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Elemental and biochemical responses of *Cantharellus cibarius* to peri-urban environmental conditions

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Abstract

Aim: This study aimed to characterise and compare the elemental and biochemical composition of *Cantharellus cibarius* fruiting bodies obtained from traders and reported to originate from six peri-urban forest areas, and to assess differences in their chemical profiles across the reported sampling locations.

Methods: Proximate composition, macro- and trace elements, fatty acids (FA), free sterols, water-soluble B-group vitamins, ascorbic acid, total phenolic content, and 2,2'-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) radical-scavenging activity were determined using gravimetric, ICP-OES, gas chromatography-mass spectrometry (GC-MS), and liquid chromatographic methods. Multiple factor analysis was used to integrate the metal, fatty-acid, sterol, and vitamin data blocks.

Results: Moisture and protein contents were relatively stable across locations, whereas crude fat, fatty-acid composition, sterols, vitamins, and several elements showed pronounced site-dependent variation. Unsaturated FA predominated, and samples from the central-southern region contained the highest levels of acetylenic and polyunsaturated FA, ergosterol, and fungisterol. Site-related differences were observed in several elements, particularly Fe, Mn, Ni, and Zn. The first two dimensions of multiple-factor analysis explained 56.7% of the total variation and revealed clear geographical differentiation. Central-southern samples were distinguished mainly by fatty-acid and sterol profiles, whereas coastal samples occupied a contrasting position, particularly associated with fatty-acid and metal contributions. Samples from western, east-northern, and north-eastern locations were differentiated by varying contributions of the four chemical data blocks. Permutational multivariate analysis of variance confirmed significant differences among locations for all four data blocks and for the integrated multiple-factor analysis space.

Conclusions: *C. cibarius* showed clear site-dependent chemical variation across peri-urban locations. Multiple factor analysis (MFA) confirmed that this differentiation reflected coordinated changes across

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elements, FA, sterols, and vitamins. The observed patterns may relate to local environmental conditions, but cannot be attributed solely to anthropogenic pressure.

Keywords

Cantharellus cibarius, chemical profile, elements, sterol, B-group vitamins

Introduction

Cantharellus cibarius is an edible ectomycorrhizal fungus that forms long-lived mutualistic associations with forest trees, including Scots pine (*Pinus sylvestris*) and downy birch (*Betula pubescens*) [1]. Through these associations, the fungus supplies the host with soil-derived nutrients and water, while receiving photosynthetically fixed carbon that is incorporated into fungal carbohydrates and other metabolites [2]. Consequently, differences in host-tree identity, physiological condition, and stand composition may alter carbon allocation and nutrient availability to the fungal partner, thereby contributing to variation in the elemental and biochemical composition of chanterelle fruiting bodies. This may be particularly relevant to lipid profiles, although direct host-to-fungus fatty-acid transfer has been demonstrated for arbuscular rather than ectomycorrhizal mycorrhiza. These findings indicate that plant–fungus carbon exchange can be closely linked to fungal lipid biosynthesis and should therefore be considered when interpreting site-dependent fatty-acid variation in *C. cibarius* [3].

Heavy metal compounds are among the most dangerous pollutants in urban environments due to their toxicity, mobility, and potential for bioaccumulation [4]. Given the pronounced bioaccumulation properties of mushrooms, chanterelles (*C. cibarius*) can serve as a useful bioindicator species for assessing environmental pollution. In comparative studies, chanterelles have been observed to show relatively lower concentrations of Hg, Ni, Cd, and Cu [mg/kg dry weight (dw)] than many other mushroom species [5]. Calculating the bioconcentration factor (BCF) values for metals in representatives of *Agaricomycetes* (ectomycorrhizal fungal species) shows that *C. cibarius* in various topographic regions in unpolluted environments actively concentrates Rb and K from soils, followed by Cu, P, Zn, Mg, and finally Fe and Pb [6, 7].

In addition to anthropogenic pressures, the geological and soil background of the collection areas may contribute to spatial variation in the elemental composition of mushrooms. Differences in parent material and soil development influence the abundance and bioavailability of mineral elements, which may subsequently affect their uptake by ectomycorrhizal fungi. Latvia encompasses contrasting geological settings, ranging from coastal Baltic Ice Lake and Littorina Sea sandy deposits to glacial, glaciofluvial and glaciolacustrine deposits in the inland and upland regions [8]. Accordingly, geological and soil characteristics were considered part of the environmental context when interpreting site-associated differences in the elemental composition of *C. cibarius*.

Plasma membrane lipids significantly regulate fungal defence, and glycolipids confer virulence to several fungal species [9]. The total lipid content typically ranges from 2% to 6% of the mushroom's dw [10]. A broad spectrum of fatty acids has been identified in the lipid fraction of chanterelles [11]. It is largely composed of polyunsaturated fatty acids (PUFA), which comprise approximately 75% of the total fatty acids, with linoleic acid (18:2 Δ9,12) and oleic acid (18:1 Δ9) being the most prevalent, while palmitic acid (C16:0) accounts for the majority of the saturated fatty acids (SFA) [12]. However, the fatty acid composition of mushrooms varies significantly across growing regions [13, 14].

Acetylenic fatty acids (AcEFA) are specific fungal metabolites produced as part of the defence response [15, 16]. Chanterelles are recognised as the most prolific producers of AcEFA [17]. However, most research has focused on the biological mechanisms of these compounds and their effects in treating diseases [18] and in organoleptic studies [19], with less attention paid to determining their content. Although the classification of fungi has shifted from a morphological system to a DNA-based system, the presence of dehydrocrepenynic acid unites fungi within the order *Cantharellales*. This AcEFA has been found in mushrooms of the genera *Cantharellus*, *Craterellus*, *Clavulina*, and *Hydnum* [20].

Chanterelles, whether fresh or processed, contain fungal sterols, mainly ergosterol (ergosta-5,7,22-trien-3β-ol). Additionally, it has been reported that *C. cibarius* contains ergosta-7,22-dienol, fungisterol (ergosta-7-enol), and ergosta-5,7-dienol [21, 22]. There are differences in the amounts of free and esterified forms within the Cantharellaceae family. Fruit bodies of *C. tubaeformis*, *Craterellus cornucopioides*, and *C. cibarius* contain free ergosterol at levels of 1.73 mg/g [23], 0.44 mg/g, and 0.23 mg/g dw [24], respectively. Chromatographic analyses, based on various literature data, show that, after releasing esterified forms of fungal sterols, relatively high amounts of ergosterol were found in *C. cibarius*, *C. cornucopioides* (harvested in Spain), and *C. cibarius* (harvested in Canada), with values of 2.61 mg/g, 0.79 mg/g [25], and 2.26 mg/g dw [26], respectively. It is also important to note that ergosterol content varies within different parts of the fruit, ranging from 1.00 mg/g dw in the stem to 2.78 mg/g dw in the gills, as observed in *C. cibarius* [21].

As can be seen, the fruiting bodies of *C. cibarius* contain a diverse range of nutritionally and physiologically relevant constituents, including proteins, fatty acids, sterols, vitamins, and mineral elements, whose levels may vary with growing conditions and local environmental characteristics [27]. Therefore, comprehensive biochemical characterisation of *C. cibarius* is relevant not only for assessing its nutritional composition but also for understanding site-associated variation in its chemical profile.

This study aimed to characterise and compare the elemental and biochemical composition of *C. cibarius* fruiting bodies obtained from traders and reported to originate from six peri-urban forest areas in Latvia, and to assess site-associated differences in their chemical profiles. The observed variation was interpreted in the context of documented differences in geological and soil background, vegetation, regional meteorological conditions, and potential anthropogenic pressures, without attributing the chemical differences to any single environmental factor.

Materials and methods

Sample collection

C. cibarius Fr. fruit bodies were purchased from multiple traders at major cities' marketplaces in early September 2022. Sampling sites were chosen to span the country from west to east, and collection areas were confirmed with traders, selecting only mushrooms harvested near suburban zones, with a mean distance of 7.0 km between individual collection areas around each town (Figure 1). Within each town, approximately 0.4 kg of fruiting bodies from each vendor were pooled in equal proportions to produce three independent composite samples representing the reported collection area. Because the mushroom material was inherently heterogeneous, three independent composite samples were prepared for each location and processed separately through the complete analytical procedure. Thus, triplicate measurements represent analyses of independently prepared composite sample material. Species identification was performed visually at purchase [28] and verified in the laboratory using morphological traits under light microscopy and sporophore structures [29]. See the supplementary materials for weather conditions (Supplementary material).

Table 1 summarises the regional characteristics of the *C. cibarius* collection area near trade sites, including host trees, geological and soil characteristics, and major potential anthropogenic pressures.

Table 1. Characteristics of the *C. cibarius* sampling sites.

