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REVIEW ARTICLE

Mushrooms: from nutrition to mycoremediation

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Abstract Mushrooms are well known as important food items. The uses of mushrooms in the cuisine are manifolds and are being utilized for thousands of years in both Oriental and Occidental cultures. Medicinal properties of mushrooms show an immense potential as drugs for the treatment of various diseases as they are rich in a great variety of phytochemicals. In this review, we attempted to encompass the recent knowledge and scientific advancement about mushrooms and their utilization as food or curative properties, along with their natural ability to accumulate (heavy) metals/radionuclides, which leads to an important aspect of bioremediation. However, accumulation of heavy metals and radionuclides from natural or anthropogenic sources also involves potential nutritional hazards upon consumption. These hazards have been pointed out in this review incorporating a selection of the most recently published literature.

Keywords Nutraceutical · Phytochemical · Disease · Anti-oxidant · Radionuclides · Bioremediation

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Introduction

Mushrooms (or toadstool), the spore-bearing fruiting bodies of fungi, have gained lots of varying reputations throughout the history as both food and foe and are adorned as delicious, deadly, magical, cultural, traditional, intoxicating, mysterious, and legendary (Arora and Shepard 2008; Avey 2014). Humans have been attracted to mushrooms since ancient times. Romans termed mushroom as "food of the gods"; Greeks used them to provide strength for soldiers in battles (Zhang et al. 2014). It is one of the ingredients of gastronomic cuisine and valued by humankind as a culinary wonder for their unique flavor and tastes, especially for vegetarians (Chang and Miles 2008; Li et al. 2011; Nnorom et al. 2012; Giannaccini et al. 2012; Valverde et al. 2015). Mushrooms are being used from early ages especially for nutrition purposes. The knowledge on mushrooms for generations helps in obtaining safe mushrooms of high quality. This crucial knowledge on the toxicity or innocuousness of mushrooms had to be gathered basically due to painstaking (and partly fatal) efforts by cohorts of mushroom hunters resulting in the identification of food-safe mushrooms. In the mid-seventeenth century, a melon grower of Paris first stumbled upon the significant discovery of sprouting mushrooms over some melon leftovers (Scelta Mushrooms 2017). This novel mushroom rapidly gained the name "champignon de Paris" (Paris mushroom), which was later identified as *Agaricus bisporus* (also known as common mushroom, button mushroom, white mushroom, cultivated mushroom, table mushroom, etc.). People began to grow the mushrooms in various substrates mixed up with manure. In 1780, French gardener Chambray discovered that the cave climates were ideal for mushroom growth and sooner, French town of Saumus (having many deserted marl caves) became the city of mushroom farms (Scelta Mushrooms 2017).

Edible mushrooms have high nutritional and functional food value with medicinal properties, some of which also are of economic significance. Further, mushrooms have significant organoleptic food properties as an individual experience via the senses like smell, taste, sight, and touch (Chang and Miles 2008; Ergonul et al. 2013; Valverde et al. 2015). All edible mushrooms have therapeutic properties, and therefore, it is difficult to distinguish mushroom species as only for medicinal values (Guillamon et al. 2010; Kozarski et al. 2015). However, wild mushrooms are a treasure for newer components for nutrition, sensory, and therapeutic characteristics (Ergonul et al. 2013), followed by *Lentinus edodes*, *Pleurotus* spp., and *Flammulina velutipes* (Aida et al. 2009; Patel and Goyal 2012; Kozarski et al. 2015; Valverde et al. 2015).

In nature, around 150,000 species of mushrooms exist; among all, ample of known edible and/or wild mushroom species grow in different ecological locations (Sullivan et al. 2006; Wasser 2011; Paterson and Lima 2014). Some species of mushroom are being used in medicine for thousands of years. However, only 10–15% of mushroom species have been scientifically described, leaving a huge yet undiscovered resource of potentially important natural products (Paterson and Lima 2014). Around 25 species are generally accepted as food, and few are commercially cultivated at large scale (Valverde et al. 2015). The most commonly cultivated mushroom species are *Agaricus* spp., *Pleurotus* spp. (oyster), *Lentinula edodes* (shiitake), *Grifola frondosa* (maitake), *Volvariella volvacea* (straw), *Hericium erinaceus* (Lion's head or pompom), *Auricularia auricula-judae* (ear), *Ganoderma lucidum* (lingzhi), *F. velutipes*, *Tremella fuciformis*, *Pholiota nameko*, *Lepista nuda* (blewit), and *Coprinus comatus* (shaggy mane) (Caglarirmak 2011; Kozarski et al. 2015; Valverde et al. 2015). *Agaricus bisporus* is the most cultivated mushroom worldwide, having highest economic value in the market. Other economically important mushrooms such as *L. edodes*, *Pleurotus* spp., and *F. velutipes* are usually cultivated under artificial conditions having a well-defined substrate, scientifically proven processing, and controlled environment (Kozarski et al. 2015).

Food and nutritional value of mushrooms

Mushroom production is unceasingly increasing throughout the world. They are quite rich in protein and hence have a high nutritional value. Mushroom extracts are commercially available as dietary supplements and claim enhancing human immunity. In several cultures, mushrooms are habitually utilized for health care and common disease protection. They are also considered as a part of balanced diet that helps in supporting treatment for anticipating ailments and particularly oxidative stress mitigation (Valverde et al. 2015). Mushrooms are a valuable source of new anti-microbial, secondary metabolites such as steroids, terpenes, anthraquinones, quinolones, and benzoic acid derivatives and primary metabolites such as peptides, and proteins, and oxalic acid, important fatty acids, essential amino acids, dietary fibers, glycosides, alkaloids, volatile oils, terpenoids, tocopherols, phenolics, flavonoids, carotenoids, folates, lectins, enzymes, ascorbic, and organic acids and nutritionally important vitamins (B1, B2, B12, C, D, and E) nutraceuticals, and β-glucan (a versatile metabolite with a varied range of biological activities) (Chen and Seviour 2007; Chang and Wasser 2012; Finimundy et al. 2013; Ribeiro et al. 2009; Rop et al. 2009; Singh et al. 2010; Lee et al. 2013; Reis et al. 2012; Kalac 2013). Their use in treatment of ailments through their immunomodulatory and anti-neoplastic properties is a new area of research (Ferreira et al. 2010). Having many biological properties, mushrooms are used for more than hundred different medicinal functions, such as anti-cancer, anti-diabetic, anti-oxidant, anti-allergic, anti-inflammation, anti-viral, anti-bacterial, anti-parasitic, anti-fungal, detoxification, cardiovascular protection, immunomodulation, anti-cholesterolemic, and hepatoprotective and effects against tumor development (Brown and Waslien 2003; Sarikurkcu et al. 2008; Chang and Wasser 2012; Carneiro et al. 2013).

