Eur Food Res Technol (2017) 243:1555–1566
DOI 10.1007/s00217-017-2864-8

ORIGINAL PAPER

Comparison of multielemental composition of Polish and Chinese mushrooms (*Ganoderma* spp.)

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Received: 9 December 2016 / Revised: 1 February 2017 / Accepted: 19 February 2017 / Published online: 17 March 2017

Abstract This study analyzed the content of 62 elements in 10 *Ganoderma* species cultivated in China and Poland and wild growing in Polish forests. Thirty elements (25 micro- and 5 macro-elements) were identified in all species, whereas 32 trace elements only in a very limited number of samples. The highest contents of major elements were observed in cultivated *G. pfeifferi* and *G. sinense* originated from Poland and China, respectively. Among wild growing species, *G. applanatum* showed the highest content of In, Mg, and P, *G. pfeifferi* of Te, both *G. pfeifferi* and *G. resinaceum* of K. Principal component analysis (PCA) showed that among tested group of mushroom species, fruit bodies of wild growing *G. resinaceum* and cultivated *G. pfeifferi* were characterized by a higher level of all elements jointly than the other analyzed *Ganoderma* species. The greatest similarity was observed for *G. atrum, G. capense, G. carnosum* and cultivated *G. lucidum* as regards accumulation of all elements. Significant differences between cultivated and wild growing *G. lucidum* were observed only for K and In, whereas in *G. pfeifferi* differences were found for Ba, Cd, Eu, Ge, Ni, Rh, Sr, Te, Zn, Mg, and Na. Significant differences in Ca, P, and Pr contents were determined for both the species.

Keywords Bioaccumulation · Elements · *Ganoderma* spp. · Mineral composition · Wild and cultivated mushrooms

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Introduction

The genus *Ganoderma* is one of the best known of the so called 'medicinal mushrooms. It encompasses several wood-inhabiting species with *G. lucidum* being the most widely recognized by the food industry [1]. In China, *G. lucidum* has been used in traditional medicine for at least 2000 years as a medicinal mushroom for promoting health and longevity [2, 3]. Its bioactive properties are currently under extensive research and some have already been proven, not only through in vitro and in vivo experimental studies but also in randomized clinical trials [4]. At the same time, the biological properties of other species belonging to the genus of *Ganoderma* are attracting interest from the scientific community. These include *G. tsugae* [5], *G. oerstedii* [6], *G. applanatum* [7], *G. pfeifferi* [8], *G. theaecolum* [9], and *G. sinense* [10]. In Japan, *Ganoderma* mushrooms are generally known under the popular names of Reishi or Mannentake while in China *G. lucidum* is referred to as Lingzhi [3].

The numerous health benefits of *Ganoderma* mushrooms are anecdotally and traditionally known. Over

recent years, some of these effects have been evidenced by scientific means and through identification and isolation of bioactive compounds such as polysaccharides, triterpenes, and lucidenic acids [11–13].

Ganoderma mushrooms are generally rare in natural habitats and in the past, they were regarded as available only for the wealthiest people [14]. The development of cultivation methods has increased its popularity and use, initially on the Asian continent and later, in other parts of the world [1]. However, a high content of triterpenes causes these mushrooms to taste rather bitter, therefore the fruiting bodies, mycelia, and spores are mostly used to produce extracts, tea, powders or food supplements [3], with an industry value estimated at 2.5 billion $ (US) [15].

The mineral content of *Ganoderma* species may account for up to 10% of dry matter (dm). It was reported to be mainly constituted of P, Mg, Ca, K, Na, Fe, Zn, Mn, and Cu with their contents of 3210, 1670–4480, 1370–9449, 457–84650, 179–1612, 115–211, 18–257, 8.7–179, 11–47 mg kg^{-1} dm, respectively. The reported contents of toxic elements in *G. lucidum* were <0.15–1; 31.9–69; 0.01–0.07; 0.96–89, and 7.37–28 mg kg^{-1} dm for Cd, Cr, Hg, Pb, and Sr, respectively [16–20]. Baldrian et al. [21] also investigated the content of selected trace elements in *G. applanatum*. Nevertheless, to date the elemental composition of different *Ganoderma* species, occurring in the wild as well as commercially cultivated, has not been extensively studied.

The aim of the present study was to characterize and compare the content of 62 elements in different *Ganoderma* species cultivated for commercial purposes in Poland and China. For comparison, the elemental composition of wild-growing specimens of *G. pfeifferi* and *G. lucidum* collected in Poland was also assessed.

Materials and methods

Experimental material

Dried fruiting bodies of *Ganoderma* species were collected from different marketplaces in Shanghai (China) in 2014–2016 and from cultivations at the Poznan University of Life Sciences (Poland) during 2014–2016. 200 g dm of each species was collected. In addition, wild growing *Ganoderma* fruit bodies were gathered from different forest sites in Poland between 2014 and 2016 as three individual samples each year (i.e. 3×3) of each species. The characteristics of the *Ganoderma* mushrooms analyzed in this study are summarized in Table 1.

Procedure

The fruiting bodies of wild specimens were dried at 105 ± 5 °C for 96 h in an electric oven (Pol-Eko, Wodzisław Śląski, Poland) and then ground in a laboratory Cutting Mill SM 200 (Retsch GmbH, Haan, Germany) and homogenized using a B-400 homogenizator (Buchi Labortechnik AG, Switzerland). The mass 0.300 ± 0.001 g of a dry mushroom sample was digested in ultra-pure concentrated (65%) nitric acid (Merck, Darmstadt, Germany) in closed Teflon containers (55 mL) in microwave sample preparation system Mars 5 Xpress (CEM, Matthews, USA). After digestion, the samples were filtered and diluted with water (Milli-Q, Millipore, Saint Luis, USA) to a final volume of 15.0 mL. Each of the samples was analyzed in triplicate.

Instruments

An inductively coupled plasma spectrometer with the optical emission detection (Agilent 5100 ICP-OES, Agilent

Table 1 Characteristics of *Ganoderma* species used in the present study

No of species	*Ganoderma* species	Origin	Substrate or purchase location
Cultivated			
1	G. adspersum	Poland	Beech and oak sawdust (1:1)
2	G. atrum	China	Market in Shanghai
3	G. capense	China	Market in Shanghai
4	G. carnosum	Poland	Beech and oak sawdust (1:1)
5	G. hainanense	China	Market in Shanghai
6	G. lucidum	Poland	Beech and oak sawdust (1:1)
7	G. pfeifferi	Poland	Beech and oak sawdust (1:1)
8	G. sinense	China	Market in Shanghai
Wild growing			
9	G. appalanatum	Poland	Log of dyed beech (*Fagus* sp.)
10	G. lucidum	Poland	Oak stump (*Quercus* sp.)
11	G. pfeifferi	Poland	Maple stump (*Acer* sp.)
12	G. resinaceum	Poland	Dying chestnut (*Aesculus* sp.)