Site	Market city and geographical setting	Urbanisation hierarchy [30]	Main potential anthropogenic pressures [31]	Geological and soil context [8, 32]	Habitat [33]
1NW	Ventspils; north-western Baltic coastal region	National development centre	Port operations, cargo handling and storage, industrial production, freight transport, urban traffic, and coastal tourism	Coastal sandy deposits associated mainly with the Baltic Ice Lake and Littorina Sea stages; predominantly sandy Podzols and Arenosols, with locally hydromorphic soils	Scots pine (*Pinus sylvestris*) host in coastal pine forests; birch (*Betula pubescens*) and black alder (*Alnus glutinosa*) may occur locally

Table 1. Characteristics of the *C. cibarius* sampling sites. (*continued*)

Site	Market city and geographical setting	Urbanisation hierarchy [30]	Main potential anthropogenic pressures [31]	Geological and soil context [8, 32]	Habitat [33]
2WN	Tukums; western–northern continental region and North Kurzeme Upland	Regional development centre	Agriculture, food production, forestry and wood processing, road and railway transport, smaller-scale manufacturing, and tourism	Glacial and glaciofluvial deposits of the upland landscape; heterogeneous mineral soils, including Podzols and Luvisols, with locally occurring Gleysols	*P. sylvestris*, Norway spruce (*Picea abies*) and birch (*Betula pendula)* species
3S	Jelgava; central–southern Latvia, Zemgale Plain	National development centre	Intensive agriculture in the surrounding lowlands, manufacturing and food processing, logistics, road and rail transport, and urban development	Flat glaciolacustrine and alluvial lowland; relatively fertile mineral soils, including Luvisols and Stagnosols, with locally occurring alluvial and hydromorphic soils	*B. pendula* and *P. sylvestris* as hosts in peri-urban forest stands; *P. abies* occurs in mixed forests
4EN	Sigulda; eastern–northern region, Gauja valley and western Vidzeme Upland	Regional development centre	Tourism and recreation, seasonal visitor traffic, road and railway transport, urban expansion, and forest management	Glacial and glaciofluvial upland deposits dissected by the Gauja valley, with local exposures of Devonian sandstone; predominantly acidic mineral forest soils, including Podzols	*Pinus sylvestris*, *Picea abies* and *B. pendula*; mixed deciduous trees may also be present
5NE	Cēsis; north-eastern upland region, within the broader Gauja National Park landscape	Regional development centre	Tourism, recreation, forestry, local transport and limited urban activity	Glacial and glaciofluvial upland deposits; predominantly acidic mineral soils, including Podzols and Luvisols, with locally occurring Gleysols	*Pinus sylvestris*, *P. abies*, and *B. pendula*
6NE	Smiltene; north-eastern upland region	Regional development centre	Forestry and wood processing, agriculture, regional road transport, smaller-scale manufacturing, and dispersed settlement	Heterogeneous glaciogenic upland deposits, including glacial till and glaciofluvial sands; predominantly Podzols and Luvisols, with locally occurring hydromorphic soils	*Pinus sylvestris* and *B. pendula*, but *P. abies* in the north-eastern upland forest landscape

Reagents

All chemicals were used as received from commercial sources (LaboChema Latvia, Latvia). All reference compounds used were of the highest grade (Sigma-Aldrich). The enzyme taka-diastase (α-amylase from *Aspergillus oryzae*, ~100 U/mg) was acquired from Fisher Scientific (Sigma-Aldrich).

Gross characteristics of chanterelles

The moisture content was measured with a moisture analyser (Kern, DBS 60–3, UK) at 105°C by calculating the mass difference between the wet and dry samples. The protein content was estimated from nitrogen content using the Kjeldahl method [34] and a conversion factor of 4.38 [35]. The crude lipid content was determined through Soxhlet extraction with hexane as the solvent [36]. Macro and trace elements were quantified using ICP-OES (Thermo Scientific iCAP 7000 series) after microwave mineralisation. Wavelength settings were adjusted in accordance with Chapter 5 of EN ISO 11885:2009 [37], and data analysis was performed using Qtegra ISDS Software 2.10.

Chromatography methods

Fatty acids were extracted using Soxhlet with hexane, transesterified into fatty acid methyl esters (FAMEs) following Barros and coauthors [12], and analysed by gas chromatography-mass spectrometry (GC-MS) (PerkinElmer™, Clarus 580/Clarus SQ8C) on an Omegawax 250 column (30 m × 0.25 mm × 0.25 µm; Supelco) under the conditions of Borska and coauthors [38]. FAMEs were quantified by external calibration with methyl heptadecanoate. Fatty acids, including conjugated linoleic acid (CLA), were identified by comparing retention data and mass spectra with published reports [39, 40] and the NIST spectral library.

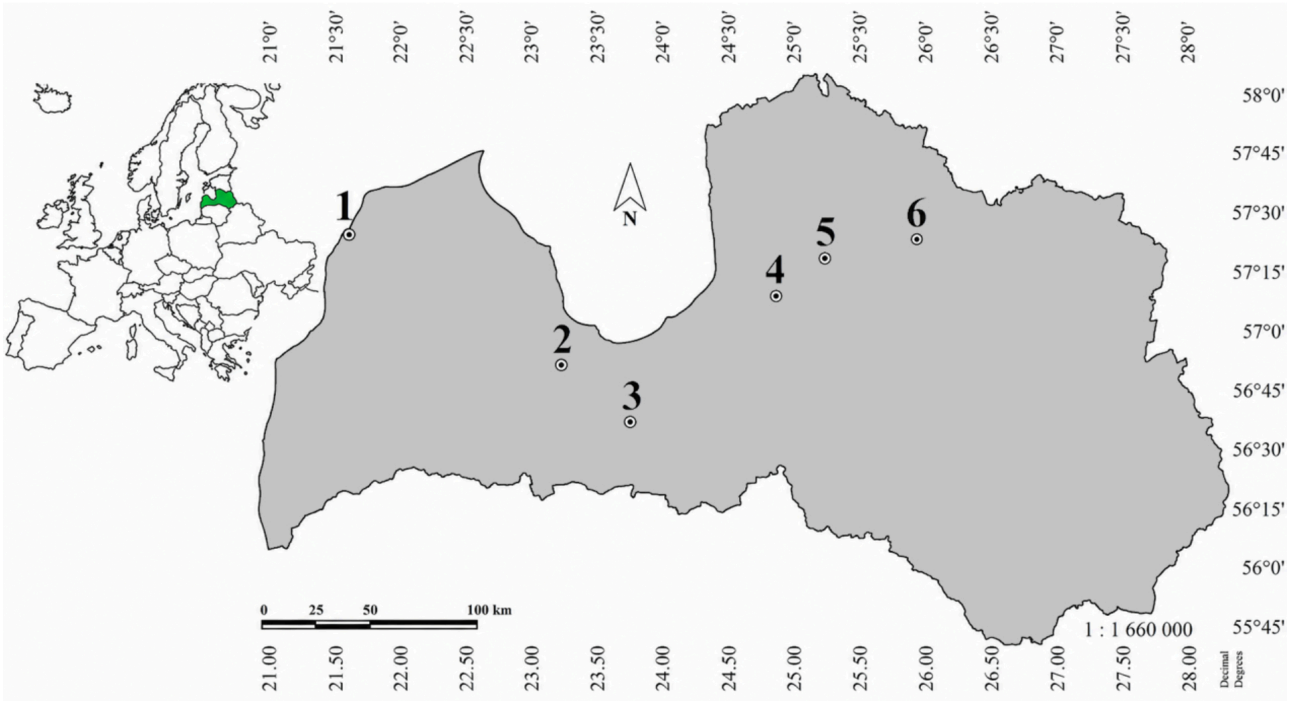


Figure 1. Location of six *C. cibarius* sampling sites in Latvia. *C. cibarius* mushrooms were purchased from urban markets in the northwest coastal region 1 (1NW, Ventspils), the west-north continental region 2 (2WN, Tukums), the central southern parts of the country 3 (3S, Jelgava), the east-north region 4 (4EN, Sigulda), and from a geographic upland area in the northeast 5 and 6 (5NE, Cēsis; 6NE, Smiltene).

Free sterols were extracted from the mushroom samples by ultrasonic extraction with dimethyl sulfoxide (DMSO) at 45°C for 30 min, following the protocol of Huang and coauthors [41]. Free sterol measurements were performed as described by Phillips and coauthors [22].

Riboflavin (B2) and pantothenic acid (B5) were extracted by takadiastase-assisted enzymatic hydrolysis [42]. Nicotinic acid (B3) and nicotinamide (B3') were obtained by alkaline hydrolysis followed by autoclaving (121°C, 30 min), with minor modifications [43]. After centrifugation, the supernatant pH was adjusted to 7.0 with 2 M sodium acetate. The supernatant was passed through a cation-exchange resin (Dowex 50 W-X8 in H^+ form, 250 mg) column, which was successively washed with 70% aqueous ethanol and water, then eluted with 1.0 N ammonia. The eluate was evaporated to dryness and redissolved in deionised water. L-ascorbic acid (vitamin C) was extracted according to Bernaś and Jaworska [44].

The determination of water-soluble vitamins was performed using ultra-performance liquid chromatography (UPLC) coupled with ultraviolet (UV) and mass spectrometric (MS) detection. MS parameters, including multiple reaction monitoring (MRM) and the monitored ion transitions (Table S1 and S2), were set according to Waters™ application notes [45]. The UPLC conditions were based on the method previously developed and validated by our group [46].

Total phenolic content and ABTS free radical scavenging activity

The antioxidant activity and total phenolic content (TPC) from *C. cibarius* extracts were determined as described by Klavins and coauthors [47] using a 96-well microplate reader (Tecan™, Nanoquant Infinite M200, Männedorf, Switzerland). Antioxidant activity was expressed as Trolox equivalents (TE), and TPC as gallic acid equivalents (GAE).

Statistical analysis

At each sampling location, three independent composite mushroom samples were prepared from separate, non-overlapping groups of vendors. Each composite samples was processed independently through the complete analytical procedure. The triplicate measurements were used to account for heterogeneity among the composite sample and analytical variability. Correlations were calculated using the Pearson

product–moment correlation coefficient (r), with significance assessed by two-tailed tests ($p < 0.05$). Differences among sites were evaluated by one-way ANOVA followed by Tukey's HSD test; within tables, different letters indicate significant differences between means ($p < 0.05$). Multiple factor analysis (MFA) was used to integrate the metal, fatty-acid, sterol, and vitamin data blocks. Differences in multivariate composition among sampling sites were subsequently assessed separately for each data block and for the MFA score space using permutational multivariate analysis of variance (PERMANOVA) based on Euclidean distances and 9,999 permutations.

Results

General characteristics

C. cibarius biomass was first characterised by sampling site (Table 2). Moisture content ranged from 88.5% to 91.1% and did not differ significantly among sites. Protein content was similarly stable, varying only slightly between 22.43% and 23.01% (dw), indicating a weak site effect. In contrast, crude fat content showed the greatest site-dependent variability, ranging from 4.39% to 5.43%, corresponding to approximately a 24% relative difference between the lowest and highest value sites and including statistically significant differences ($p < 0.05$).