Apart from other vitamins, mushroom is a unique food that can provide vitamin D. The level of vitamin D can significantly be enhanced by exposure to UV irradiation (UVB) or sunlight. In case of *A. bisporus*, a significant increase occurs in the amount of vitamin D (up to 11.2 μg of vitamin D 100 g^{-1} in comparison with 0.2 μg in non-exposed one) when it is exposed to UV light during cultivation (Roupas et al. 2014). Many mushrooms are therefore a good source of vitamin D, even after cooking. Mushrooms like tree ears, shiro kikurage, provides a substantial 970 μg/100 g dried weight (Roupas et al. 2014).

Biocomponents vary throughout the various species of mushrooms. Further, their content of chemical components and the nutritive value depend upon mushroom strains, substrate, cultivation, developmental stage, age, post-harvest storage conditions, processing, and cooking practices (Mattila et al. 2001; Reis et al. 2012; Kalac 2013). In general, mushrooms have low quantities of fat (1–4% dry weight basis), with oleic (C18:1), linoleic (C18:2), and palmitic (C16:0) the major fatty acids. Protein content also varies greatly in different mushroom species (about 4–35% dry weight basis), but they are always treated as a good source of protein, with leucine, valine, glutamine, glutamic, and aspartic acids the most abundant amino acids. Essential elements such as potassium, magnesium, calcium, phosphorus, copper, iron, and zinc are also present in mushrooms. However, carbohydrates are the major constituents and are found in higher quantities in edible mushrooms. Edible mushrooms contain higher amounts of glucose, mannitol, and trehalose, whereas fructose and sucrose are present in lower amounts along with chitin, hemicelluloses, *β*-glucans, and pectic substances.

Nutraceuticals in mushroom

Mushrooms are rich in various bioactive compounds, although the quality and quantity of those substances may vary considerably in different species. It is also reported that selected mushrooms can produce a total of 126 medicinal functions (Wasser 2011; Kalac 2013; Roupas et al. 2014) contributing mainly in biotechnological applications in health care research and development of new drugs. Further, availability of various enzymes, proteases and protease inhibitors, lignocellulases, components such as glycoproteins and polysaccharides (mostly *β*-glucans), lectins, ribosome-inactivating proteins, hydrophobins, sterols, terpenoids, polyphenols, sesquiterpenes, alkaloids, lactones, metal chelators, nucleotide analogs, and vitamins is widely reported in mushroom (Wang et al. 2014). Given the low percentage of taxonomically classified mushrooms, there is a significant potential for useful and novel nutritive source and therapeutic molecules (Hassan et al. 2015).

Mushroom carbohydrates and their importance

Varieties of carbohydrate molecules are present in different species of mushrooms having anti-tumor and immune-modulating properties. The molecules include rhamnose, xylose, fructose, glucose, fucose, arabinose, mannitol, mannose, sucrose, trehalose, maltose ,and *β*-glucans (Ferreira et al. 2010; Heleno et al. 2012). *β*-Glucans constitute about 15% of the fungal cell wall mass and therefore are the main polysaccharides found in mushrooms. *β*-Glucans (especially beta-1,3-D-glucans and beta-1,6-D-glucans) isolated from selected mushroom species have higher biological efficiency, i.e., to promote a desired faster physiological response (Rop et al. 2009) and also potentially important molecules for various useful therapeutic purposes. The polysaccharides boost the quantity of Th1 lymphocytes, helping in protecting organisms against allergic reactions. *β*-Flucans can have many other functions, including immunity-stimulating effect, fat metabolism in human body, weight reduction, and anti-cholesterolemic, anti-oxidant, neuroprotective actions, and anti-carcinogenic effects (especially of oyster and shiitake) (Rop et al. 2009; Volman et al. 2010; Valverde et al. 2015).

β-glucans and related polysaccharides augment host immune defense by enhancing macrophages, neutrophils, monocytes, activating complement system, dendritic cells, and natural killer cell function (Akramiene et al. 2009; Chan et al. 2009). A number of cell membrane receptors are involved with the stimulation of cellular responses, which include complement receptor 3 (CR3; CD11b/CD18), TLR-2/6, lactosylceramide, selected scavenger receptors, and dectin-1 (betaGR) (Akramiene et al. 2009). *β*-Glucans also have an effect on intestinal immune system, when edible mushrooms come in contact with intestinal enterocytes. These molecules protect against infectious diseases and carcinogenesis and help patients recovering from radiotherapy and chemotherapy (Hung and Nhi 2012; Lee et al. 2013). Volman et al. (2010) demonstrated that bone marrow-derived macrophages (BMMs) produce more nitric oxide when stimulated with mushroom such as *A. bisporus* (whereas extracts from *C. comatus* and *G. lucidum* had only minor effects) and branching of the *β*-glucan chain is crucial for the immune-stimulating activity. Thus, the mushroom *A. bisporus* is a significant species as a nutritional compound to increase depressed immunity conditions through quick immune response (Volman et al. 2010). It is reported that both innate and adaptive responses can be adapted by *β*-glucans and are capable in boosting opsonic and non-opsonic phagocytosis (Chan et al. 2009). Interestingly, the chemical structures of anti-tumor polysaccharide components vary widely (from homopolymers to highly complex heteropolymers), which usually do not kill tumor cells, but instead act by lowering the stress burden of the affected cells and therefore reducing the tumor size and prolonging the survival time (Zhang et al. 2007; Xu et al. 2011; Hung and Nhi 2012).