USA) was used for sample analysis as previously described [22]. Common conditions were used for multielemental determination: Radio Frequency (RF) power 1.2 kW, nebulizer gas flow 0.7 L min^{-1}, auxiliary gas flow 1.0 L min^{-1}, plasma gas flow 12.0 L min^{-1}, viewing height for radial plasma observation 8 mm, detector CCD (Charge Coupled Device) temperature −40 °C, signal accusation time 5 s for 3 replicates. The detection limits for all determined elements (Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co Cr, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hf, Ho, In, Ir, K, La, Li, Lu, Mg, Mn, Mo, Na, Nd, Ni, Os, P, Pb, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sc, Se, Sm, Sr, Tb, Te, Th, Ti, Tl, Tm, U, V, Y, Yb, Zn, Zr) were determined (as 3-sigma criteria) on the level of 0.01 mg kg^{-1} dm. The uncertainty for total analytical procedure (including sample preparation) was at the level of 20%. The recovery (80–120%) in certified reference materials analysis (CRM S-1—loess soil; CRM NCSDC (73349)—bush branches and leaves; CRM 2709—soil; CRM 405—estuarine sediments; CRM 667—estuarine sediments) was acceptable for most the elements determined. Recovery in the standard addition method was applied for non-certified elements.

Statistical analysis

The contents of 30 (25 microelements and 5 macroelements) (variables) in 10 *Ganoderma* species (experimental factor) were statistically analyzed because only these element contents were above the limit of detection. Comparison was performed based on the mean content of elements in fruit bodies of particular mushroom species. One-way analysis of variance (ANOVA) with the *F* Fisher test ($\alpha = 0.05$) was used to verify the general hypothesis about the equality of mean content of particular elements in mushrooms. In case of the null hypothesis rejection, the multiple comparison Tukey procedure was used to show the uniform groups of mushroom species ($\alpha = 0.05$).

Principal Component Analysis (PCA) was used to show relationships between independent variables (content of elements) for the studied Ganoderma species. A transformation of the initial population of variables (mean content of elements) into the population of principal components was made. Interpretation of obtained results was performed based on the factorial charge being the correlation coefficients between variable and components. This revealed the similarities and differences in accumulation of particular elements within the tested Ganoderma species.

For graphical presentation of diversity in element content in all studied *Ganoderma* species and to show the similarities in element contents in eight *Ganoderma* species cultivated in China and Poland, heatmaps were prepared. Hierarchical Cluster Dendrograms were applied to illustrate the grouping of fruit bodies and mushroom species with respect to the similarity of element content. Homogenous groups were created by the ward.D2 agglomeration method (hclust {stats}) with Euclidean Distance. All analyses were performed using the agricole package (R).

Results

All 62 elements analyzed in mushroom species were divided into three groups:

A: elements present in all collected and analyzed fruit bodies—Ag, Al, B, Ba, Bi, Ca, Cd, Cu, Eu, Fe, Ge, Ho, In, K, La, Mg, Mn, Na, Nd, Ni, P, Pb, Pr, Pt, Rh, Sr, Te, Ti, Zn, and Zr;

B: elements present in some fruit bodies over the limit of detection—As, Au, Ce, Dy, Er, Ga, Gd, Os, Rb, Re, Sb, Sc, Se, Th, Tl, V, Y;

C: elements always below the limit of detection—Be, Co, Cr, Hf, Ir, Li, Lu, Mo, Pd, Ru, Sm, Tb, Tm, U, and Yb.

The element contents of group A were evaluated statistically.

Content of elements present in all fruit bodies

The tested *Ganoderma* species varied as regards the content of elements in their fruit bodies. For cultivated species, the highest content (mg kg^{-1} dm) of most of elements were observed for *G. pfeifferi* (Ba: 59.8 ± 16.2; Cd: 4.71 ± 0.26; Cu: 42 ± 6; Ge: 1.44 ± 0.27; Pr: 3.51 ± 0.52; Sr: 43.9 ± 6.5; Zn: 113 ± 8; Ca: 7458 ± 228 and Na: 334 ± 87) and *G. sinense* (Al: 1208 ± 137; Eu: 0.29 ± 0.04; Fe: 5285 ± 276; Ho: 0.20 ± 0.03; La: 6.23 ± 1.24; Nd: 7.26 ± 0.94; Ni: 1.60 ± 0.66; Pb: 7.4 ± 1.4; Pt: 60.5 ± 7.1; Ti: 6.97 ± 2.13 and Zr: 0.16 ± 0.10 mg kg^{-1} dm). The mean contents of the studied elements in the investigated mushroom species are collated in Table 2.

Wild growing *G. applanatum* was characterized by the highest content of In, Mg, and P (6.72 ± 0.76, 883 ± 94, and 10,961 ± 1768 mg kg^{-1} dm, respectively). In turn, *G. capense* contained the highest level of B and Bi (29.74 ± 8.76 and 1.73 ± 0.34 mg kg^{-1} dm, respectively), *G. carnosum* of Ag (0.45 ± 0.21 mg kg^{-1} dm), while wild growing *G. pfeifferi* contained the highest level of Te (6.65 ± 2.48 mg kg^{-1} dm). The highest content of was observed K in wild growing *G. pfeifferi* and *G. resinaceum* (8905 ± 158 and 6622 ± 182 mg kg^{-1} dm, respectively). The ranges (difference between the highest and the lowest content) presented in Table 2 confirm the high diversity in element contents between particular *Ganoderma* species. The comparison of all 12 *Ganoderma* species with respect to content of all 30 elements was illustrated by PCA (Fig. 1).

Wild growing *G. resinaceum* and cultivated *G. pfeifferi* contained higher levels of all elements jointly than the rest

Table 2 Mean content [mg kg^{-1} dm] of analyzed elements in fruit bodies of cultivated (A) and wild growing (B) *Ganoderma* species