Table 2. Biomass attributes of *C. cibarius* by collection sites.

***C. cibarius* samples**		**Proximate composition content**		
Designation	**Peri-urban forests locality**	**Moisture of mushroom g/100 g (SD), fw**	**Protein g/100 g (SD), dw**	**Crude fat (lipids) g/100 g (SD), dw**
1NW	Ventspils	90.59^{a} (2.05)	23.01^{a} (0.72)	5.43^{a} (0.30)
2WN	Tukums	90.03 (2.03)	22.77 (0.81)	5.15^{abc} (0.37)
3S	Jelgava	91.11 (1.95)	22.82 (0.87)	5.25^{ab} (0.28)
4EN	Sigulda	89.24 (2.08)	22.68 (0.80)	4.53^{bc} (0.26)
5NE	Cēsis	89.27 (1.92)	22.55 (1.02)	5.04^{abc} (0.35)
6NE	Smiltene	88.47 (1.97)	22.43 (0.92)	4.39^{c} (0.23)

In each column, different letters indicate significant differences ($p < 0.05$) according to Tukey's HSD test. For each location, values are means ± SD from three independent composite samples processed separately through the complete analytical procedure.

Fatty acid profile

Thirty fatty acid-related compounds were identified in *C. cibarius* and classified into six groups, namely unsaturated fatty acids (UFA), SFA, monounsaturated fatty acids (MUFA), PUFA, acetylenic fatty acids (AcEFA), and CLA. Overall, UFAs clearly dominated over SFAs (77.8% vs. 14.4%) (Table 3), rising to 85.6% when AcEFA and CLA were included. In most samples, PUFA was the most abundant, followed by MUFA, SFA, AcEFA, and CLA. This pattern mainly reflected the high proportion of linoleic acid (18:2 Δ9c,12c) (Table S3 and S4). Linoleic acid ranged from 4.18–10.1%, with site 3S significantly higher ($p < 0.05$). The main MUFAs were cis-vaccenic (18:1 Δ11c), oleic (18:1 Δ9c), and *cis*-palmitvaccenic acids (16:1 Δ11c). At sites 5NE and 6NE, MUFA exceeded PUFA, mainly because cis-vaccenic acid was relatively high (6.08% and 4.70%, respectively), whereas oleic acid (18:1 Δ9c) varied from 0.58% to 1.43%. Palmitoleic acid (16:1) geometric isomers were minor in all samples (≤ 0.11% for Δ9c and ≤ 0.06% for Δ9t). α-Linolenic acid (18:3 Δ9c,12c,15c) was low overall (3.42–8.86%) and absent at 5NE and 6NE, consistent with previous reports [12, 48]. No short-chain SFAs (C4–C10, C13) or SFAs longer than C24 were detected. Total SFA ranged from 1.38–3.59%, dominated by palmitic acid (0.88–2.35%).

Based on published mass spectra and fragmentation pathways [49, 50], three AcEFA were tentatively identified (Figure S1 and S2): dehydrocrepenynic acid (18:3 Δ9c,12a,14c), octadeca-9,12-dien-6-ynoic acid (18:3 Δ6a,9c,12c), and octadeca-9,12-dien-14-ynoate (18:3 Δ9c,12c,14a) (Table S3 and S4). Total AcEFA content (see Table 3) varied markedly across sites, peaking at 3S (417.7 mg/100 g dw) and reaching its lowest level at 5NE (42.0 mg/100 g dw). CLA was present only in trace amounts (0.04–0.18%) and consisted mainly of the rumenic acid (18:2 Δ9c,11t) and 18:2 10t,12c isomers.

Table 3. Main groups of fatty acids in the *C. cibarius* mushroom for various sites.

Site	Fatty acids, mg/100 g dw (SD) (as FAMEs)					
	AcEFA	MUFA	PUFA	SFA	CLA	UFA/SFA
1NW	200.45^{d} (4.15)	708.61^{c} (24.18)	1,103.82^{d} (34.83)	340.34^{c} (16.63)	16.75^{d} (0.74)	5.36
2WN	377.34^{b} (16.33)	610.77^{c} (12.47)	1,275.81^{c} (52.25)	267.40^{d} (22.87)	23.65^{c} (1.94)	7.09
3S	417.70^{a} (9.75)	1,391.23^{a} (25.48)	2,420.89^{a} (41.89)	696.19^{a} (18.69)	34.46^{a} (1.15)	5.52
4EN	288.71^{c} (6.48)	1,162.19^{b} (24.21)	1,617.36^{b} (25.42)	401.98^{b} (11.32)	27.15^{b} (1.06)	6.95
5NE	42.02^{e} (4.78)	1,520.68^{a} (22.33)	1,262.36^{c} (15.36)	642.18^{a} (12.01)	7.87^{e} (0.61)	4.34
6NE	53.38^{e} (2.87)	1,136.85^{b} (114.31)	882.45^{e} (69.82)	454.02^{b} (44.62)	13.59^{d} (0.41)	4.45

For each location, values are means ± SD from three independent composite samples obtained from separate, non-overlapping groups of vendor. Results are expressed as mg/100 g dw as fatty acid methyl esters. Means followed by different letters on the same column are significantly different ($p < 0.05$) by Tukey's test. MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids; SFA: saturated fatty acids; UFA: unsaturated fatty acids; CLA: conjugated linoleic acid; AcEFA: acetylenic fatty acids; UFA/SFA: the ratio of total UFA to total SFA.

Pearson correlation analysis of the full fatty acid GC profile revealed distinct association patterns among the three AcEFA (Figure 2). Octadeca-9,12-dien-14-ynoic acid (18:3 Δ9c,12c,14a) was very strongly correlated with linoleic acid (18:2 Δ9c,12c) (r = 0.923, df = 10, $p < 0.001$) and α-linolenic acid (18:3 Δ9c,12c,15c) (r = 0.840, $p < 0.001$), suggesting that its variation was closely linked to conventional C18 PUFA metabolism. In contrast, dehydrocrepenynic acid (18:3 Δ9c,12a,14c) and octadeca-9,12-dien-6-ynoic acid (18:3 Δ6a,9c,12c) were almost perfectly correlated with each other (r = 0.977, $p < 0.001$), indicating closely coordinated accumulation. Both compounds were strongly negatively associated with azelaic acid (AZA), palmitelaidic acid (16:1 Δ9t), and behenic acid (22:0), while showing positive associations with 9*Z*, 11*E*-octadecadienoate (CLA; 18:2 Δ9c,11t). These contrasting correlation profiles indicate that octadeca-9,12-dien-14-ynoic acid and the dehydrocrepenynic acid (octadeca-9,12-dien-6-ynoic acid; 18:3 Δ6a,9c,12c) pair may be subject to different metabolic regulation. Nevertheless, the correlations do not establish direct precursor–product relationships.

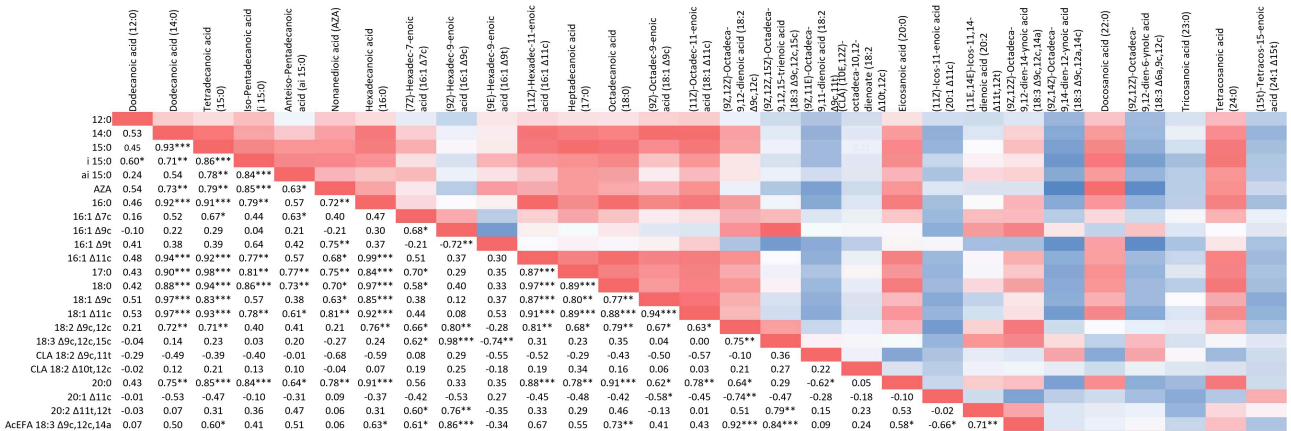


Figure 2. Pearson correlation matrix of fatty acid content in *C. cibarius* samples. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. The intensity of the colour depends on the strength of the correlation coefficient; the darker the shade of blue, the more negative the correlation.

Macro and trace elements content

Potassium was the preponderant element (Figure 3a) in all mushroom samples, especially those collected from the northwestern coast and the northeastern uplands. The northwestern coastal region is characterised predominantly by sandy deposits associated with the Baltic Ice Lake and Littorina Sea stages, on which Arenosols and Podzols may develop, with hydromorphic soils occurring locally in poorly drained areas. In contrast, the northeastern uplands are dominated by heterogeneous glaciogenic and glaciofluvial

parent materials, associated mainly with Podzols and Luvisols, and hydromorphic soils occur locally [8]. *C. cibarius* also showed high accumulation of Mg, Zn, Al, Fe, Cu, and Mn (Figure 3a–3c). The elemental contents in *C. cibarius* samples ranged from 810.0 to 990.0 mg/kg for Mg, 49.40 to 92.02 mg/kg for Zn, 59.81 to 90.58 mg/kg for Al, 38.3 to 76.5 mg/kg for Fe, 21.90 to 36.84 mg/kg for Cu, 12.42 to 26.02 mg/kg for Mn, 1.43 to 3.00 mg/kg for Ti, 0.32 to 1.08 mg/kg for Cr, 0.50 to 1.40 mg/kg for Ni, 0.00 to 0.50 mg/kg for Co, and 0.10 to 0.28 mg/kg for Cd. The concentrations of several elements were below the method detection limits and consisted of As, B, and Se < 1.2 mg/kg dw; Sb and Li < 0.8 mg/kg dw; Pb < 0.5 mg/kg dw; Mo, and V < 0.1 mg/kg dw and < 0.01 mg/kg dw for Be.