The precise linear backbone (1–3-beta-glycosidic chain) of *β*-glucans is not digested in the stomach. Most of the *β*-glucans are absorbed at the proximal part of small intestine within the first 30 min of oral administration, and some are taken up by the macrophages via the Dectin-1 receptor and are subsequently transported to the spleen, lymph nodes, and bone marrow (Rice et al. 2004; Vetvicka et al. 2007; Chan et al. 2009). CR3 of marginated granulocytes takes up smaller soluble β-1,3-glucan fragments after degradation of larger β-1,3-glucans. Interestingly, researchers showed that these granulocytes with CR3-bound β-glucan (with fluorescein tagged) are capable of destroying inactivated complement 3b (iC3b)-opsonized tumor cells (Hong et al. 2004; Vetvicka et al. 2007; Chan et al. 2009; Wang et al. 2015). Wan-Mohtar et al. (2016) recently studied on 1,3-β-D-glucan and its sulfated derivative form *G. lucidum* BCCM 31549; they found improved solubility and therapeutic activities on sulfation. Sulfated glucan showed prospective multifunctional effects including anti-microbial activities against a diverse group of test bacteria and significant anti-proliferation against cancerous Human Caucasian histiocytic lymphoma (U937 cells) at low concentration (Wan-Mohtar et al. 2016). Thus, β-glucans of selected mushroom species have an important market value for various nutritional and therapeutic purposes, where ultrasonic treatment and other commercially available methods are in use for faster and efficient extraction (McIntosh et al. 2005; McCleary and Draga 2016; Alzorqi et al. 2016). However, careful selection of appropriate beta-glucans and its proper extraction process is necessary for investigating the clinical effects of β-glucans. Further, in a recent report, it has been proposed that some mushroom (*Phellinus linteus*, *G. lucidum*, and *A. auricula*) polysaccharide-treated HepG2 cells are helpful in alteration in expression of a small number of differentially expressed proteins, resulting in the polysaccharide-treated effects on the protein-protein interaction, which may help determining marker proteins to develop natural foods with anti-tumor properties (Chai et al. 2016).

Proteins in mushrooms

Mushrooms produce various kinds of bioactive proteins and peptides like lectins, anti-microbial proteins, fungal ribosome inactivating proteins, immunomodulatory proteins, ribonucleases, and laccases (Xu et al. 2011; Ismaya et al. 2016). Bioactive proteins of mushrooms are also potential candidates for the application as adjuvants for tumor/immunotherapy due to their activity in suppressing tumor invasion and metastases (Lin et al. 2010). Among proteins and glycoproteins (non-immunoglobulin proteins), lectins have gained much attention especially in cancer biology. Lectins are capable to bind diverse cell surface carbohydrates with specific selectivity. They play a vital role in various biological processes including cell-cell interactions and cellular signaling; differentiation and protein targeting to cellular compartments; host immune system; anti-viral, anti-bacterial, and anti-fungal activity inflammation; and cancer (Hassan et al. 2015). Specific mushroom lectins also have immunomodulatory, anti-proliferative, and anti-tumor activities (Ismaya et al. 2016). Some of the lectin molecules are extremely effective in anti-proliferative activity to some tumor cell lines, such as hepatoma HepG2 cells, human leukemic T cells, and breast cancer MCF7 cells (Xu et al. 2011; Valverde et al. 2015).

Mushroom lipids

Edible mushrooms mainly contain polyunsaturated fatty acids, whereas trans-isomers of unsaturated fatty acids have hardly been detected. Therefore, mushrooms help reducing serum cholesterol (Ferreira et al. 2010; Alves et al. 2012). Ergosterol is the major sterol compound produced, having important anti-oxidant properties, and helps in prevention of cardiovascular diseases (Guillamon et al. 2010; Kalac 2013). Natural anti-oxidants such as tocopherols perform as free radical scavengers, thus promoting many biological activities. These anti-oxidants help protecting against cardiovascular diseases, degenerative malfunctions, and cancer. Essential fatty acids such as linoleic acid are present in the mushrooms, which has positive health effects in a range of physiological functions by reducing the risk of cardiovascular diseases, high blood pressure, and arthritis (Reis et al. 2012; Valverde et al. 2015).

Phenolic compounds

Secondary metabolites such as phenolic compounds (simple molecules or complex polymers) are present in the mushrooms and exhibit various physiological properties, especially as anti-oxidant agents, free radical scavengers, singlet oxygen quenchers, or metal ion chelators (Balasundram et al. 2006; Ferreira et al. 2009). Therefore, they help in anti-allergenic, anti-microbial, anti-thrombotic, cardioprotective, anti-atherogenic, anti-inflammatory, and vasodilator effects. Several studies showed that mushrooms contain 1–6 mg phenolics per gram of dried mushroom. Further, flavonoid (chiefly, myricetin and catechin) concentrations ranged between 0.9 and 3.0 mg per gram of dried mushroom. Palacios et al. (2011) estimated the total phenolic and flavonoid contents in eight types of edible mushrooms (*A. bisporus*, *Boletus edulis*, *Calocybe gambosa*, *Cantharellus cibarius*, *Lactarius deliciosus*, *Craterellus cornucopioides*, *Hygrophorus marzuolus*, and *Pleurotus ostreatus*), *A. bisporus*, and *B. edulis*) which showed highest content of phenolic compounds, whereas *L. deliciosus* has a high amount of flavonoids (Palacios et al. 2011; Valverde et al. 2015).

Edible mushroom production

Mushrooms are attaining popularity among health-conscious consumers as rich sources of nutrition, with low cholesterol and fat and gluten-free and very low in sodium content. The cultivation of mushrooms, for the past half century, has experienced a rapid growth of about a factor of 10 from 1969 to 2009. According to FAO data (Food and Agriculture Organization of the United Nations (FAO) 2017), remarkable increases in mushroom production occurred in China, USA, The Netherlands, India, and Vietnam (Zhang et al. 2014). In 2013, the global market for mushrooms was valued at $29,428 million and is anticipated to grow to reach $50,000 million by 2019. Europe, followed by the Asia-Pacific region, also dominates the market (MARKETS and MARKETS 2017). Among approximately 200 genera of useful macro fungi in the world, button mushrooms (*A. bisporus*), shiitake mushrooms (*L. edodes*), and oyster mushrooms (*Pleurotus* spp.) account for almost 76% of the overall mushroom market in 2013 (MARKETS and MARKETS 2017). It can be used fresh or preserved/processed (like dried, deep frozen, and canned). Further, edible wild-grown mushrooms are also used. In China, many species of such wild-grown edible mushrooms (such as *Tricholoma matsutake*, *Lactarius hatsudake*, or *Boletus aereus*) are acceptable as food and are also used as Chinese traditional medicine. Now, China is the biggest producer around the world, and about 25 million farmers are currently engaged in the production of mushrooms worth US$24 billion in 2011 (Zhang et al. 2014). Farming of saprotrophic species such as oyster and shiitake mushrooms has grown rapidly recently (Arora and Shepard 2008). However, some mushroom species may also be considered as one of the most expensive foods of the world. The Japanese mushroom mattake or matsutake (*T. matsutake*, that grows on pine trees), a mycorrhizal fungus that has been collected and consumed from ancient times, is the most expensive mushroom species (in Japan, with a price range of retail for US$200–2000 per kilogram) (Gover 2017).