Ganoderma species	Ag	Al	B	Ba	Bi	Cd	Cu	Eu	Fe	Ge
F	10.2***	214***	21.33***	36.7***	8.07***	39.26***	48***	40.78***	995***	21.74***
p value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
A										
G. adspersum	$0.08^{bc} \pm 0.02$	$17^{b} \pm 4$	$10.16^{b} \pm 2.08$	$12.7^{c} \pm 1.3$	$0.47^{cde} \pm 0.10$	$2.54^{b} \pm 0.66$	$15^{b} \pm 2$	$0.01^{f} \pm 0.00$	$50^{b} \pm 7$	$1.38^{ab} \pm 0.18$
G. atrum	$0.07^{c} \pm 0.02$	$35^{b} \pm 19$	$2.25b^{c} \pm 0.42$	$4.2^{c} \pm 1.1$	$0.52^{bcde} \pm 0.12$	$0.25^{c} \pm 0.08$	$8^{bc} \pm 1$	$0.03^{def} \pm 0.01$	$176^{b} \pm 20$	$1.24^{ab} \pm 0.22$
G. capense	$0.15^{bc} \pm 0.03$	$11^{b} \pm 2$	$29.74^{a} \pm 8.76$	$7.0^{c} \pm 1.7$	$1.73^{a} \pm 0.34$	$1.09^{c} \pm 0.14$	$16^{b} \pm 3$	$0.01^{f} \pm 0.00$	$29^{b} \pm 4$	$0.05^{d} \pm 0.02$
G. carnosum	$0.45^{a} \pm 0.21$	$21^{b} \pm 8$	$3.53^{bc} \pm 0.97$	$6.2^{c} \pm 2.4$	$1.25^{abc} \pm 0.10$	$0.56^{c} \pm 0.19$	$6^{c} \pm 3$	$0.05^{cdef} \pm 0.01$	$73^{b} \pm 17$	$0.26^{d} \pm 0.40$
G. hainanense	$0.06^{c} \pm 0.02$	$32^{b} \pm 3$	$6.86^{bc} \pm 1.58$	$1.8^{c} \pm 0.9$	$0.74^{bcde} \pm 0.26$	$0.38^{c} \pm 0.10$	$11^{bc} \pm 2$	$0.07^{cde} \pm 0.02$	$223^{b} \pm 36$	$0.07^{d} \pm 0.02$
G. lucidum	$0.04^{c} \pm 0.02$	$33^{b} \pm 22$	$6.56^{bc} \pm 3.59$	$6.8^{c} \pm 2.6$	$1.33^{ab} \pm 0.84$	$0.41^{c} \pm 0.52$	$12^{bc} \pm 4$	$0.04^{cdef} \pm 0.02$	$96^{b} \pm 56$	$0.52^{cd} \pm 0.20$
G. pfeifferi	$0.27^{ab} \pm 0.06$	$10^{b} \pm 2$	$5.97^{bc} \pm 1.68$	$59.8^{a} \pm 16.2$	$0.48^{bcde} \pm 0.14$	$4.71^{a} \pm 0.26$	$42^{a} \pm 5$	$0.06^{cdef} \pm 0.01$	$46^{b} \pm 9$	$1.44^{a} \pm 0.27$
G. sinense	$0.01^{c} \pm 0.00$	$1208^{a} \pm 137$	$5.98^{bc} \pm 1.47$	$33.4^{b} \pm 3.7$	$0.82^{bcde} \pm 0.15$	$0.42^{c} \pm 0.04$	$9^{bc} \pm 3$	$0.29^{a} \pm 0.04$	$5285^{a} \pm 276$	$0.21^{d} \pm 0.05$
B										
G. applanatum	$0.05^{c} \pm 0.01$	$10^{b} \pm 1$	$2.25^{bc} \pm 0.25$	$1.8^{c} \pm 0.2$	$0.39^{de} \pm 0.06$	$0.41^{c} \pm 0.17$	$8^{bc} \pm 1$	$0.09^{bc} \pm 0.02$	$101^{b} \pm 6$	$0.33^{cd} \pm 0.08$
G. lucidum	$0.04^{c} \pm 0.01$	$22^{b} \pm 3$	$1.29^{c} \pm 0.16$	$1.3^{c} \pm 0.2$	$0.87^{bcde} \pm 0.09$	$1.09^{c} \pm 0.20$	$8^{bc} \pm 1$	$0.06^{cdef} \pm 0.02$	$63^{b} \pm 6$	$0.13^{d} \pm 0.03$
G. pfeifferi	$0.10^{bc} \pm 0.02$	$10^{b} \pm 1$	$3.71^{bc} \pm 1.06$	$4.6^{c} \pm 0.9$	$0.01^{e} \pm 0.00$	$1.09^{c} \pm 0.19$	$38^{a} \pm 4$	$0.13^{b} \pm 0.03$	$24^{b} \pm 4$	$0.49^{cd} \pm 0.19$
G. resinaceum	$0.09^{bc} \pm 0.08$	$29^{b} \pm 6$	$0.01^{d} \pm 0.00$	$4.4^{c} \pm 0.8$	$1.06^{abcd} \pm 0.18$	$2.56^{b} \pm 0.83$	$11^{bc} \pm 3$	$0.09^{bcd} \pm 0.03$	$70^{b} \pm 15$	$0.87^{bc} \pm 0.21$
Mean value										
A	0.14	170	8.88	16.5	0.92	1.28	15	0.07	747	0.65
B	0.07	17.55	1.82	3.0	0.58	1.29	16	0.09	65	0.46
Range	0.44	1198	29.73	58.5	1.72	4.46	36	0.28	5261	1.39
Ganoderma species	Ho	In	La	Mn	Nd	Ni	Pb	Pr	Pt	Rh
F	12.20***	16.87***	69.99***	106***	134.10***	8.64***	17.0***	13.45***	159.5***	11.33***
p value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
A										
G. adspersum	$0.16^{ab} \pm 0.04$	$3.01^{cd} \pm 0.20$	$0.16^{b} \pm 0.04$	$43^{cd} \pm 2$	$0.55^{b} \pm 0.08$	$0.13^{c} \pm 0.04$	$1.9^{bc} \pm 0.7$	$1.67^{bcd} \pm 0.15$	$2.3^{b} \pm 0.4$	$0.06^{de} \pm 0.02$
G. atrum	$0.12^{bc} \pm 0.03$	$2.13^{d} \pm 0.13$	$0.11^{b} \pm 0.03$	$48^{bc} \pm 5$	$0.39^{b} \pm 0.06$	$0.08^{c} \pm 0.02$	$1.5^{bc} \pm 0.6$	$1.73^{bcd} \pm 0.28$	$5.0^{b} \pm 0.7$	$0.38^{a} \pm 0.06$
G. capense	$0.06^{cd} \pm 0.02$	$3.04^{cd} \pm 0.35$	$0.08^{b} \pm 0.01$	$12^{e} \pm 3$	$0.51^{b} \pm 0.02$	$0.11^{c} \pm 0.02$	$0.2^{c} \pm 0.1$	$0.24^{e} \pm 0.03$	$3.6^{b} \pm 0.8$	$0.35^{ab} \pm 0.11$
G. carnosum	$0.05^{cd} \pm 0.01$	$5.48^{ab} \pm 1.12$	$0.08^{b} \pm 0.03$	$9^{e} \pm 1$	$0.28^{b} \pm 0.29$	$0.47^{bc} \pm 0.58$	$1.8^{bc} \pm 1.0$	$1.07^{cde} \pm 0.16$	$5.0^{b} \pm 1.2$	$0.11^{cde} \pm 0.04$
G. hainanense	$0.03^{d} \pm 0.02$	$5.09^{abc} \pm 0.57$	$0.33^{b} \pm 0.18$	$190^{a} \pm 26$	$0.70^{b} \pm 0.04$	$0.46^{bc} \pm 0.04$	$1.2^{bc} \pm 0.8$	$0.69^{de} \pm 0.04$	$3.5^{b} \pm 0.7$	$0.24^{abcd} \pm 0.09$
G. lucidum	$0.03^{d} \pm 0.03$	$6.67^{a} \pm 1.53$	$0.18^{b} \pm 0.13$	$18^{de} \pm 10$	$0.47^{b} \pm 0.18$	$0.41^{bc} \pm 0.18$	$2.1^{bc} \pm 1.5$	$2.32^{ab} \pm 1.12$	$3.3^{b} \pm 2.1$	$0.33^{ab} \pm 0.09$
G. pfeifferi	$0.04^{cd} \pm 0.03$	$6.07^{ab} \pm 0.42$	$0.17^{b} \pm 0.03$	$18^{e} \pm 4$	$0.81^{b} \pm 0.07$	$1.10^{ab} \pm 0.07$	$1.7^{bc} \pm 0.3$	$3.51^{a} \pm 0.52$	$4.9^{b} \pm 0.5$	$0.01^{e} \pm 0.00$
G. sinense	$0.20^{a} \pm 0.03$	$1.78^{d} \pm 0.48$	$6.23^{a} \pm 1.24$	$72^{b} \pm 8$	$7.26^{a} \pm 0.94$	$1.60^{a} \pm 0.66$	$7.4^{a} \pm 1.4$	$2.22^{bc} \pm 0.30$	$60.5^{a} \pm 7.1$	$0.30a^{bc} \pm 0.07$
B										
G. applanatum	$0.10^{bcd} \pm 0.03$	$6.72^{a} \pm 0.76$	$0.06^{b} \pm 0.02$	$17^{e} \pm 3$	$0.26^{b} \pm 0.07$	$0.42^{bc} \pm 0.06$	$1.3^{bc} \pm 0.3$	$1.36^{bcde} \pm 0.23$	$4.6^{b} \pm 1.2$	$0.37^{ab} \pm 0.05$
G. lucidum	$0.07^{cd} \pm 0.02$	$2.26^{d} \pm 0.41$	$0.04^{b} \pm 0.01$	$14^{e} \pm 2$	$0.35^{b} \pm 0.09$	$0.35^{bc} \pm 0.03$	$2.7^{b} \pm 0.3$	$0.69^{de} \pm 0.19$	$1.8^{b} \pm 0.7$	$0.18^{bcde} \pm 0.04$