Pearson correlation analysis revealed several strong positive relationships among the elements (Figure 4). The strongest correlations were observed for K–Mg, Cu–S, Ca–Mn, Mn–Ni, Cr–Fe ($r > 0.924$, $p < 0.001$), and Fe–Ti ($r = 0.910$, $p < 0.001$). Al was also strongly correlated with Ti ($r = 0.864$, $p < 0.001$), whereas Fe and Mn were not significantly correlated ($r = 0.504$, $p = 0.094$). Among the macronutrients, only K and Mg showed a very strong association; the correlations of K with P ($r = 0.622$, $p = 0.031$) and Mg with P ($r = 0.700$, $p = 0.011$) were moderate to strong but less pronounced. In contrast, Cu and Zn ($r = 0.773$, $p = 0.003$) and Ni and Co ($r = 0.810$, $p = 0.001$) showed significant selective correlations, implying biologically mediated uptake, whereas Cd and Na displayed weaker or inconsistent relationships, pointing to site-specific controls rather than a common source.

Water-soluble B-group vitamins and ascorbic acid content

Table 4 summarises the B-group vitamins and ascorbic acid content of *C. cibarius* collected from different locations. Chromatograms of *C. cibarius* extract obtained by LC-MS/MS (ESI+ ion mode) are shown in Figure S3. The total content of the B vitamins studied also varied significantly, ranging from 185 mg/100 g to 526 mg/100 g, with niacin accounting for the majority (71–90%) of the total vitamin pool. Nicotinic acid levels ranged from 93.4 to 154.1 mg/100 g, while nicotinamide exhibited the greatest variability among sites (36.3–318.0 mg/100 g), with the highest niacin content recorded at site 4EN (east-north region). Pantothenic acid (B5) varied less across locations, indicating relatively stable biosynthesis. Overall, samples from 4EN and 5NE showed the highest B-vitamin content, particularly vitamin B3, whereas 2WN and 3S tended to contain lower levels of several B vitamins. Ascorbic acid content ranged from 112.8 mg/100 g at 6NE to 199.1 mg/100 g at 3S.

Table 4. Influence of growing site on the concentrations of water-soluble B group vitamins and ascorbic acid in *C. cibarius* mushrooms.

Site	Content of vitamins, mg/100 g dw (SD)				
	Riboflavin (B2)	Pantothenic acid (B5)	Nicotinamide (B3')	Nicotinic acid (B3)	Ascorbic acid (C)
1NW	0.62^{c} (0.02)	32.4^{bc} (5.2)	134.3^{b} (6.6)	120.2^{bc} (11.5)	172.8^{ab} (10.9)
2WN	0.36^{d} (0.04)	24.2^{c} (4.5)	112.5^{c} (6.1)	93.4^{c} (7.8)	106.3^{c} (8.7)
3S	0.27^{d} (0.04)	53.3^{a} (2.1)	36.3^{d} (1.2)	94.9^{bc} (14.5)	199.1^{a} (7.9)
4EN	1.22^{b} (0.09)	52.8^{a} (6.3)	318.0^{a} (12.6)	154.1^{a} (11.3)	150.5^{b} (13.3)
5NE	1.92^{a} (0.09)	46.4^{a} (6.1)	133.9^{b} (6.2)	125.0^{ab} (11.4)	179.7^{a} (9.7)
6NE	1.06^{b} (0.08)	45.1^{ab} (2.8)	125.9^{bc} (6.2)	96.0^{bc} (9.2)	112.8^{c} (10.5)

In each column, different letters indicate significant differences ($p < 0.05$) according to Tukey's HSD test. For each location, values are means ± SD from three independent composite samples prepared from separate, non-overlapping groups of vendors.

Pearson correlations indicated that variations in vitamins were mainly driven by B3 forms (Figure 5). Nicotinamide and nicotinic acid were strongly correlated ($r = 0.833$, $df = 16$, $p < 0.001$), showing consistent co-variation across sites. Riboflavin (B2) was moderately linked with nicotinic acid ($r = 0.557$, $p < 0.05$), and pantothenic acid (B5) was correlated with ascorbic acid ($r = 0.547$, $p < 0.05$).

Ergosterol derivatives

Free ergosterol and its derivatives (ergosta-7,22-dienol and ergosta-7-enol) identified in *C. cibarius* are presented in Table 5. Ergosterol was found in all samples and accounted for 92.6–96.3% of the identified

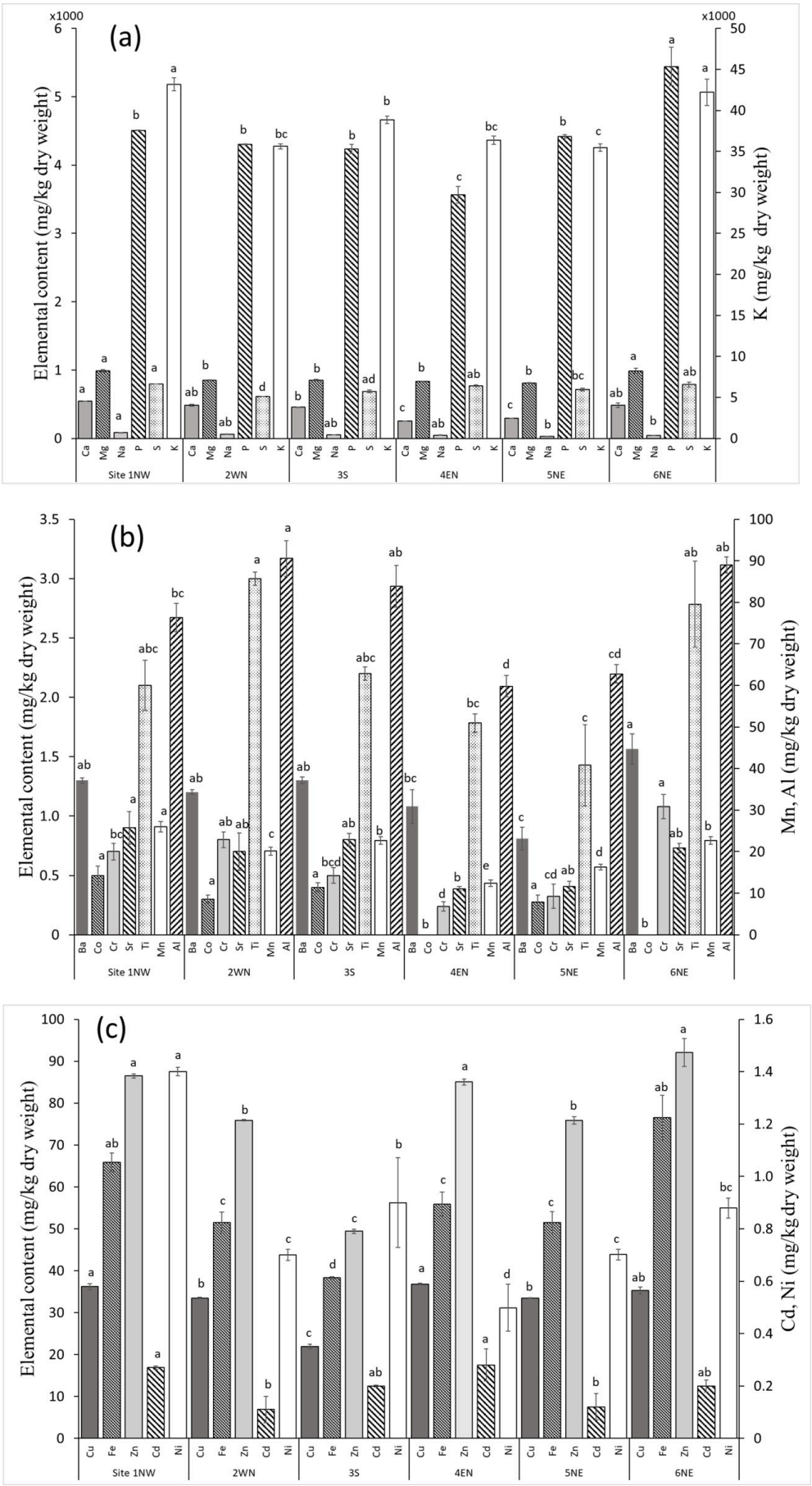


Figure 3. Concentrations of macro and trace elements (mg/kg) in *C. cibarius* mushrooms from different regions of Latvia. 1NW: the northwest coastal region; 2WN: the west-north continental region; 3S: the central southern parts of the country; 4EN: the east-north region; 5NE and 6NE: from a geographic upland area in the northeast. a: Ca, Mg, Na, P and S are shown on the primary y-axis, whereas K is shown on the secondary y-axis; b: Ba, Co, Cr, Sr, Ti (primary y-axis) and Mn, Al (secondary y-axis); c: Fe, Zn, Cu (primary y-axis) and Cd, Ni (secondary y-axis).