Macro and trace mineral constituents in mushrooms

Mushrooms also play an important role in geomycology by transforming organic and inorganic components, element cycling, interacting with metals, and forming mycogenic minerals (Gadd 2007; Gadd et al. 2012; Falandysz and Borovička 2013). Mycelia of mushrooms (saprophytes), at the zone of colonization, produce a range of active chemical compounds such as enzymes and organic acids that help in biotransformation, solubilization, and mobilization of nutrients including amino acids, peptides, proteins, amino sugars, chitin, and nucleic acids and organic nitrogen and phosphorus (van Schöll et al. 2006; Baldrian 2008). Similarly, mushroom can also solubilize various metals and minerals (Fomina et al. 2006, 2007; Plassard et al. 2011) and subsequently may be complemented by precipitation of various mycogenic minerals (Urban 2011; Gadd et al. 2012; Rhee et al. 2012). The type and quantity of the extracellular enzymes and other bioactive components vary as per the mushroom species. However, the intricate processes of chemical action of mineralization in soils also lead to the phenomena like uptake, transport, and accumulation of different metals in fruit bodies, which is still not well understood (Falandysz and Borovička 2013).

It has been reported that along with the mycelium, rhizomorphs also play a critical role in elemental uptake; Fig. 1 shows the typical metal uptake routes in mushrooms. Together, mycelium and rhizomorphs can spread far into the soil (as for example, mushroom *Armillaria bulbosa* can spread over 150,000 m^2 of forest floor) that help in elemental uptake (Smith et al. 1992). The chemical constituents of edible fruit bodies are of much interest for researchers as it may directly affect consumers. More than a century ago, Zellner (1907) first reported on the chemical composition of a mushroom. This work was followed by several researchers, although the taxonomical identification and reliable chemical data from advanced instrumentations started only after 1970 (Falandysz and Borovička 2013). It has been reported by several researchers that accumulation of various essential and non-essential or even toxic elements takes place within the mushroom, which naturally depends upon the substrate on which they are growing. Falandysz et al. (2012) reported the presence of Hg and Ag in fruiting bodies of *Armillaria solidipes*. Relatively high concentrations of elements including Hg, Cd, As, Se, Sb, Ag, Au, Cs, Rb, V, and Zn have been reported to be accumulated by the mushrooms (Drbal et al. 1975; Byrne et al. 1976; Bakken and Olsen 1990; Falandysz et al. 2001, 2012; Falandysz and Borovička 2013). Interestingly, mushrooms can also be studied to investigate metal transport and sequestration patterns for environmental/ecological monitoring purposes, including accumulation pattern of radionuclides (Vinichuk et al. 2011; Aloupi et al. 2011; Blaudez and Chalot 2011; Osobová et al. 2011; Gryndler et al. 2012).

Macrofungi have variable but highly specific capabilities of accumulating very high concentrations of metallic elements within their fruit body, even when growing at low metalliferous soils (Falandysz and Borovička 2013) (Table 1). The ability of accumulation of an element of a fungus is termed as a bioaccumulation factor (BAF). The BAF stands for the ratio of a radionuclide in a fruiting body to the (bioavailable) concentration in soil. A BAF > 1 represents the ability of macrofungi to typically accumulate certain elements in higher concentrations, which include Ag, As, Au, Br, Cd, Cl, Cs, Cu, Hg, Rb, Se, V, and Zn, whereas BAF < 1 includes elements (typically accumulate in low concentrations) Co, Cr, F, I, Ni, Sb, Sn, Th, and U and rare earth elements (Falandysz and Borovička 2013).

However, several factors influence the bioaccumulation of trace elements in mushrooms. In natural condition, elemental accumulation may vary due to major factors like the substrate on which they are growing (and related bedrock geochemistry), fungal lifestyle (as for example, growing as saprotrophs), species, etc. (Falandysz et al. 2011). It is known that other factors such as organic matter content, pH/Eh conditions, moisture availability, and porosity influence the elemental uptake. However, the uptake process is poorly understood in case of macrofungi (Kabata-Pendias 2011). Gast et al. (1988) studied naturally emerged mushrooms such as *Amanita muscaria*, *Amanita rubescens*, *Lepista nabularis*, *Hygrophoropsis aurantiaca*, *Paxillus involutus*, and *Suillus luteus* and did not report any influence of soil pH or organic matter on accumulation of Cd, Cu, Pb, and Zn. Further studies on *A. muscaria*, *P. involutus*, and *Leccinum scabrum* also confirm the non-influential characteristics of other substrate factors on accumulation pattern of several elements (Brzostowski et al. 2009, 2011; Falandysz and Borovička 2013; Kojta and Falandysz 2016). However, substrate amendments may augment metal accumulation, as reported for Cd,