Table 2 (continued)

Ganoderma species	Ho	In	La	Mn	Nd	Ni	Pb	Pr	Pt	Rh
G. pfeifferi	$0.02^{d} \pm 0.01$	$3.97^{bcd} \pm 0.28$	$0.04^{b} \pm 0.03$	$9^{e} \pm 2$	$0.24^{b} \pm 0.08$	$0.14^{c} \pm 0.03$	$0.7^{bc} \pm 0.2$	$1.94^{bc} \pm 0.30$	$2.2^{b} \pm 0.3$	$0.26^{abc} \pm 0.07$
G. resinaceum	$0.07^{cd} \pm 0.05$	$6.24^{ab} \pm 1.49$	$0.07^{b} \pm 0.01$	$9^{e} \pm 3$	$0.38^{b} \pm 0.06$	$0.33^{bc} \pm 0.13$	$1.3^{bc} \pm 0.2$	$1.41^{bcde} \pm 0.41$	$4.8^{b} \pm 0.9$	$0.26^{abc} \pm 0.06$
Mean										
A	0.09	4.16	0.92	51	1.37	0.54	2.23	1.68	11.0	0.22
B	0.06	4.80	0.05	12	0.31	0.31	1.51	1.35	3.3	0.27
Range	0.18	4.94	6.19	182	7.02	1.52	7.26	3.27	58.7	0.37
Ganoderma species	Sr	Te	Ti	Zn	Zr	Ca	K	Mg	Na	P
F	69.5***	15.00***	29.06***	27***	3.90**	353***	8***	12***	28***	60***
p value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
A										
G. adspersum	$20.9^{b} \pm 3.5$	$0.73^{c} \pm 0.09$	$0.13^{b} \pm 0.05$	$79^{b} \pm 11$	$0.05^{b} \pm 0.02$	$5259^{b} \pm 244$	$4213^{c} \pm 96$	$412^{cde} \pm 25$	$116^{c} \pm 9$	$2319^{efg} \pm 253$
G. atrum	$2.4^{c} \pm 0.6$	$0.42^{c} \pm 0.05$	$0.11^{b} \pm 0.07$	$72^{bc} \pm 3$	$0.05^{b} \pm 0.01$	$1437^{def} \pm 101$	$3263^{c} \pm 99$	$577^{abcd} \pm 24$	$62^{c} \pm 4$	$925^{g} \pm 34$
G. capense	$4.8^{c} \pm 1.7$	$2.44^{bc} \pm 0.39$	$0.05^{b} \pm 0.02$	$70^{bcd} \pm 3$	$0.03^{b} \pm 0.01$	$1909^{de} \pm 195$	$6541^{abc} \pm 290$	$729^{ab} \pm 17$	$217^{b} \pm 27$	$4052^{de} \pm 64$
G. carnosum	$4.7^{c} \pm 1.8$	$6.26^{a} \pm 0.51$	$0.25^{b} \pm 0.12$	$45^{ef} \pm 5$	$0.05^{b} \pm 0.01$	$3064^{c} \pm 301$	$4585^{bc} \pm 1944$	$525^{bcde} \pm 67$	$85^{c} \pm 8$	$4045^{de} \pm 101$
G. hainanense	$6.2^{c} \pm 1.6$	$5.30^{ab} \pm 0.90$	$0.18^{b} \pm 0.06$	$62^{bcde} \pm 2$	$0.04^{b} \pm 0.01$	$2051^{d} \pm 334$	$4213^{c} \pm 159$	$750^{ab} \pm 44$	$24^{c} \pm 2$	$4508^{cd} \pm 326$
G. lucidum	$4.2^{c} \pm 2.4$	$1.98^{c} \pm 2.37$	$0.38^{b} \pm 0.43$	$31^{f} \pm 17$	$0.05^{b} \pm 0.03$	$7302^{a} \pm 413$	$3729^{c} \pm 3694$	$699^{abc} \pm 312$	$73^{c} \pm 17$	$3858^{de} \pm 432$
G. pfeifferi	$43.9^{a} \pm 6.5$	$1.82^{c} \pm 0.49$	$0.14^{b} \pm 0.02$	$113^{a} \pm 8$	$0.02^{b} \pm 0.01$	$7458^{a} \pm 228$	$3169^{c} \pm 118$	$343^{de} \pm 22$	$334^{a} \pm 87$	$2723^{def} \pm 169$
G. sinense	$7.4^{c} \pm 1.5$	$1.25^{c} \pm 0.29$	$6.97^{a} \pm 2.13$	$46^{ef} \pm 5$	$0.16^{a} \pm 0.10$	$1316^{efg} \pm 90$	$3021^{c} \pm 252$	$225^{e} \pm 39$	$108^{c} \pm 19$	$1153^{fg} \pm 113$
B										
G. applanatum	$2.8^{c} \pm 0.7$	$0.16^{c} \pm 0.07$	$0.14^{b} \pm 0.03$	$52^{cdef} \pm 4$	$0.03^{b} \pm 0.01$	$1111^{fg} \pm 116$	$7932^{ab} \pm 301$	$883^{a} \pm 94$	$68^{c} \pm 6$	$10961^{a} \pm 1768$
G. lucidum	$1.8^{c} \pm 0.1$	$0.12^{c} \pm 0.04$	$0.13^{b} \pm 0.03$	$34^{f} \pm 5$	$0.04^{b} \pm 0.02$	$1082^{fg} \pm 38$	$8905^{a} \pm 158$	$779^{ab} \pm 47$	$84^{c} \pm 5$	$6206^{bc} \pm 900$
G. pfeifferi	$4.1^{c} \pm 0.4$	$6.65^{a} \pm 2.48$	$0.07^{b} \pm 0.03$	$50^{def} \pm 4$	$0.08^{ab} \pm 0.03$	$1389^{efg} \pm 180$	$6622^{abc} \pm 182$	$718^{ab} \pm 63$	$67^{c} \pm 5$	$6352^{b} \pm 340$
G. resinaceum	$3.5^{c} \pm 1.9$	$0.98^{c} \pm 0.47$	$0.35^{b} \pm 0.12$	$52^{cdef} \pm 8$	$0.07^{ab} \pm 0.02$	$742^{g} \pm 139$	$3550^{c} \pm 764$	$384^{de} \pm 83$	$267^{ab} \pm 50$	$3051^{de} \pm 47$
Mean										
A	11.8	2.53	1.03	65	0.06	3725	4092	532	127	2948
B	3.1	1.98	0.17	47	0.06	1081	6753	691	122	6643
Range	42.1	6.53	6.92	82	0.14	6717	5884	658	310	10,036