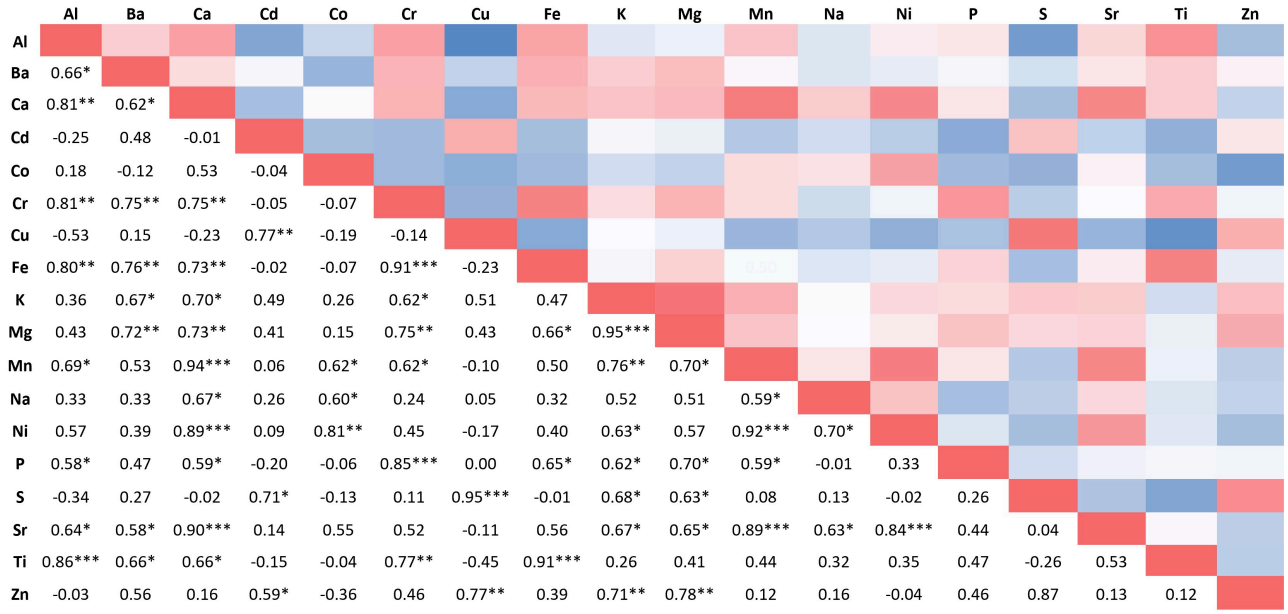


Figure 4. Pearson correlation matrix of 18 elements in *C. cibarius* samples. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. The intensity of the colour depends on the strength of the correlation coefficient; the darker the shade of blue, the more negative the correlation.

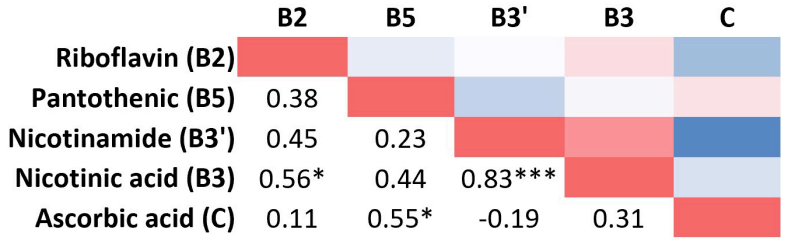


Figure 5. Pearson correlation matrix of 5 vitamin contents in *C. cibarius* samples. * $p < 0.05$, *** $p < 0.001$. Colour intensity reflects the strength of the correlation coefficient; the darker the shade of blue, the more negative the correlation.

sterols (Figure S4). Overall, higher ergosterol concentrations were observed in samples from the central southern site (3S) and the east-north site (4EN). At five of the six sampling locations, 7-ergostenol (fungisterol) levels were higher than those of 7,22-ergostadienol, ranging from 4.6 mg/100 g to 34.8 mg/100 g, consistent with literature values of approximately 0.35–2.53 mg/100 g fresh weight (approx. > 3.1–28.4 mg/100 g dw) reported for chanterelle samples [22]. The lowest concentrations of 7,22-ergostadienol were detected in *C. cibarius* from site 3S (4.4 mg/100 g dw), followed by 6NE (5.2 mg/100 g dw). The low 7,22-ergostadienol content was mainly offset by the higher abundance of fungisterol, especially from site 3S, where the concentration reached 34.8 mg/100 g dw. Although fungisterol represented less than 4% of total sterols, its site-dependent variation was evident. In this context, the site-dependent variation in fungisterol and 7,22-ergostadienol suggests that local environmental conditions may differentially influence sterol biosynthesis and the distribution of ergosterol pathway intermediates.

Table 5. Influence of growing site on the concentrations of free sterols in *C. cibarius* mushroom.

Site	Content of sterols, mg/100 g dw (SD)			
	7,22-Ergostadienol	Ergosta-5,7,22-trien-3β-ol (ergosterol)	7-Ergostenol (fungisterol)	Total
1NW	6.8^{c} (0.19)	458^{c} (9.96)	16.5^{b} (0.6)	481 (11)
2WN	9.3^{b} (0.07)	417^{d} (3.67)	11.2^{c} (0.5)	437 (4)
3S	4.4^{d} (0.08)	840^{a} (9.80)	34.8^{a} (0.4)	879 (10)
4EN	14.0^{a} (0.81)	754^{b} (3.20)	15.3^{b} (0.6)	783 (5)
5NE	12.9^{a} (0.62)	224^{f} (3.02)	4.6^{d} (0.2)	242 (4)
6NE	5.2^{d} (0.31)	324^{e} (8.70)	10.4^{c} (0.6)	339 (10)

In each column, different letters indicate significant differences ($p < 0.05$) according to Tukey's HSD test. For each location, values are means ± SD from three independent composite samples prepared from separate, non-overlapping groups of vendors.

Correlation analysis revealed several significant patterns (Figure 6). A very strong positive correlation was observed between ergosterol and fungisterol ($r = 0.852$, $p < 0.001$), probably reflecting a common metabolic control. In contrast, fungisterol correlated negatively with 7,22-ergostadienol ($r = -0.557$, $df = 16$, $p < 0.05$), which may indicate competition or bias between sterol biosynthetic pathways. The correlation between ergosterol and 7,22-ergostadienol was not statistically significant.

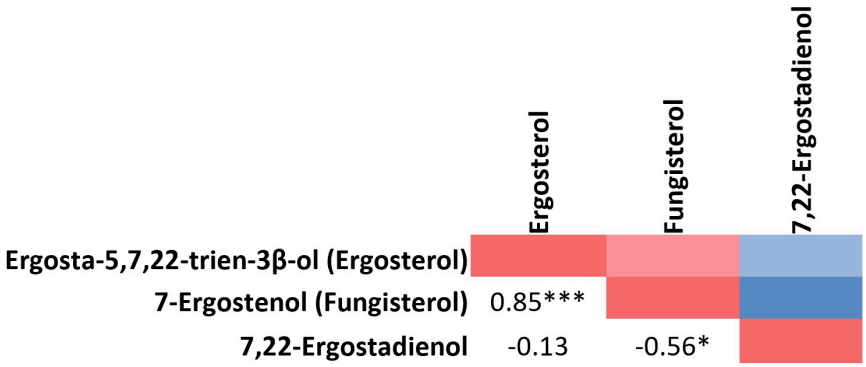


Figure 6. Pearson correlation matrix for three sterol contents in *C. cibarius* samples. * $p < 0.05$, *** $p < 0.001$. Colour intensity reflects the strength of the correlation coefficient; the darker the shade of blue, the more negative the correlation.

Characterisation of antioxidant potential

Among the extraction solutions used (Table 6), the hot water (90°C, 6 h) fraction showed the highest TPC (2.40–3.47 g GAE/100 g dw) and 2,2'-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) (1,118–1,367 µmol TE/g dw), demonstrating a strong ability to extract components with antioxidant activity. The aqueous-ethanol 50% (v/v) solution (60°C, 6 h) system provided efficient extraction of phenolic compounds from biomass, yielding 79.5–113.1 mg GAE/100 g dw, with the greatest differences observed for sample 3S. The antioxidant activity of *C. cibarius*, determined in the aqueous-ethanol extract, ranged from 44.8 to 56.7 µmol TE/g dw. The lowest values were observed in the water extraction (25°C, 6 h), with an average TPC 34% lower (51.2–72.8 mg GAE/100 g dw) and ABTS 75% lower (9.5–20.8 TE µmol TE/g dw) compared to the 50% aqueous-ethanol extraction. No significant correlation was found between TPC and ABTS in the water extraction solutions ($p > 0.05$).

Table 6. Total phenolic content (TPC) and ABTS antioxidant activity of *C. cibarius* extracts from different collection areas.

Type of extract	Site					
	1NW	2WN	3S	4EN	5NE	6NE
ABTS (µmol TE/g dw)						
50% EtOH	56.7^{a} (1.0)	44.8^{c} (2.0)	48.5^{bc} (5.3)	50.0^{abc} (3.0)	53.2^{ab} (2.6)	46.8^{bc} (2.3)
Hot H_2O	$1,284^{a}$ (47)	$1,118^{b}$ (49)	$1,367^{a}$ (48)	$1,325^{a}$ (46)	$1,287^{a}$ (58)	$1,153^{b}$ (34)
H_2O	9.5^{b} (1.0)	10.1^{b} (1.8)	20.8^{a} (1.6)	12.7^{b} (1.9)	11.2^{b} (1.8)	9.7^{b} (1.1)
TPC (mg GAE/100 g dw)						
50% EtOH	98.4^{a} (11.7)	113.1^{a} (16.5)	79.5^{a} (5.0)	95.6^{a} (9.8)	99.8^{a} (11.3)	89.8^{a} (10.2)
Hot H_2O	$3,471^{a}$ (113)	$3,097^{ab}$ (276)	$2,398^{c}$ (235)	$3,267^{ab}$ (128)	$3,357^{a}$ (178)	$2,913^{b}$ (146)
H_2O	72.8^{a} (16.6)	51.2^{a} (16.2)	61.6^{a} (13.2)	66.6^{a} (9.9)	72.6^{a} (9.1)	56.6^{a} (8.6)

Different letters within the same row indicate statistically significant differences at $p < 0.05$ (Tukey's HSD test).