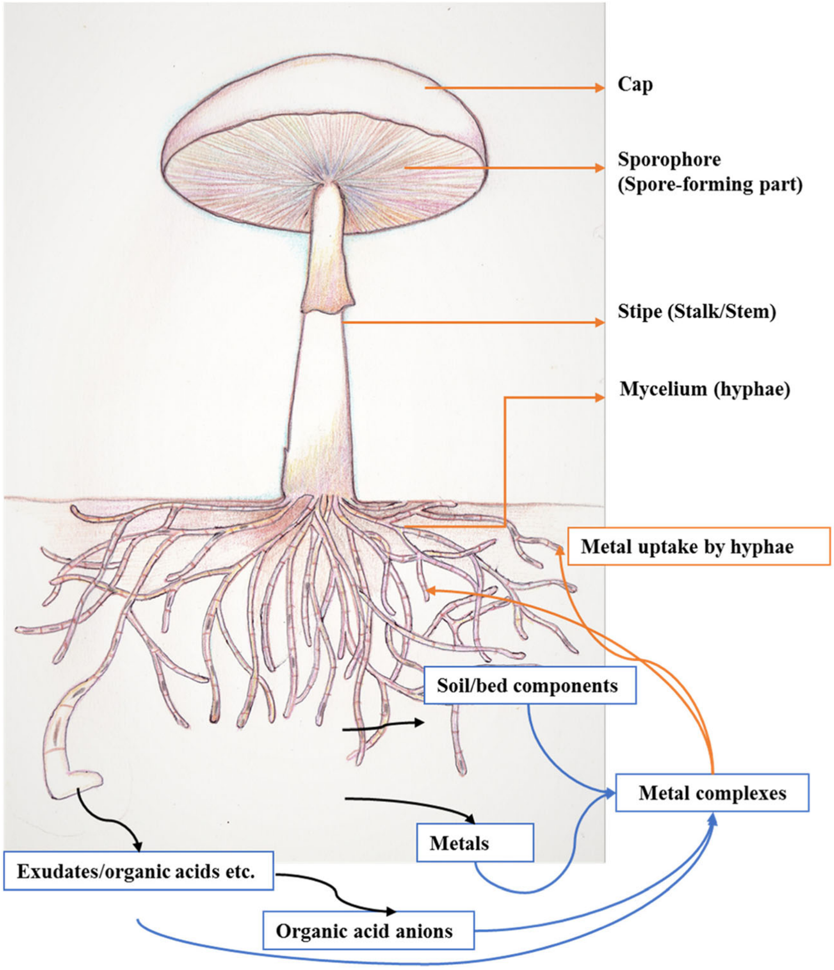

Fig. 1 A typical figure of mushroom showing routes of metal uptake inside organelles

Cu, and Pb in *C. comatus* after using ethylenediaminetetraacetic acid (Cen et al. 2012). Again, accumulation and concentration of elements in mushroom may differ significantly from species to species (Lavola et al. 2011).

Biodegradation potential in mushroom species

Cleanup of contaminated soil and groundwater using microorganism on the basis of bioremediation (https://www.epa.

Table 1 Element concentrations (g kg^{-1} dry mass) in mushrooms

Species	K	P	Na	Mg	Ca	Cu	Zn	Hg	Cd	Pb	Ag
Boletus edulis	25–29	NA	150–360	590–960	38–190	26–64	74–210	1.2–7.6	2.0–3.8	0.5–2.6	0.51–2.0
Macrolepiota procera	26–49	10–15	44–410	860–2000	68–620	110–210	74–200	1.1–8.4	0.63–7.6	1.3–8.5	0.1–5.5
Leccinum pseudoscabrum	40	NA	520	1200	110	29	240	0.34	3.3	0.53	0.57
Leccinum duriusculum	37	5.8	340	1100	88	18	150	NA	1.5	0.36	0.93
Leccinum scabrum	34–52	6.1	270–530	900–1200	54–140	21–30	110–240	0.38–1.2	3.3–6.6	0.56–4.1	0.47–0.76
Leccinum rufum	35–42	NA	60–620	900–1300	60,170	73–100	91–240	0.27–1.3	0.36–4.5	0.26–1.2	0.12–0.93
Agaricus bisporus	38–40	10–12	700–860	1100–1400	860–1400	40–65	60–65	NA	NA	NA	0.3–0.55
Agaricus subrufescens	28–32	10–13	110–220	1000–1300	570–1100	63–220	200–320	NA	NA	NA	NA
Pleurotus spp.	22–40		220–1400	1300–2000	190–490	NA	NA	NA	NA	NA	NA
Pleurotus ostreatus	31	7.0	270	1400	820	19	77	NA	NA	NA	NA
Lentinula edodes	23–26	7.4	400–1000	1200–1300	420–1100	13	88	NA	NA	NA	NA

After Falandysz and Borovička (2013) and Falandysz et al. (2015)

gov/remedytech/citizens-guide-bioremediation) is simply a technique to manage wastes using organisms to eliminate or neutralize pollutants (heavy metals/radionuclides) from a contaminated site (Gupta et al. 2013; Chatterjee et al. 2017). Fungi are interesting components for the environmental clean-up practices as they have the ability to biotransform different pollutants without requiring any pretreatment to the particular pollutant (Adenipekun and Lawal 2012). As for example, white-rot basidiomycetes fungi have ligninolytic enzymes that can digest lignin in wood substrates (Asamudo et al. 2005). Further, several reports suggested the ability of such fungi in transforming recalcitrant pollutants like polycyclic aromatic hydrocarbon (PAH), accumulation of heavy metals, biodegradation of different lignocellulosic substrates, etc. (Bennet et al. 2002; Adenipekun and Lawal 2012). A common widely distributed mushroom *Ganoderma* could secrete lignin-modifying enzymes (LME), including laccase (Lac), lignin peroxidases (LiP), and manganese peroxidase (MnP) having likely industrial applications of industrial wastewater treatment (Xu et al. 2017). Gong et al. (2017) reported increment of compost temperature, longer duration at the thermophilic temperature stage, reduction in maturity time, and the better quality of final compost when green waste was inoculated with *Trametes versicolor* and *Phanerochaete chrysosporium*. Similarly, a higher degrading ratio and a better degree of maturity were reported in municipal solid wastes when inoculated with *T. versicolor* and *Fomes fomentarius* (Voběrková et al. 2017). Su et al. (2016) reported to develop a process for the degradation and detoxification of highly lignin-rich tobacco crop residue using white-rot fungi *P. chrysosporium* and *Trametes hirsute*. Again, the medicinal mushroom *G. lucidum* showed the degradation potential of broad-spectrum organochlorine pesticide lindane (Kaur et al. 2016). In a recent report, it has been stated that the highly carcinogenic secondary metabolites aflatoxins, which can contaminate approximately 25% of crops, can be degraded using common edible industrial mushroom *P. ostreatus* and bioconvert crops into mushrooms to reduce the crop loss (Das et al. 2015; Jackson and Pryor 2017). In a study by Křesinová et al. (2017), *P. ostreatus* HK 35 was tested for its degradation potential against common endocrine disrupters (EDCs; bisphenol A, estrone, 17β-estradiol, estriol, 17α-ethinylestradiol, triclosan and 4-*n*-nonylphenol), where a highly satisfactory result was documented. *Lentinus squarrosulus* Mont. mushrooms are reported to bioremediate polluted soil contaminated with engine oil (Adenipekun and Isikhuemhen 2008). Adenipekun et al. (2011) also reported the decontamination of soils polluted with cement and battery wastes using *Pleurotus pulmonarius*. Cultures of *L. edodes* showed production of a number of hydrolytic enzymes like, celluloses, laminarinases, and xylanases, which are more during the production of fungal fruiting bodies (Mata et al. 2016). Yan et al. (2016) reported that small GTPases play significant roles in the development, growth, and environmental responses in mushroom *V. volvacea*. Mushrooms thus have a huge potential in utilization for biodegradation. The first scale-up of the biodegradation process of 2-naphthalenesulfonic acid polymers (NSAP) using packed-bed bioreactors for petrochemical wastewater was reported by Palli et al. (2016) using two white-rot fungi *Bjerkandera adusta* and *P. ostreatus*. It has been shown by the authors that the combined treatment of fungi and activated sludge could tentatively be able to decrease the original COD by up to 73% (Palli et al. 2016).

