Kaišarević S, Šibul F, Rašeta M, Karaman M (2019) The polysaccharide extracts from the fungi *Coprinus comatus* and *Coprinellus truncorum* do exhibit AChE inhibitory activity. Natural Product Research 33(5):750–754. https://doi.org/10.1080/14786419.2017.1405417

Phan CW, David P, Sabaratnam V (2017) Edible and medicinal mushrooms: emerging brain food for the mitigation of neurodegenerative diseases. Journal of Medicinal Food 20(1):1–10. https://doi.org/10.1089/jmf.2016.3740

Phan CW, Wong WL, David P, Naidu M, Sabaratnam V (2012) *Pleurotus giganteus* (Berk.) Karunarathna & KD Hyde: nutritional value and *in vitro* neurite outgrowth activity in rat pheochromocytoma cells. BMC Complementary and Alternative Medicine 12:102. https://doi.org/10.1186/1472-6882-12-102

Phan CW, David P, Tan YS, Naidu M, Wong KH, Kuppusamy UR, Sabaratnam V (2014) Intrastrain comparison of the chemical composition and antioxidant activity of an edible mushroom, *Pleurotus giganteus,* and its potent neuritogenic properties. Science World Journal 2014:378651. https://doi.org/10.1155/2014/378651

Phan CW, David P, Naidu M, Wong KH, Sabaratnam V (2015) Therapeutic potential of culinary-medicinal mushrooms for the management of neurodegenerative diseases: diversity, metabolite, and mechanism. Critical Review in Biotechnology 35(3):355–368. https://doi.org/10.3109/07388551.2014.887649

Pleszczyńska M, Lemieszek MK, Siwulski M, Wiater A, Rzeski W, Szczodrak J (2017) *Fomitopsis betulina* (formerly *Piptoporus betulinus*): the iceman's polypore fungus with modern biotechnological potential. World Journal of Microbiology and Biotechnology 33(5):83. https://doi.org/10.1007/s11274-017-2247-0

Pop RM, Puia IC, Puia A, Chedea VS, Leopold N, Bocsan IC, Buzoianu AD (2018) Characterization of *Trametes versicolor*: medicinal mushroom with important health benefits. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 46(2):343–349. https://doi.org/10.15835/nbha46211132

Qin DW, Han C (2014) Medicinal and edible fungi as an alternative medicine for treating age-related disease. Evidence Based Complementary and Alternative Medicine 2014:ID638561. https://doi.org/10.1155/2014/638561

Rahman MA, Hossain S, Abdullah N, Aminudin N (2020) Reishi medicinal mushroom, *Ganoderma lucidum* (Agaricomycetes) ameliorates spatial learning and memory deficits in rats with hypercholesterolemia and Alzheimer's disease. International Journal of Medicinal Mushrooms 22(1):93–103. https://doi.org/10.1615/IntJMedMushrooms.2020033383

Rathore H, Prasad S, Sharma S (2017) Mushroom nutraceuticals for improved nutrition and better human health: a review. Pharma Nutrition 5(2):35–46. https://doi.org/10.1016/j.phanu.2017.02.001

https://doi.org/10.6092/issn.2531-7342/12542

Rossi P, Cesaroni V, Brandalise F, Occhinegro A, Ratto D, Perrucci F, Lanaia V, Girometta C, Orrù G, Savino E (2018) Dietary supplementation of lion's mane medicinal mushroom, *Hericium erinaceus* (Agaricomycetes), and spatial memory in wild-type mice. International Journal of Medicinal Mushrooms 20(5):485–494. https://doi.org/10.1615/IntJMedMushrooms.2018026241

Rupcic Z, Rascher M, Kanaki S,, Köster RW, Stadler M, Wittstein K (2018) Two new cyathane diterpenoids from mycelial cultures of the medicinal mushroom *Hericium erinaceus* and the rare species, *Hericium flagellum*. International Journal of Molecular Sciences 19(3):E740. https://doi.org/10.3390/ijms19030740

Sabaratnam V, Phan CW (2018) Neuroactive components of culinary and medicinal mushrooms with potential to mitigate age-related neurodegenerative diseases. In: Discovery and development of neuroprotective agents from natural products. Brahmachari G (ed), 1st edn. Elsevier, pp. 401–413. https://doi.org/10.1016/B978-0-12-809593-5.00010-0

Scuto M, Di Mauro P, Ontario ML, Amato C, Modafferi S, Ciavardelli D, Trovato Salinaro A, Maiolino L, Calabrese V (2020) Nutritional mushroom treatment in Meniere's disease with *Coriolus versicolor*: A rationale for therapeutic intervention in neuroinflammation and antineurodegeneration. International Journal of Molecular Sciences 21(1):284. https://doi.org/10.3390/ijms21010284