Mean ± SD (standard deviation); F-statistic different letters points at significant differences between content of element in column at $p \leq 0.05$ (Tukey's HSD test)

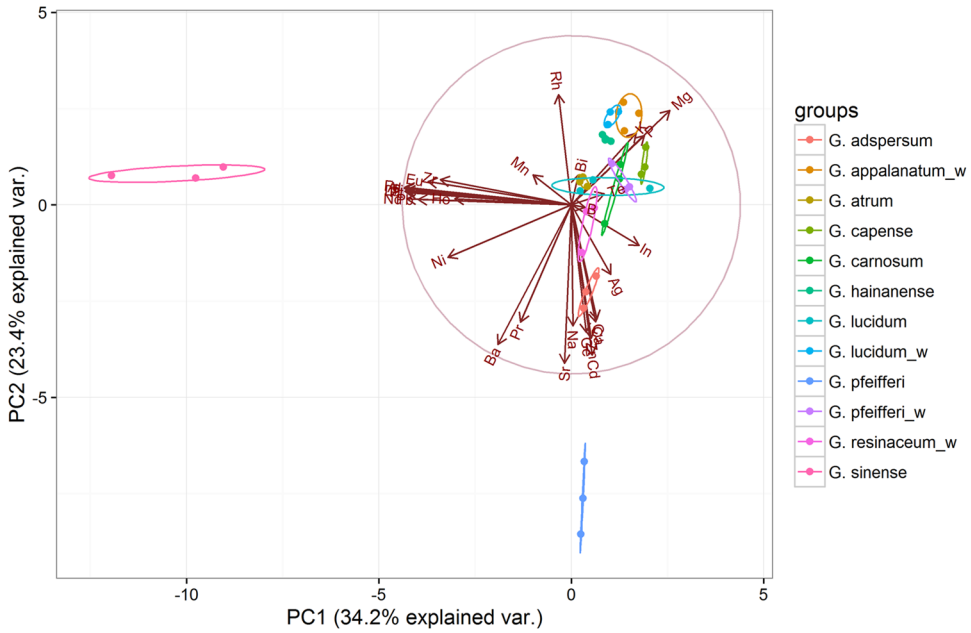

Fig. 1 Principal component analysis for studied elements with regard to the coordinate factor variables (element contents and mushroom species)

of the analyzed *Ganoderma* species. The greatest similarity was observed for *G. atrum, G. capense, G. carnosum* and cultivated *G. lucidum*. For a graphical presentation of similarities/differences between particular *Ganoderma* species, as regards their ability to accumulate elements, a heatmap analysis was performed separately for each sample (Fig. 2a) and mean values for each *Ganoderma* (Fig. 2b) were calculated.

Comparison of cultivated and wild growing *Ganoderma* species from Poland

According to data presented in Table 2, significant differences between Polish cultivated and wild species were observed in only some cases. Significant differences in *G. lucidum* occurred sporadically (for In and K only), whereas in *G. pfeifferi* these differences were significant for Ba, Cd, Eu, Ge, Ni, Rh, Sr, Te, Zn, Mg, and Na. Cultivated *G. lucidum* contained a higher level of In (6.67 ± 1.53 mg kg^{-1} dm) and a lower level of K (3729 ± 3694 mg kg^{-1} dm) than wild growing counterparts (2.26 ± 0.41 and 8905 ± 158 mg kg^{-1} dm, respectively). In *G. pfeifferi*, significantly higher contents of Ba (59.76 ± 16.17), Cd (4.71 ± 1.09), Ge (1.44 ± 0.49), Ni (1.10 ± 0.14), Sr (43.90 ± 4.12), Zn (113 ± 50), and Na (334 ± 67 mg kg^{-1} dm) were observed in cultivated fruit bodies than in wild growing ones. On the other hand, wild growing fruit bodies contained a significantly higher level of Eu (0.13 ± 0.04), Te (6.65 ± 2.49), Rh (0.26 ± 0.07), and Mg (718 ± 63 mgkg^{-1} dm) in comparison with cultivated counterparts. Cultivated *G. lucidum* and *G. pfeifferi* were characterized by a higher content of Ca (7302 ± 413 and 7458 ± 228 mg kg^{-1} dm, respectively) and Pr (2.32 ± 1.12 and 3.51 ± 0.52 mg kg^{-1} dm, respectively) than wild growing samples of these species, which, conversely, were characterized by a significantly higher content of P (6206 ± 900 and 6352 ± 340 mg kg^{-1} dm, respectively).