Hyperaccumulation of elements: a pathway for bioremediation

Some mushroom species have been reported to accumulate specific trace elements within their fruiting bodies to reach concentrations that are least 100 times higher than the concentration values of the respective element in other species on the same substrate. These species are called hyperaccumulators for that specific element. As for example, in case of vanadium (V), *Amanita regalis* and *Amanita velatipes* can accumulate hundreds of milligrams per kilogram of dry mass (dm) of the element, whereas other mushrooms barely exceed 1 mg kg^{-1} of dm for the same element in the same location. It has been reported in case of V hyperaccumulators, amavadin, an eight-coordinate V complex, the dominant chemical species in their fruit bodies (Garner et al. 2000). The fungus *Sarcosphaera coronaria* was reported as a hyperaccumulator of arsenic (with the highest reported value of 7090 mg kg^{-1} dm, in comparison to commonly as high as 1000 mg kg^{-1} dm). The key arsenic compound in fruit body was methylarsonic acid (Stijve et al. 1990; Byrne et al. 1995; Borovička et al. 2011). Amanita species (such as *Amanita strobiliformis*) are known to accumulate silver in a very high quantity (may be more than 2000 times greater than the other species) within their tissue by intracellular sequestration using metallothioneins within extra radical mycelium and fruit bodies (Borovička et al. 2007; Osobová et al. 2011). However, the significance of hyperaccumulation in mushroom is still unclear; some researchers hypothesized that it is a defense mechanism against natural enemies like bacteria, pathogenic microfungi, insect larvae, or gastropoda (Boyd 2007). It is also possible that hyperaccumulating fungi simply lack biochemical mechanisms that prevent them from excluding these elements (upon uptake) or excreting these elements (after uptake). On the flip side, scientists are attempting to utilize the accumulation capability of mushroom (as for example, *L. edodes*) to make desired trace element (such as Ag, Se, and Li)-rich nutraceuticals (food supplements) (Turło et al. 2010; Bhatia et al. 2011; Assunção et al. 2012; Stefanović et al. 2016).

Radionuclides and mushrooms

Environmental presence of radionuclides is a common phenomenon, especially for the heavy elements (heavier than bismuth) having unstable nuclei with excess available energy (Gupta et al. 2016). Accidental or otherwise release of radionuclides into the environment may include volatile fission products such as iodine, tellurium, and cesium (^{131}I, ^{132}Te, ^{134}Cs, and ^{137}Cs, all of which are strong γ-emitters) or less volatile elements such as strontium, ruthenium, barium, lanthanides, and actinides (some of which are more challenging analytes). The contamination of foods with these elements is a potential health threat (Merz et al. 2015). Wild-growing mushrooms are rich in minerals (including radionuclides), the amount of which varies considerably in different species collected from the same area. Several reports exemplified that mushrooms are efficient and remarkable accumulators and bioindicators of radionuclides of cesium (^{134,137}Cs), potassium (^{40}K), and strontium (^{90}Sr) and are therefore potentially dose-relevant (Haselwandter 1978; Vinichuk et al. 2011, 2013; Falandysz and Borovička 2013; Falandysz et al. 2015, 2017; Saniewski et al. 2016). Uptake of ^{40}K, however, plays a different role than other elements: as a highly abundant essential element, the human body keeps potassium levels remarkably constant within the tissue. Uptake of additional ^{40}K hence immediately causes excretion of ^{40}K and, therefore, only marginally increases the dose upon uptake. Non-essential elements such as cesium or strontium are taken up by “mistake,” as they are literally mistaken for their chemically related homologues potassium or calcium, respectively. After uptake, these elements are excreted with a biological half-life that, among other factors, depends on the type of tissue in which the radionuclide is primarily accumulated. Bone-seeking strontium exhibits a much longer persistence within the human body than soft tissue-seeking cesium.

Table 2 shows a selected range of ^{40}K and ^{137}Cs concentrations in various mushrooms. Among the anthropogenic radionuclides, mushrooms are mostly associated with the presence of remarkable activities of ^{137}Cs, a relatively long-lived radionuclide ($T_{1/2}$ = 30.08 years) that has become an ubiquitous pollutant of the earth’s surface due to global radioactive fallout atmospheric nuclear explosions of the twentieth century as well as nuclear accidents (Guillen and Baeza 2014). For ^{90}Sr, the atmospheric nuclear explosions are typically a much more significant source than nuclear accidents, especially the Fukushima nuclear accident, because radiostrontium has lower volatility and is released from a damaged reactor only in smaller amounts than in a nuclear explosion. Detections of ^{90}Sr in environmental samples around Fukushima—in stark contrast to Chernobyl—have therefore been reported only for the close vicinity of the nuclear reactors (Steinhauser et al. 2015; Kavasi et al. 2015). Other significant naturally occurring radionuclides mentioned are ^{40}K and ^{87}Rb, as well as sometimes, ^{235,238}U, ^{232}Th, and ^{226,228}Ra (Castro et al. 2012; Rakić et al. 2014; Gupta et al. 2016).