Multiple factor analysis (MFA) of compositional data

MFA was used to integrate the elements, fatty-acid, sterol, and vitamin data blocks and to evaluate the overall differentiation of the chemical profiles of *C. cibarius* among sampling sites (Table S5). The first two dimensions of the MFA score plot explained 56.7% of the total variation, with Dim1 (Dimension 1) accounting for 34.1% and Dim2 (Dimension 2) for 22.6% (Figure 7, Table S6).

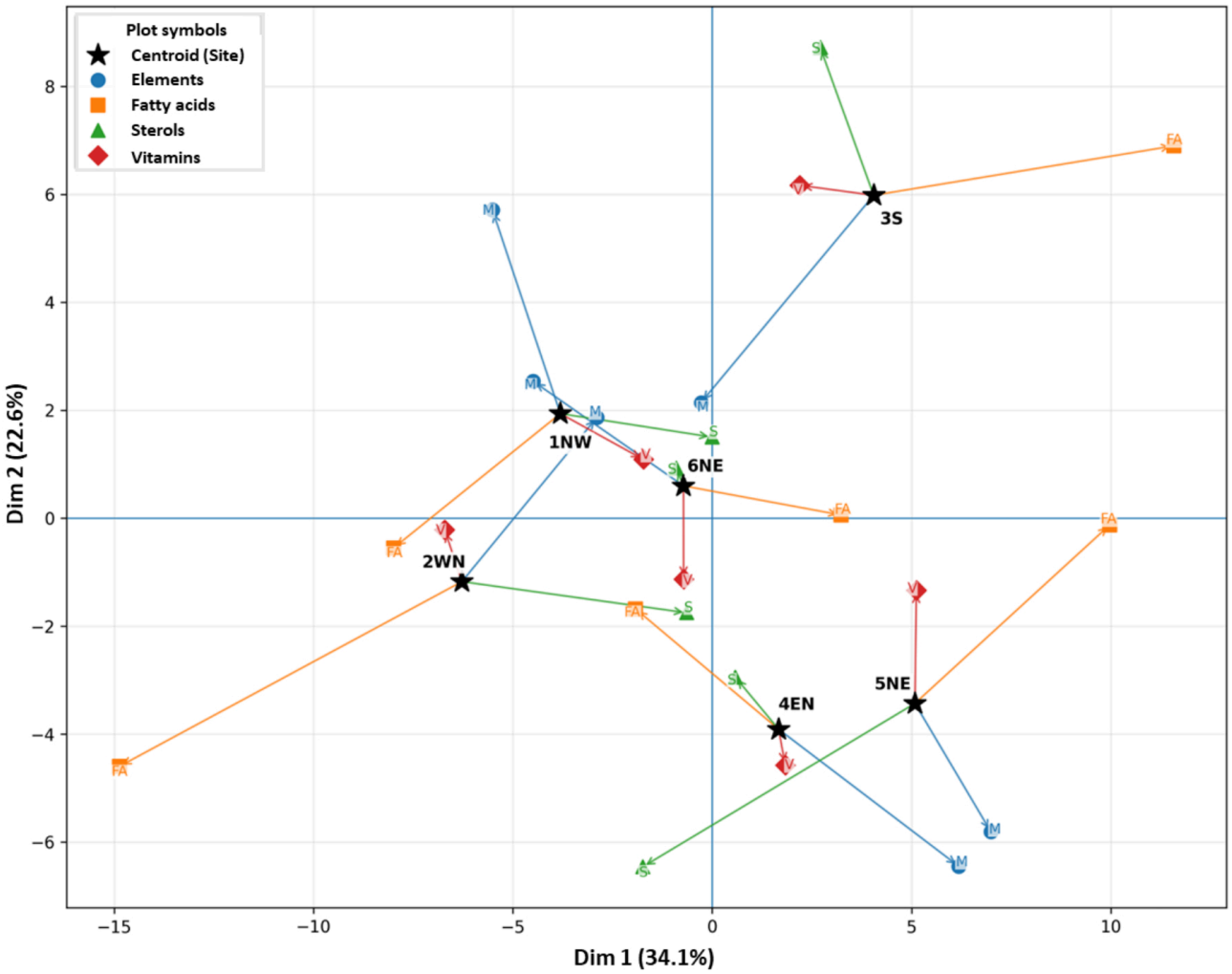


Figure 7. Individual factor map from the MFA showing the global and partial positions of the sampling sites for the elements, fatty acid, sterol, and vitamin data blocks.

The MFA partial-factor map showed the positions of the sampling sites and the corresponding partial positions of the four chemical data blocks. Site 3S was separated in the positive directions of both Dim1 and Dim2, whereas 1NW and 2WN were located on the negative side of Dim1. Sites 4EN and 5NE were distinguished mainly along the negative direction of Dim2, while the position of 6NE was comparatively close to the centre of the MFA space.

The partial positions indicated that the separation of 3S was predominantly associated with the fatty-acid and sterol blocks. The position of 2WN was also strongly influenced by its fatty-acid profile. At 4EN, the vitamin and sterol blocks contributed substantially to the observed position, whereas 5NE showed pronounced divergence among the partial positions of the four data blocks. Although 6NE was located close to the centre of the MFA score space, its partial positions indicated contrasting block-specific patterns that partially offset one another.

PERMANOVA confirmed significant differences among sampling sites for the metal (pseudo-F = 16.73, R^2 = 0.933, permutation p = 0.0002), fatty acid (pseudo-F = 21.14, R^2 = 0.946, p = 0.0001), sterol (pseudo-F

= 224.20, R^2 = 0.995, p = 0.0002), and vitamin blocks (pseudo-F = 11.38, R^2 = 0.905, p = 0.0001) (Table S7). Significant site-related differentiation was also observed in the partial-factor map space (pseudo-F = 19.06, R^2 = 0.941, p = 0.0002).

Discussion

The moisture content of *C. cibarius* in our study (88.5–91.1%) was consistent with published values for chanterelles (86–92%) [12, 51]. During the first part of September 2022, the mean relative humidity in Latvia was approximately 76%, with regional values ranging from about 67% in the north-western coastal area to 82% in the eastern part of the country. The ambient air humidity at each study site was 84%, except in Ventspils 1NW, where it was 80%. Areas with the least precipitation included Smiltene 6NE (56.7 mm), Tukums 2WN (59.0 mm), and Jelgava 3S (60.3 mm), whereas Cēsis 5NE (61.0 mm), Ventspils 1NW (64.6 mm), and Sigulda 4EN (66.4 mm) received the most. Despite this regional variation in atmospheric humidity, the moisture content of the fruiting bodies did not differ significantly among sites, suggesting it remained comparatively stable under prevailing environmental and short-term post-harvest conditions.

The protein content of *C. cibarius* was high (22.43–23.01% dw), and exceeded the value reported in the Romanian study (17.60% dw) [52], but was comparable to that reported in the Chinese study (23.24% dw) [53]. A review of available literature data on protein content across different ecological-trophic groups and soils shows that the highest values are observed in Portugal (49.61%, dw) [12], intermediate values (21.10%, dw) are reported in the Khasi Hills of India [54], and the lowest in Turkey, in the Black Sea region [55].

The observed variation in crude fat content across sites may reflect differences in growth conditions and substrate nutrient status, as carbon and nitrogen availability can influence fungal lipid biosynthesis and accumulation [27]. However, because substrate C/N ratios and related environmental variables were not measured directly, their contribution to the observed site-associated differences cannot be determined.

Although the presence of *trans*-fatty acids in mushrooms is not expected [10], the literature reports a small amount of 18:1 (Δ9t), accounting for 4.35% of the total peak area in the GC chromatogram [14]. In our study, 18:1 (Δ9t) was not detected, whereas the trans isomer 16:1 (Δ9t) was present. An important point to highlight is that the levels of 16:1 (Δ11c) in the extract exceeded those of 16:1 (Δ9c) at all tested sites, although comparisons with previous studies suggest that *C. cibarius* contains less or no 16:1 (Δ11c).

In mushrooms, α-linolenic acid (18:3 Δ9c12c15c) plays an important role in membrane lipid composition, and its abundance may be regulated by environmental and growth conditions, thereby influencing membrane homeostasis. In the closely related *Cantharellus formosus*, Blacklock et al. [17] demonstrated that fungal AcEFA biosynthesis is directly linked to conventional C18 (C-18 carbon fatty acids) lipid metabolism through the sequential conversion of oleate to linoleate, crepenynate, and subsequently dehydrocrepenynate. We observed a strong association between octadeca-9,12-dien-14-ynoic acid and linoleic and α-linolenic acids; therefore, this is consistent with a close dependence of at least part of the acetylenic fraction on the availability and turnover of the polyunsaturated C18 fatty acid pool. The particularly close covariation of dehydrocrepenynic acid and octadeca-9,12-dien-6-ynoic acid in the present samples may thus indicate coordinated regulation of downstream or parallel acetylenation reactions rather than simple proportional changes in total lipid content. Earlier studies further demonstrated enzymatically induced conversion of fatty acid precursors in damaged *C. cibarius* fruiting bodies [15], indicating that these metabolites can participate in rapidly regulated specialised lipid metabolism. The prevalence of specific AcEFA forms is difficult to explain, but a trend shows that total amounts increase in the central part of the country, an area of high economic activity, and decrease in the northern part, where recreational areas predominate due to the terrain. Taken together, the present correlations therefore support metabolic coupling between the conventional unsaturated and AcEFA pools, although they do not establish the precise precursor-product sequence for the individual AcEFAs detected here.

Rumenic acid was previously identified as the main component of the ethyl acetate extract from the boiled aqueous broth of *A. bisporus* [56]. In our data, CLA varied in parallel with AcEFA, suggesting a possible link. However, there is no evidence that acetylenic acids arise via 12-desaturation followed by isomerisation of a Δ12 double bond to the *trans*-11 configuration. Instead, 18:2 (Δ9c,12a) appears to be formed directly via the *cis*-12 desaturation pathway [17]. Although conjugated dienes could, in principle, accumulate through enzymatic linoleic acid (18:2 Δ9c,12c) transformations involved in mushroom aroma formation (e.g., 1-octen-3-ol) [57], lipid peroxidation requires free-radical initiation and lipoxygenase (LOX)-catalysed oxygen insertion into PUFA. Because no linoleic-acid hydroxylation products (ω2/ω3 alcohols) were detected in our chanterelles, a direct contribution of CLA to AcEFA formation cannot be demonstrated.