Content of elements present only in selected mushroom species

A high diversity was observed among the elements quantifiable only in some samples in *Ganoderma* species (group b). *G. adspersum* contained Ga (0.17 ± 0.04 mg kg^{-1} dm) only, whereas *G. atrum* contained Au and Tl (0.95 ± 0.08 and 1.70 ± 0.46 mg kg^{-1} dm, respectively). In *G. capense* Re, Se, and Tl (0.32 ± 0.07, 1.37 ± 0.20, and 0.49 ± 0.22 mg kg^{-1} dm, respectively) were observed in only some fruit bodies. None of the elements included in this group were detected in cultivated *G. carnosum, G. hainanense* or wild growing *G. appalanatum* and *G. resinaceum*. On the other hand, *G. sinense* was characterized by the presence of the majority of elements belong to this group. Contents of Au, Ce, Dy, Er, Ga, Gd, Sc, Th, V, and Y were as follows: 0.82 ± 0.12, 17.93 ± 2.08, 1.58 ± 0.21, 0.47 ± 0.08, 0.42 ± 0.10, 1.43 ± 0.41, 0.50 ± 0.18, 1.26 ± 0.19, 1.34 ± 0.31, and 3.56 ± 0.99 mg kg^{-1} dm, respectively. Cultivated *G. pfeifferi* contained As, Sb, Se, and Rb (0.98 ± 0.17, 0.67 ± 0.21, 0.99 ± 0.14, and 2.08 ± 0.45 mg kg^{-1} dm, respectively), in its fruit bodies whereas its wild growing counterparts contained As, Ga, Re, and Tl (1.37 ± 0.13, 0.26 ± 0.05, 0.36 ± 0.06, and 1.12 ± 0.17 mg kg^{-1} dm, respectively). In *G. lucidum*, Se and Tl (1.41 ± 0.38 and 0.72 ± 0.19 mg kg^{-1} dm,

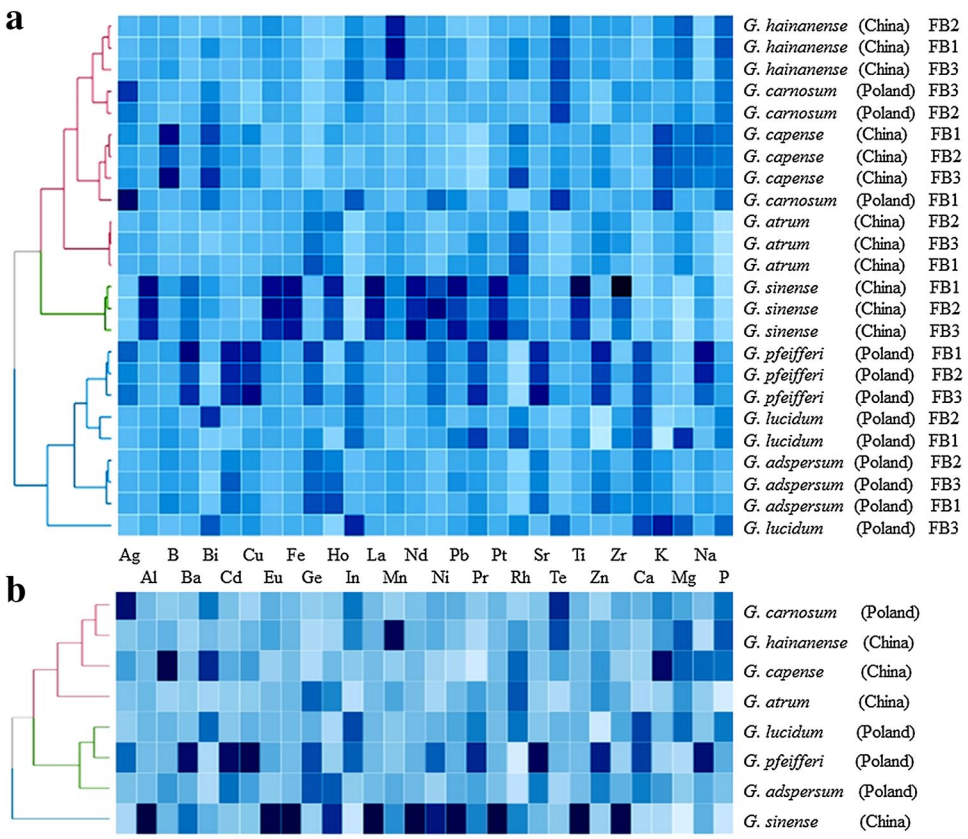

Fig. 2 Correlation between cultivated *Ganoderma* species collected from China and Poland with regard to the content of particular elements (Heatmap) in all collected fruit bodies (**a**) and the mean values (**b**) with presentation of a hierarchical tree plot

respectively) occurred in the cultivated fruit bodies, while As was present in its wild counterparts (0.45 ± 0.08 mg kg^{-1} dm).

Discussion

The results presented in this paper are the most comprehensive to date on the element contents present in fruiting bodies of ten mushroom species belonging to the genus *Ganoderma*. Until now, most available data was limited to studies of *G. lucidum* and *G. applanatum*, although confined to selected elements only. This study is a part of a project to screen the most commercially important mushrooms for their elemental composition [22]. *Ganoderma* mushrooms are valued for their evidence-based beneficial effects on health (mostly exerted by polysaccharides) which include immunomodulation, anti-tumor activities and cardioprotective effects [4, 10, 23]. Contrary to many other popular culinary mushrooms, such as species of *Agaricus* or *Pleurotus* genera, inedible *Ganoderma* mushrooms are mostly cultivated for the production of food supplements or extracts (alcohol- or water-based). This is due to their bitter taste owing to a high content of triterpenes [24], which discourages most people from readily consuming *Ganoderma* fruiting bodies.

Our study has demonstrated the high variability of element composition between the investigated *Ganoderma* species as additionally illustrated using heatmaps. This observation can be attributed to (1) inter-specific differences in uptake of elements from overgrown substrate, (2) different contents of elements in the overgrown substrates, or (3) both. It has been widely demonstrated that mushrooms, including *Ganoderma* spp., can be grown on different substrates, not only in terms of their type but also origin and quality [25–28]. Moreover, different species of the *Ganoderma* genus may require different conditions for growth and cultivation [29]. The element content in overgrown substrate or soil has been directly shown to affect their bioaccumulation in fruiting bodies [30]. It should also be noted that mushroom processing after harvest, particularly the conditions under which they are dried, can influence element content [31]. Moreover, the elemental content in fruiting bodies, especially those from the wild, can to a small extent result from direct aerial or wet deposition [32]. In the case of wild mushrooms, metal content in fruiting bodies can also be affected by age of the mycelium which can grow up to several years in nature (compared to several months in the case of cultivated mushrooms) [33].