Tang D, Xu Y-Z, Wang W-W, Yang Z, Liu B, Stadler M, Liu L-L, Gao J-M (2019) Cyathane diterpenes from cultures of the bird's nest Fungus *Cyathus hookeri* and their neurotrophic and anti-neuroinflammatory activities. Journal Natural Products 82(6):1599–1608. https://doi.org/10.1021/acs.jnatprod.9b00091

Thangthaeng N, Miller MG, Gomes SM, Shukitt-Hale B (2015) Daily supplementation with mushroom (*Agaricus bisporus*) improves balance and working memory in aged rats. Nutrition Research 35(12):1079–1084. https://doi.org/10.1016/j.nutres.2015.09.012

Trovato Salinaro A, Pennisi M, Di Paola R, Scuto M, Crupi R, Cambria MT, Ontario ML, Tomasello M, Uva M, Maiolino L et al. (2018) Neuroinflammation and neurohormesis in the pathogenesis of Alzheimer's disease and Alzheimer-linked pathologies: modulation by nutritional mushrooms. Immunity and Ageing 15:8. https://doi.org/10.1186/s12979-017-0108-1

Wang C, Liu X, Lian C, Ke J, Liu J (2019b) Triterpenes and aromatic meroterpenoids with antioxidant activity and neuroprotective effects from *Ganoderma lucidum*. Molecules 24(23):4353. https://doi.org/10.3390/molecules24234353

Wang M, Gao Y, Xu D, Tonishi T, Gao Q (2014) *Hericium erinaceus* (yamabushitake): a unique resource for developing functional foods and medicines. Food Funct 5(12):3055–3064. https://doi.org/10.1039/c4fo00511b

Wang XY, Zhang DD, Yin JY, Nie SP, Xie MY (2019a) Recent developments in *Hericium erinaceus* polysaccharides: extraction, purification, structural characteristics and biological activities. Critical Review in Food Science and Nutrition 59(1):S96–S115. https://doi.org/10.1080/10408398.2018.1521370

Wasser SP, Didukh MY (2005) Mushroom polysaccharides in human health care. In: Deshmukh SK, Rai MK (eds) Biodiversity of fungi: their role in human life. Oxford & IBH Publishing, pp 289–328.

Wu YJ, Wei ZX, Zhang FM, Linhardt RJ, Sun PL, Zhang AQ (2019) Structure, bioactivities and applications of the polysaccharides from *Tremella fuciformis* mushroom: A review. International Journal of Biological Macromolecules 121:1005–1010. https://doi.org/10.1016/j.ijbiomac.2018.10.117

https://doi.org/10.6092/issn.2531-7342/12542

Yadav SK, Ir R, Jeewon R, Doble M, Hyde KD, Kaliappan I, Jeyaraman R, Reddi RN, Krishnan J, Li M et al. (2020) A mechanistic review on medicinal mushrooms-derived bioactive compounds: potential mycotherapy candidates for alleviating neurological disorders. Planta Medica. 86:1–15. https://doi.org/10.1055/a-1177-4834

Yin X, Wei J, Wang WW, Gao YQ, Stadler M, Kou RW, Gao JM (2019) New cyathane diterpenoids with neurotrophic and anti-neuroinflammatory activity from the bird's nest fungus *Cyathus africanus*. Fitoterapia 134:201–219. https://doi.org/10.1016/j.fitote.2019.02.013

Yin Z, Chen J, Zhang J, Ren Z, Dong K, Kraus VB, Wang Z, Zhang M, Zhai Y, Song P et al. (2018) Dietary patterns associated with cognitive function among the older people in underdeveloped regions: finding from the NCDFaC study. Nutrients 10(4):E464. https://doi.org/10.3390/nu10040464

Zhang CJ, Guo JY, Cheng H, Lin L, Liu Y, Shi Y, Xu J ,Yu HT (2020) Protective effects of the king oyster culinary-medicinal mushroom, *Pleurotus eryngii* (Agaricomycetes), polysaccharides on β-amyloid-induced neurotoxicity in PC12 cells and aging rats, *in vitro* and *in vivo* studies. International Journal of Medicinal Mushrooms 22(4):325–333. https://doi.org/10.1615/IntJMedMushrooms.2020033990

Zhang CJ, Shi R, Li H, Xiang Y, Xiao L, Hu M, Ma F, Ma CW, Huang Z (2016b) Antioxidant and neuroprotective effects of *Dictyophora indusiata* polysaccharide in *Caenorhabditis elegans*. J Ethnopharmacology 192:413–422. https://doi.org/10.1016/j.jep.2016.09.031

Zhao C, Zhang C, Xing Z, Ahmad Z, Li JS, Chang MW (2019) Pharmacological effects of natural *Ganoderma* and its extracts on neurological diseases: a comprehensive review. International Journal of Biological Macromolecules 121:1160–1178. https://doi.org/10.1016/j.ijbiomac.2018.10.076