The FA composition of wild forest mushroom fruiting bodies is not only species-specific, as reflected by the UFA/SFA ratio [13], but is also statistically related to environmental factors. In our samples, the highest UFA/SFA ratio (7.09) occurred at 2WN (North Kurzeme Upland), exceeding both other sites and previously reported values (2.43 and 1.56) [13, 58], indicating substantial site-related variability that may be associated with differences in environmental and growth conditions.

Among macro elements, K co-varied with Mg, with higher values for both at 1NW (43,170 and 990 mg/kg dw) and 6NE (42,226 and 989 mg/kg dw), suggesting physiological synergy. Mean S and Mg concentrations (730 and 890 mg/kg dw) were broadly consistent across sites. Mg levels align with Polish regional data [59], while S was lower than the general European range for wild mushrooms (1,000–3,000 mg/kg dw) reported by Kalač [10]. Site 4EN showed lower P and the lowest Ca concentrations across the analysed composite samples. Because 4EN is a tourist area with uneven forest distribution shaped by topography (forests concentrated in valleys and recreation zones) and pine-dominated stands (55.5%), Ca supply via litter may be constrained. Pine-stand litter inputs average 24.4 kg Ca ha^{-1} yr^{-1} [60], implying limited replenishment where litter and decaying plant matter are reduced. This may have been aggravated by pest damage (*Ips typographus*) in 2022, affecting approximately 2,300 ha of spruce forest [61]. Across regions, Ca in *C. cibarius* ranged from 298–545 mg/kg dw, with slightly higher values in western coastal chanterelles, consistent with regional soil evidence of higher Ca in topsoil (1.5 wt% in unfertilised arable topsoil) compared with other areas [62]. The P content of *C. cibarius* fruiting bodies ranged from 3.6 g/kg to 5.4 g/kg dw, potentially reflecting site-related variation in the nutrient status of the forest-floor system. Poor litter formation and the naturally low mobility of phosphorus likely contributed to the low phosphorus levels observed in the fruiting bodies.

Al ranged from 59.81 mg/kg (4EN; western Vidzeme upland) to 90.58 mg/kg (2WN) (Figure 3b). Al uptake depends on soil element pools, availability, co-absorption, and decreasing basic cations (NH_4^+, Ca^{2+}, Mg^{2+}, K^+, Na^+), which increase acidity and competition for Al^{3+}. However, organically bound Al is generally less toxic than Al^{3+} or monomeric hydroxocomplexes. In the national forest context, 55.1% of forests occur on dry mineral soils, with *Hylocomiosa* and *Oxalidosa* types occupying 20.2% and 20.9%, respectively [63]. Soil diversity data show these forest types differ little in reactive Al in the O-horizon (586 vs. 1,020 mg/kg) and in mineral topsoil (0–10 cm; 654 vs. 1,190 mg/kg), with slightly higher reactive Al at 20–40 cm (1,564 vs. 1,309 mg/kg) [32]. Despite such high soil Al (often > 100 mg/kg, a suboptimal condition for conifers) [64], BCF for Al in *C. cibarius* are < 1.0 [7], indicating that chanterelles are Al bioexcluders.

Finally, although chanterelles are known for Mn accumulation [65], Mn levels here were within expected ranges, with the lowest at 4EN. Site 4EN was generally characterised by low levels of transition metals (Co, Cr, Ti, Mn), which were broadly similar to those at 5NE. Both sites are in tourism-sector areas with minimal impact from undesirable conditions. The low transition-metal content of chanterelles in these regions contrasts with the higher content in the 6NE samples, despite all being located over the same *Glacigenic* deposits [32].

Cd levels were low at all sites (< 0.30 mg/kg dw) but variable: higher near the port/tourist-influenced areas (1NW, 4EN) and lower at 2WN and 5NE (< 0.13 mg/kg dw), consistent with transfer primarily from the mineral soil fraction and no clear signal of a local pollution source (Figure 3c). This contrasts with

higher Cd reported in Lithuania (up to 1.0 mg/kg dw) in *C. cibarius* collected about 15 km from an emission source [66]. The relatively low Cd concentrations in the fruiting bodies did not indicate pronounced Cd accumulation in the analysed mushroom samples. Strong positive correlations between Cd and Cu (r = 0.768) and between Cu and Zn (r = 0.773, df = 16, $p < 0.01$) indicate shared accumulation patterns. Co did not exceed critical concentrations and was absent at 4EN and 6NE. Although this element accumulates primarily in the fruiting bodies of macromycetes, its presence cannot be attributed to pollution, as highlighted by Borovička and Řanda [67].

Ni and Cu concentrations in *C. cibarius* were lower than those of Fe and Zn, but Ni was comparatively higher at 1NW (1.40 mg/kg dw) and 3S (0.90 mg/kg dw), while remaining below the values reported for Lithuania (1.84 mg/kg dw near Vilnius and Varėna) [68]. The elevated Ni content at the 1NW site may reflect the combined influence of greater diffuse anthropogenic pressure associated with port bulk cargo transport, industrial activities, and urban heavy-goods traffic. However, Ni concentrations in *Pleurozium schreberi* mosses used to assess atmospheric heavy metal deposition tend to decrease, with values in the Ventspils area (1NW) of 0.55–0.72 mg/kg, in contrast to 1.94 mg/kg recorded in Europe [69]. Ni concentrations at 1NW and 3S cannot be attributed to a single pollution source and most likely reflect an interaction between local soil geochemistry and diffuse anthropogenic inputs.

At the 3S site, the Jelgava region is characterised by intensive agriculture, manufacturing, logistics and metalworking, which can contribute to the accumulation of diffuse metal dust in suburban soils. This is evidenced by a snow monitoring study that found Ni in urban atmospheric deposition and non-uniform heavy metal pollution [70]. The study indicates a combined effect of stationary industrial sources and transport but usually does not allow attribution of heavy metal concentrations to a specific source.

Notably, Cu, as well as Fe, Zn and Ni, showed similar levels and distributions at 2WN and 5NE despite their geographical separation. Fe and Zn were positively correlated across sites, especially at 1NW, 4EN and 6NE, indicating a strong capacity of chanterelles to concentrate exchangeable and acid-soluble Zn. Studies of the chemical composition of Latvian forest soils [32] indicate that statistically significant ($p < 0.05$) differences in reactive Fe concentration were found only in the mineral soil layers (0–80 cm) between Oxalidosa and Vacciniosa, Myrtillosa, Hylocomiosa, and Myrtillosa mel. Although Oxalidosa forests, only 2WN of the studied areas, are characterised by relatively high concentrations of reactive Fe in mineral soil horizons, *C. cibarius* Fe concentrations in 2WN were only moderate. This indicates that Fe differences in the soil mineral sublayer are relatively small across forest types and are driven mainly by the origin of geological deposits rather than by the dominant tree species. Studies confirm [32] that the reactive Fe concentration in sediments of different genesis differs statistically significantly between glaciolimnic, glaciofluvial, and glacigenic sediments on the one hand and eolian and Baltic Ice Lake sediments on the other, where the reactive Fe concentration is lower. The origin of the samples at the 4EN and 6NE sites may change the relationship between regional reactive Fe abundance and concentrations in fruiting bodies, but the 1NW site is located on Baltic Ice Lake sediments that are poor in reactive Fe. These contrasting patterns indicate that the Fe content of *C. cibarius* can be linked to port activity and related diffuse anthropogenic inputs, as reflected in increased Fe content in *P. schrebery* mosses collected in the peri-urban forests of Ventspils [69].

The concentrations of As, B, Be, Sb, Se, Li, Mo, Ti, V, and Pb remained below the respective detection limits. Low concentrations of several of these elements are consistent with previous observations for *C. cibarius*. In chanterelles from European background areas, As and V have been reported at sub mg/kg dw levels, and the occurrence of As, Li, V, and Pb in fruiting bodies has been associated with the geochemical background of the underlying substrate [71]. Ectomycorrhizal fungi do not accumulate all elements in proportion to their concentrations in soil, and *C. cibarius* has been reported to show comparatively low bioconcentration of several non-essential and potentially toxic elements, including Pb [7], while Be and Mo have been reported below detection limits [72]. These findings suggest that their non-detection in the present material should not be interpreted as a general characteristic of the species.

The factors underlying the comparatively high ascorbic acid concentration at 3S cannot be determined from the present data, but it can be assumed to reflect metabolic activation, potentially influenced by protein availability. This interpretation is partly supported by cultivation experiments showing increased vitamin content in *Agaricus blazei* when corn flour was added to the substrate [73]. Although the literature does not explain the drivers of ascorbic acid variability in ectomycorrhizal mushrooms, light and temperature may contribute, as shown for *Pleurotus ostreatus*, where light stimulation at low temperature (10 ± 2°C) triggered a marked increase in L-ascorbic acid and erythroascorbic acid glycosides in vegetative mycelia [74]. In our study, however, regional temperature differences were modest (13%) and unlikely to account for the observed variation. Elevated Mg salts in the substrate have also been reported to increase ascorbic acid in *Pleurotus djamor* [75], but we found no direct macronutrient–vitamin relationship in chanterelles.