Interestingly, the investigated *Ganoderma* samples collected from cultivation had a higher mean content of various elements than mushrooms found in natural habitats. Cultivation methods for these wood-decaying mushrooms mostly involve sawdust, more readily available for decay than hardwood on which wild *Ganoderma* spp. grow. The only exception was found for P and Mg (particularly high levels in wild *G. applanatum*), and K (the highest content in wild *G. lucidum*).

On the other hand, *G. adsperum, G. carnosum, G. lucidum*, and *G. pfeifferi* were all experimentally cultivated in this study on the same substrate of beech and oak sawdust. Yet the contents of various elements, including essential (e.g. Ca, Fe) and toxic ones (e.g. Cd, Ni), in their fruiting bodies were significantly different. This clearly indicates some distinct differences in the elemental uptake by mycelia between these mushroom species. From these four species, *G. pfeifferi* was found to accumulate the greatest content of Cd and Ni. This underlines the necessity to select a substrate for *G. pfeifferi* cultivation whose a content of these elements is as low as possible to avoid consumer exposure to harmful levels and further health consequences. At the same time, *G. pfeifferi* contained the greatest levels of minerals such as Ca, Na, Cu, and Zn. These observations are important because knowledge of *G. pfeifferi*, a European relative of *G. lucidum*, is still very limited [8].

The present study did not investigate the bioactive properties of *Ganoderma* mushrooms, although their elemental composition is likely to influence such properties. As previously demonstrated, uptake of elements such as Se by *G. lucidum* can weaken the antitumor and immunomodulatory effects of its polysaccharides and proteins [34, 35]. As demonstrated in the present study, the Se was detected only in some fruiting bodies with the highest mean contents identified for cultivated *G. capense* (1.37 mg kg^{-1}) and *G. lucidum* (1.41 mg kg^{-1}). Importantly, *Ganoderma* mushrooms were shown to incorporate a high share of Se in organic forms (even when supplemented with inorganic salts) through which the biological role of this element is exerted [28, 36]. All tested mushrooms contained detectable levels of Ge, a non-essential element that at low doses has been reported to exert potentially beneficial effects through antitumor, antioxidant, and antimutagenic activities [37]. As previously demonstrated, fruiting bodies of wild growing *G. lucidum* can contain a relatively high content of this element (0.5 mg kg^{-1}) [38]; a finding that has been used to promote some *Ganoderma*-based products (Wachtel-Galor). In the present study, the mean Ge content reached 0.65 mg kg^{-1} but there was some variation between the tested species. Wild-growing *G. lucidum* was found to contain four-fold lower Ge content than cultivated forms (0.13 vs 0.52 mg kg^{-1}). In turn, the highest levels of Ge, decidedly exceeding 1 mg kg^{-1} were found in cultivated *G. adspersum, G. atrum*, and *G. pfeifferi*. At this stage it is unknown whether these differences may be attributed to Ge content in substrate or species-specific differences in Ge uptake. Nevertheless, it should be stressed that there is no clear evidence for health-beneficial effects of dietary Ge and that in certain forms Ge can be harmful [39]. Therefore, the potentially high Ge content in some *Ganoderma* mushrooms should be subjected to further investigations.

It is known that mushrooms contain nutritional elements with K, P, Ca, Mg, Se, Fe, Zn, and Cu reported to account for most of the mineral content [3]. In the current study the general mean content of minerals in the investigated *Ganoderma* mushrooms decreased in the order K>Ca>P>Fe>Mg>Na>Zn>Mn>Cu. Nevertheless, if one considers the Recommended Daily Allowances (RDAs) for daily intake set by the Food and Nutrition Board [40], the total daily use of 1.5 g of dried *Ganoderma* (as recommended by most producers of food supplements based on these mushrooms) would constitute a rather low nutritional value in this regard for all the investigated essential elements. In this regard, none of investigated species could be considered as a sufficient source of minerals in the human diet. The only exception here is the high content of Fe found in *G. sinense*—the daily consumption of 1.5 g of its dried fruiting bodies by males and females aged 19–30 years would provide 99 and 44% of RDA, respectively. Although the decidedly increased levels of Fe in this mushroom require further confirmation, this finding may be important in view of the fact that Fe deficiency is considered as one of the most common micronutrient deficiencies worldwide and that certain groups are at increased risks: e.g. pregnant women, blood donors and some groups of patients [41]. One should, however, note that simultaneous intake of Ca (second most abundant mineral in *Ganoderma* mushrooms) may interfere with the absorption of iron [42]. Overall, the bioavailability of Fe from *G. sinense* and its use as a potential Fe supplement would require further attention.

The present study also evaluated the content of non-essential metals of evidenced toxicity such as Cd, Pb, Ni, and Al. This is important since the use of traditional Chinese medicines has been linked to metal poisoning [43], and that among three groups of supplement formulations which are based on mushrooms, *Ganoderma*-based supplements were initially found to have increased levels of contaminants (e.g. Pb, Cr, and Ni) [44]. One should note that there is no universal guideline as regards daily doses at which *Ganoderma*-based supplements should be used. A variety of doses have been applied in different studies with a maximum of 1.8 g taken three times a day [45]. To discuss the potential risks arising from the occurrence of

toxic metals in the studied *Ganoderma*, we have assumed a 1.5 g daily dose, which is often recommended by the manufacturers.

The cultivated *Ganoderma* spp. accumulated generally higher levels of Al than wild species. Nevertheless, their mean content in cultivated and wild mushrooms, 170 and 17.5 mg kg^{-1}, respectively, was higher than the mean content recently reported for different *Pleurotus* species, 4.4 mg kg^{-1} [22]. A strikingly high content of Al, exceeding 1200 mg kg^{-1} dm, was observed in *G. sinense*. However, some food supplements based on natural ingredients were found to contain even higher levels of this element [46], thus the high content in *G. sinense* is a matter of some concern. It should be highlighted that Al is poorly absorbed in the gastrointestinal tract (usually 0.1–1.0% of an oral dose) and in healthy subjects almost the entire amount of absorbed Al is excreted readily from the body [47]. Increased accumulation in humans, predominantly in the brain, occurs in patients suffering renal failure or if doses exceed excretory capacity [34], and has been implicated in neurodegenerative processes [48]. The provisional tolerable weekly intake (PTWI) for Al is 2 mg kg^{-1} body weight [49]. The weekly consumption of 1.5 g of dried *G. sinense* per day investigated in the present study would constitute on average 10.5% of PTWI for an adult weighing 60 kg. It should, however, be stressed that other *Ganoderma* spp. mushrooms, including wild samples, contained insignificant Al levels as regards human exposure risks.