Table 2 ^{40}K and ^{137}Cs concentrations in different mushrooms

Mushroom species	^{40}K (Bq kg^{-1} dm)	^{137}Cs (Bq kg^{-1} dm)
Suillus luteus	2200	12,000
Boletus edulis	970–2100	5100–13,000
Leccinum amethystina	2100	5600
Tricholoma equestre	3400	10,000
Armillaria solidipes	1800	315
Macrolepiota procera	1500	1100
Paxillus involutus	2000–2300	2500–10,000

After Kalac (2001), Mietelski et al. (2010), Falandysz and Borovička (2013), and Falandysz et al. (2015)

Half a century ago, Gruter (1964) first reported elevated levels of radioactivity of ^{137}Cs in some wild-growing mushroom. Concern over environmental impact on radionuclide accumulation in the human food chain (including mushrooms) has gained a lot of public attention, in many parts of the Europe after the accident at the Chernobyl nuclear power station in 1986 (former Soviet Union, today Ukraine) and subsequent radioactive fallout (Kalac and Svoboda 2000; Kalac 2001). In the culinary tradition of Central and Eastern Europe, wild-growing mushrooms are often used in the cuisine as a delicacy with an annual per capita consumption nearing 7 kg or more (Kalac 2001). The normal statutory limit of radioactivity concentration for foods is 6 kBq kg^{-1} of dry matter (where Bq or Becquerel is the unit of radioactivity, defined as decay per second). However, after Chernobyl accident, European Communities published Council Regulation (CEC 1987), where the maximum permitted level of ^{137}Cs for foodstuffs was 1.25 kBq kg^{-1} fresh weights (i.e., in dry matter, 12.5 kBq kg^{-1}). This level is also applicable to mushrooms. A comparable limit of 1.0 kBq kg^{-1} fresh weight (i.e., 10 kBq kg^{-1} dm for mushrooms) was suggested by the International Atomic Energy Agency (IAEA 1994; Travnikova et al. 2001). It has been reported that especially mycosymbiotrophs grown in the plants and forest litters in the areas surrounding post-Chernobyl period are the main repository of radionuclides, like radiocesium (Grodzinskaya et al. 2011).

Similarly, in Japan, the Fukushima nuclear accident on March 11, 2011, one of the most severe environmental accidents of twenty-first century, has contaminated quite large areas of Fukushima prefecture, forcing the evacuation of more than 100,000 people in order to minimize their radiological risks (Harada et al. 2014; Steinhauser et al. 2014; Merz et al. 2015). Nonetheless, public concerns about food safety are evident (Tamari et al. 2016). The route of exposure to humans may occur externally, but most importantly internally due to ingestion of contaminated food and water (Hamada and Ogino

2012; Merz et al. 2013). Ingestion of contaminated food even outperforms the health significance of inhalation of airborne radionuclides, as shown in Fukushima recently (Nomura et al. 2016).

However, the effective dose (E, expressed in the unit mSv (millisievert)) per year denotes the possible risk of radioactivity for human health, which is 5 mSv as recommended by the International Commission for Radiation Protection as calculated by a simple equation $E = Y \times Z \times d_k$ (where Y = annual intake of mushrooms (kg dm per person), Z = activity concentration (Bq kg^{-1} dm), and d_k = dose coefficient (conversion factor) defined as the dose received by an adult per unit intake of radioactivity) (ICRP 1996; Kalac 2001). For adults, the dose conversion factors for ^{90}Sr, ^{137}Cs, ^{134}Cs, and ^{40}K are 2.8×10^{-8}, 1.3×10^{-8}, 1.9×10^{-8}, and 6.2×10^{-9} Sv Bq^{-1}, respectively. The half-lives of ^{90}Sr, ^{137}Cs, ^{134}Cs, and ^{40}K are 28.8, 30.17, 28.8, 2.06, and 1.25×10^9 years, respectively. Disposing of the liquid fraction of the mushroom dish in the pan (gravy or juice) may help reduce the concentration of ^{137}Cs (Steinhauser and Steinhauser 2016). Although the monitoring of food is characterized by high efficiency (Merz et al. 2015; Steinhauser 2016), it has been shown that private mushroom collections (in addition with other private fishery or other private agricultural activities) pose the highest threat for significant exposure with radionuclides, by unintentionally bypassing the governmental monitoring regime (Hayano et al. 2013).

Mushrooms usually contain comparatively higher levels of potassium, which may vary from 1.5 to 117 g kg^{-1} of dw, and in both cultivated and wild-growing species of mushroom, normal ^{40}K activity concentrations vary between 0.8 and 1.5 kBq kg^{-1} dm and transfer factor between 1.5 and 22.7 from growth substrate to fruiting body (Kalac 2001). Eckl et al. (1986) reported that mushrooms like *Xerocomus badius*, *Lycoperdon perlatum*, and *A. rubescens* showed more than 10. Edible mushrooms such as *F. velutipes*, *L. edodes*, and *G. lucidum* showed ^{40}K radioactivity values of 7.2, 1.8, and 1.6 kBq kg^{-1} dry weight, respectively, when cultivated in sawdust substrate (Wang et al. 1998). Levels of ^{226}Ra and ^{210}Pb were also found below detection limits in tested edible species (Eckl et al. 1986). However, in another study on the fungal samples collected from different areas of France, although the activity concentrations of ^{226}Ra were lower, activity concentrations of ^{210}Pb were reported having in the range of 1.76–36.5 Bq kg^{-1} dry weight (Kirchner and Daillant 1998). ^{210}Pb incorporation in mushrooms mainly occurs through direct uptake from soil; still minor amount may come through atmospheric deposition on the fruit bodies and uptake of ^{222}Rn that subsequently decays into ^{210}Pb (Kirchner and Daillant 1998).