The mean levels of Pb and Cd in the mushrooms investigated in the present study were also higher than those determined for commercially available *Pleurotus* sp. [22] and other cultivated mushroom species (*Auricularia auricula, Pleurotus ostreatus, Tremella fuciformis, Flammulina velutipes, Agrocybe chaxinggu, Armillariella mellea, Agaricus bisporus, Pholiota nameko*) recently screened on the Chinese market [50]. The comparison of toxic metal uptake between wood decaying mushrooms (*Daedalea quercina, G. applanatum, Stereum hirsutum*, and *Schizophyllum commune*) have shown that *G. applanatum* accumulate the greatest levels of Cd. All in all, this may indicate the general affinity to uptake Cd and/or Pb by *Ganoderma* spp. but it would require further experimental studies.

In the present study, the highest mean Cd (exceeding 4.5 mg kg^{-1} dm) and Pb (over 7.0 mg kg^{-1} dm) contents were found in cultivated *G. pfeifferi* and *G. sinense*, respectively. The WHO set the PTWI of Pb at 0.025 mg kg^{-1} bodyweight (an equivalent of 0.0036 mg kg^{-1} body weight per day) [51], i.e., 1.5 g weekly (0.21 mg daily) for an adult weighing 60 kg. Thus, the weekly consumption of 1.5 g of dried *G. sinense* per day would constitute 5% of PTWI. The provisional tolerable monthly intake (PTMI) of Cd was set at 0.025 mg kg^{-1} bodyweight [51], an equivalent of 1.5 mg per month for a 60-kg adult. For such an individual the daily consumption of dried *G. pfeifferi* at a daily dose of 1.5 g would constitute over 14% of PTMI (assuming 31 days in a month). Other species investigated in the present study, including wild growing ones, would contribute insignificantly to Pb and Cd exposure.

The rare earth elements (REEs) profile was characterized in *Ganoderma* mushrooms for the first time in this study. Contents of five elements, namely Ho, La, Nd, Pr, and Eu, from 17 REEs, were detectable. Generally, the highest total content of REEs was found for *G. sinense*—16.2 mg kg^{-1} dm with La and Nd being the most abundant. The content of REEs in wild growing *Ganoderma* mushrooms was evidently lower. This is in line with our previous observations indicating low REE content in wild mushroom species [52] and high Nb level in cultivated *Pleurotus* mushrooms [22]. Due to insufficient data on the toxicity and occurrence of REEs, their allowance levels in food are not regulated in the European Union. The only regulations in this matter exist currently in China which sets maximum REEs in food content at 0.7 mg kg^{-1} fresh weight [53], the equivalent of 7.0 mg kg^{-1} dm (as a 10% level is used for calculations with an unknown factual dm level). In the present study, all the studied species with the exception of *G. sinense* fell below this regulatory level. The bioavailability of REEs from mushrooms including *Ganoderma* spp. is yet to be studied, thus our findings alone are insufficient to draw any definite conclusions as to the health risks posed by increased REE content in mushrooms, and specifically La and Nb. Nevertheless, the reasons behind the generally higher content of REEs in cultivated mushroom species in comparison to their wild counterparts is a subject for future investigations. Moreover, concern can be raised over the very high levels of Pt found in the fruiting bodies of *G. sinense*, several-fold higher than in other mushrooms (cultivated and wild) studied so far [22, 54]. It remains unknown whether such high content of Pt is due to polluted substrate, inappropriate mushroom processing or storage, although it has been experimentally proven that artificial Pt contamination of substrate may result in an extremely high accumulation of this element in mushroom fruiting bodies [55].

Comparison of elemental composition between *Ganoderma* mushrooms cultivated in China and Poland revealed some differences. For example, Chinese species were characterized by higher Nd, La (most abundant REEs in *Ganoderma*), Al and Pb contents but a fourfold lower Cd level than the species cultivated in Poland. Chinese species were also generally more nutritious as regards mineral content, significantly higher levels of Fe, K, Mn, Mg, and P were found. China has a long history of *Ganoderma* use and cultivation and currently is the greatest producer of these mushrooms worldwide [56]. At the same time, environmental pollution in China is a matter of concern and may

likely be linked to increased levels of contaminants used for *Ganoderma* production. The present study did not compare the same species from Chinese and Polish cultivations so one cannot unambiguously decide whether the differences in elemental composition between mushrooms originating from these two regions can be attributed to species-specific features in element uptake or differences in substrate content of certain elements. Further experimental studies would be required to elucidate whether *Ganoderma* species differ in uptake of essential and non-essential elements. However, considering the increasing interest in *Ganoderma* mushrooms in different parts of the world, it would be reasonable to control substrate quality for production of these mushrooms or monitor the quality of *Ganoderma* used as an ingredient in food supplements.

Conclusion

The present study provides information on the multielemental composition of ten wood-decaying mushroom species belonging to the *Ganoderma* genus, including the most popular *G. lucidum* and other species that have lately been attracting biomedical interest. Significant differences were found between (1) particular species; (2) mushrooms cultivated in Poland and China; (3) cultivated and wild growing counterparts within a species. Considering that *Ganoderma* mushrooms are mostly used as an ingredient of food supplements, the nutritional value of minerals in their fruiting bodies is relatively low with the exception of Fe content found in *G. sinense*. The level of contaminants in most of the studied species was low apart from the Cd level found in *G. pfeifferi* from Polish cultivation and Al, Pb, and REEs (particularly Nd and La) content determined in *G. sinense* from Chinese cultivation. It is unknown whether the increased content of certain elements in some species can be attributed to substrate contamination or species-specific features—these issues would require further, experimental investigation in standardized conditions. This study represents the most comprehensive information respecting elemental content in *Ganoderma* mushrooms, a reference point for further studies.

Acknowledgements Piotr Rzymski is supported by the Foundation for Polish Science within the "Start" Program (091.2016).

Compliance with ethical standards

Conflict of interest Marek Siwulski declares that he has no conflict of interest. Piotr Rzymski declares that he has no conflict of interest. Przemysław Niedzielski declares that he has no conflict of interest. Anna Budka declares that he has no conflict of interest. Monika Gąsecka declares that he has no conflict of interest. declares that he has no conflict of interest. Agnieszka Jasińska declares that he has no conflict of interest. Sylwia Budzyńska declares that she has no conflict of interest. Lidia Kozak declares that he has no conflict of interest. Mirosław Mleczek declares that he has no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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