A popular edible mushroom *C. cibarius*, collected across Poland and China (Yunnan province), was studied for the activity concentrations of ^{137}Cs and ^{40}K (Falandysz et al. 2016). The activity concentrations of ^{137}Cs in *C. cibarius* collected from Poland vary considerably over the years (4.2 ± 1.2 to 1600 ± 47 Bq kg^{-1} dry weight), while the activity level of Chinese samples was very low (< 1.2 to 1.2 ± 0.6 Bq kg^{-1} dry weight) (Falandysz et al. 2016).

A mushroom absorbs elements from the substrate where it is growing without discriminating the elements between their stable and radioactive isotopes; however, sequestration potentials for radioactive elements vary considerably among mushroom species (Skwarzec 2012; Falandysz and Borovička 2013; Falandysz et al. 2015). The ^{137}Cs accumulation is common in wild-grown mushroom. The concentration of ^{137}Cs varies between mushroom species, site/region of collection, exposure time, etc. Mushrooms are also capable to accrue ^{137}Cs from its sites, like the surface of soils, decaying litter, and somewhat deeper soil zone (which depends on the mycelium biology and soil structure) (Gryndler et al. 2012; Falandysz and Borovička 2013). Taira et al. (2011) reported some severe cases of radionuclide contamination in mushroom grown in hazardous sites. Further, bioaccumulation of ^{137}Cs by mushrooms like *Cortinarius caperatus*, *Cortinarius semisanguineus*, *Lactarius rufus*, and *Suillus variegates* is also reported (Rosén et al. 2011). However, accumulation of Cs also varies in morphological parts of mushrooms. As for example, in contrary to saprophytic mushrooms, mycorrhizal species like *B. edulis* and *L. scabrum* accumulate more Cs in caps (ranging from 1.6 to 8.7 mg Cs kg^{-1} dw) than mycelium, which refers more efficient sequestration of ^{137}Cs in the body of the mushroom (Rühm et al. 1997; Falandysz et al. 2008).

Grodzinskaya et al. (2011) reported hyperaccumulator species for radiocesium, which include mushrooms of the group Cortinariaceae, Russulaceae, Boletaceae, Suillaceae, Hydnaceae, Paxillaceae, Tricholomataceae, and Gomphidiaceae. Among these families, some species are also widely edible, such as *Boletus badius* (Fr.) Kühn. (Mleczek et al. 2016), *L. rufus* (Scop.) Fr., and *P. involutus* (Batsch) Fr. Grodzinskaya et al. (2011) found that the accumulation of radiocesium was 10–10^2 times higher than radiostrontium accumulation in the some samples collected from contaminated territories of Ukrainian Polissya.

K and Rb (including radioactive ^{40}K and ^{87}Rb) are abundant in mushrooms in relatively high amounts, ranging from 25,000 to 50,000 and ~100 to 300 mg kg^{-1} dm, respectively. Like Cs, typically, fruit bodies accumulate more amounts of K and Rb than mycelium (Mietelski et al. 2010; Vinichuk et al. 2011). As mushrooms cannot distinguish stable or radioisotope of an element, essential element like K is bioadjustable, and accordingly, the ^{40}K activity is moderately persistent in a specific cultivation site and mushroom species (Falandysz and Borovička 2013). Both naturally and artificially grown mushrooms also accumulate varied radionuclide like, ^{134}Cs, ^{60}Co, ^{90}Sr, ^{210}Po, ^{226}Ra, ^{234,238}U, ^{228,230,232}Th, ^{238}Pu, $^{239+240}$Pu, and ^{241}Am (Szántó et al. 2007; Vaartamaa et al. 2009). Recently, Falandysz et al. (2015) reported activity concentration of the radionuclides $^{134/137}$Cs, ^{40}K, and ^{226}Ra in the specimens and probable food intake of radioactive elements from Yunnan province, China, for pantropical mushroom *Macrocybe gigantea*; this mushroom showed low activity concentrations for ^{137}Cs (median values were 4.5 and 5.4 Bq kg^{-1} for dehydrated caps and stipes, respectively), but greater activity concentration (twofold to threefold) for ^{40}K. Further, in the study, authors clarified that the data on dietary intake of radioactive element like ^{137}Cs after cooking of the mushroom *M. gigantea* does not show any health risks among the people of Yunnan due to low pollution (Falandysz et al. 2015).

Accumulation of radiocesium in mushrooms is a common phenomenon even at areas with a lower degree of persisting contamination. There is a persistent risk upon consumption of mushroom either as food or as medicine grown in radionuclide (as well as heavy metal) contaminated areas (Kalac 2001; Grodzinskaya et al. 2011). Animals such as roe deer (*Capreolus capreolus*), reindeers (*Rangifer tarandus*), grazing domestic sheep and goats, and most importantly wild boars (*Sus scrofa*) are reported to augment the level of radiocesium in their body tissues, while eating on such contaminated mushrooms and lichens (Strandberg and Knudsen 1994; Kalac 2001; Steinhauser and Saey 2016).

Conclusion

In addition to being a food source, many mushroom species exhibit a rich source of bioactive compounds. Several different studies also exemplify the beneficial properties of various mushrooms in preventing and/or treating various types of diseases. Because of their low-fat content and their high content in proteins, vitamins, and anti-oxidants, they are popular as constituents for low-caloric diets. Further, there is a high potential of exploration of various indigenous and wild mushroom species for their arrays of various mushroom phytochemicals, which can further be utilized for medical purposes, i.e., for developing novel drugs, etc. Research and development on mushroom production and extraction of bioactive metabolites are therefore critically important to explore many potential properties related to nutraceuticals and health benefits. In addition, mushroom can also be used as a capable component for bioremediation. Many studies on bioaccumulation by varied mushroom species have shown their potentiality upon uptake and accumulation of various heavy metals. Since several types of mushrooms are highly specific accumulators of both heavy metals and radionuclides, they may also exhibit a potential health risk for the consumers. Anthropogenic activities on nuclear weapons or accidental fallout from nuclear power plant accidents (primarily Chernobyl and Fukushima) may involve large-scale contamination in mushrooms. The analysis on radionuclide accumulation and dispersal dynamics in edible mushroom species needs further investigations. Although many countries are gearing up for larger production of mushroom, however, proper biotechnological interventions are required to explore this food item more efficiently for the benefit of the mankind.

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