Along with other elements, Fe showed a negative, but not statistically significant, association with ascorbic acid (r = −0.79, p = 0.06). Although Fe-ascorbate redox cycling may occur at specific cellular sites, correlations between total Fe and ascorbic acid can remain non-significant because bulk elemental measurements do not capture the bioavailable, redox-active Fe pool (free/complexed Fe^{2+}/Fe^{3+}). In *Basidiomycotina* fruit bodies, ascorbic acid has been reported to occur at low free levels and predominantly as conjugated derivatives (e.g., glycosides). For example, in *P. ostreatus*, this reaches 73.76 mg/kg wet weight [76]. Because the reducing capacity of ascorbic acid depends on its enediol system, glycosylation, particularly at the C-2 position, significantly reduces its ability to directly reduce metal ions [77]. Therefore, if a substantial fraction of chanterelle vitamin C is present as ascorbate glycosides with reduced redox activity, the bulk ascorbic acid measured here may not represent the locally reactive ascorbate fraction.

Free ergosterol levels in our study were comparable to literature values for total ergosterol (261–348 mg/100 g dw) [23, 25]. However, chanterelles have been reported to contain relatively low free ergosterol (23.0 mg/100 g dw) [24]. Higher free ergosterol levels in our study likely reflect a larger membrane sterol pool in the fruiting bodies. This is probably related to nychthemeral air temperature. From September 3 to September 13, minimum air temperatures reached record lows on eight days.

Although fungisterol accounted for less than 3% (approx. 1.9–4.0% across sites) of the total sterol content, its variation, together with that of 7,22-ergostadienol, suggests coordinated changes within the sterol profile. Free ergosterol and related intermediates are metabolically linked through the shared ergosterol biosynthetic pathway, and shifts in individual sterol pools may occur in parallel. Fungisterol and 7,22-ergostadienol are intermediates of this pathway, and fungal culture studies have shown that changes in enzymes involved in ergosterol biosynthesis can alter the accumulation of 7,22-ergostadienol and related sterols [78]. Thus, the observed site-associated variation in these compounds may reflect differences in sterol-pool regulation, although the underlying enzymatic mechanisms were not examined in the present study.

Antioxidant activity in mushrooms is attributable to phytochemicals (e.g., carotenoids, ascorbic acid, flavonoids, betaines). Some studies have also demonstrated that phenolic acids contribute to antioxidant potential in various mushrooms [79, 80]. Fogarasi and coauthors [80] reported that the ABTS antioxidant activity of *C. cibarius* in the aqueous ethanol extract reached 1.00 TE μM/g dw, which was lower than ours. This may be because we used a higher extraction temperature (60°C). The aqueous-ethanol extract values were comparable to those reported by Fogarasi and coauthors [80] (66.0 mg GAE/100 g dw). Barros and coauthors [81] reported an association between fruit-body maturity stage and antioxidant activity. In general, the antioxidant activity was higher in the hot-water extract (90°C, 6 h) than in the 50% ethanolic and aqueous extracts.

The integrated MFA indicated that the geographical differentiation of *C. cibarius* samples was not attributable to a single compositional block. Instead, the relative importance of metals, fatty acids, sterols, and vitamins varied across sampling sites. Site 3S occupied the positive region of both dimensions, with separation particularly associated with the fatty-acid block along positive Dim1 and with the sterol block along positive Dim2. Site 2WN was strongly separated along negative Dim1, predominantly owing to its

fatty acid profile. Site 4EN was characterised mainly by negative Dim2, with the metal block showing the largest displacement from the global site position, whereas the fatty acid block acted in an opposing direction. Site 5NE occupied the positive Dim1/negative Dim2 quadrant and showed pronounced divergence among the compositional blocks, particularly between fatty acids and sterols. These contrasting block-specific patterns indicate that the components of the chemical profile did not vary uniformly among sites. Previous studies of *C. cibarius* have linked spatial variation in elemental composition to local soil geochemistry and element bioavailability, while variation in fatty acid composition in forest mushrooms has likewise been associated with environmental and growing conditions [7, 27].

The position of 6NE close to the MFA origin should not necessarily be interpreted as indicating an absence of site-specific characteristics. Its partial-factor pattern indicates that opposing contributions from the metal and fatty-acid blocks partly compensated for one another in the integrated space, while the sterol and vitamin profiles closely approximated the centroid. Thus, a position near the origin may represent a balance among contrasting compositional signals rather than uniformly average concentrations across all measured variables.

Overall, the MFA supports the presence of site-associated differences in the integrated chemical composition of the mushrooms. However, because the analysis did not directly incorporate environmental variables such as soil chemistry, moisture regime, vegetation, or geological substrate, the observed separation cannot be assigned to any individual environmental driver. Previous studies have nevertheless demonstrated spatial variation in the elemental composition of *C. cibarius* associated with local soil geochemistry and element bioavailability, while environmental factors have also been shown to contribute to variation in the fatty acid composition of forest mushrooms [7, 27]. The present MFA results should therefore be interpreted as evidence of site-related chemical patterning and as a basis for generating hypotheses concerning the environmental factors underlying this variation

In conclusion, *C. cibarius* exhibited clear site-associated variation in its chemical composition, although moisture and protein contents remained relatively stable. The most pronounced differences were observed in crude fat content, fatty acid profiles, AcEFA, sterols, vitamins, antioxidant-related parameters, and several elements. Unsaturated fatty acids predominated across all samples, while the central-southern site (3S) was distinguished by comparatively high levels of acetylenic and PUFA, as well as ergosterol and fungisterol. MFA confirmed that the observed geographical differentiation reflected coordinated variation across the metal, fatty acid, sterol, and vitamin data blocks, with individual sites characterised by distinct combinations of these chemical components.

These chemical patterns were considered alongside the documented characteristics of the reported collection areas, including geological and soil background, dominant forest vegetation, regional meteorological conditions, and potential anthropogenic pressures. The observed site-associated differences are consistent with the environmental heterogeneity among the collection areas. However, the available data do not allow quantification of the contributions of individual environmental factors.

Because the mushrooms were obtained from vendors and environmental variables were not measured directly at the collection sites, causal relationships between mushroom composition and specific soil, climatic, vegetation-related, or anthropogenic factors cannot be established. The environmental descriptors therefore provide contextual support for interpreting the observed chemical patterns. In addition, the pooling of fruiting bodies at mixed stages of maturity and the lack of standardised information on post-harvest storage conditions represent potential sources of uncontrolled variability in the measured chemical composition.

Abbreviations

ABTS: 2,2’-azinobis(3-ethylbenzothiazoline-6-sulfonic acid)

AcEFA: acetylenic fatty acids

AZA: azelaic acid

BCF: bioconcentration factor

CLA: conjugated linoleic acid

DMSO: dimethyl sulfoxide

dw: dry weight

FA: fatty acids

FAMEs: fatty acid methyl esters

GAE: gallic acid equivalents

GC-MS: gas chromatography-mass spectrometry

LOX: lipoxygenase

MRM: multiple reaction monitoring

MUFA: monounsaturated fatty acids

PUFA: polyunsaturated fatty acids

SFA: saturated fatty acids

TE: Trolox equivalents

TPC: total phenolic content

UFA: unsaturated fatty acids

UPLC: ultra-performance liquid chromatography

Supplementary materials

The supplementary materials for this article are available at: https://www.explorationpub.com/uploads/Article/file/1010208_sup_1.pdf.

Declarations

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Author contributions

JK: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing—original draft, Writing—review & editing. LA: Formal analysis, Data curation, Visualization, Writing—review & editing. RK: Investigation, Data curation, Writing—review & editing. MR: Investigation, Data curation, Project administration, Writing—review & editing. LD: Investigation, Resources, Data curation, Writing—review & editing. DM: Methodology, Validation, Writing—review & editing. JL: Investigation, Supervision, Resources, Data curation, Writing—review & editing. MM: Investigation, Validation, Data curation, Writing—review & editing. All authors read and approved the submitted version.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Availability of data and materials

The original contributions presented in the study are included in the article, and further inquiries can be directed to the corresponding author.

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References

1. Moore LM, Jansen AE, Van Griensven LJLD. Pure culture synthesis of ectomycorrhizas with *Cantharellus cibarius*. Acta Bot Neerl. 1989;38:273–8. [DOI]
2. Rangel-Castro JI, Danell E, Pfeffer PE. A ^{13}C-NMR study of exudation and storage of carbohydrates and amino acids in the ectomycorrhizal edible mushroom *Cantharellus cibarius*. Mycologia. 2002;94:190–9. [DOI]
3. Luginbuehl LH, Menard GN, Kurup S, Van Erp H, Radhakrishnan GV, Breakspear A, et al. Fatty acids in arbuscular mycorrhizal fungi are synthesized by the host plant. Science. 2017;356:1175–8. [DOI] [PubMed]
4. Demirbaş A. Heavy metal bioaccumulation by mushrooms from artificially fortified soils. Food Chem. 2001;74:293–301. [DOI]
5. Chen XH, Zhou HB, Qiu GZ. Analysis of Several Heavy Metals in Wild Edible Mushrooms from Regions of China. Bull Environ Contam Toxicol. 2009;83:280–5. [DOI] [PubMed]
6. Falandysz J, Drewnowska M. Macro and trace elements in Common Chanterelle (Cantharellus cibarius) mushroom from the European background areas in Poland: Composition, accumulation, dietary exposure and data review for species. J Environ Sci Health B. 2015;50:374–87. [DOI] [PubMed]
7. Drewnowska M, Falandysz J. Investigation on mineral composition and accumulation by popular edible mushroom common chanterelle (Cantharellus cibarius). Ecotoxicol Environ Saf. 2015;113:9–17. [DOI] [PubMed]
8. Kasparinskis R, Nikodemus O. Influence of environmental factors on the spatial distribution and diversity of forest soil in Latvia. Est J Earth Sci. 2012;61:48–64. [DOI]
9. Rella A, Farnoud AM, Del Poeta M. Plasma membrane lipids and their role in fungal virulence. Prog Lipid Res. 2016;61:63–72. [DOI] [PubMed] [PMC]
10. Kalač P. Chemical composition and nutritional value of European species of wild growing mushrooms: A review. Food Chem. 2009;113:9–16. [DOI]
11. Kalač P. A review of chemical composition and nutritional value of wild-growing and cultivated mushrooms. J Sci Food Agric. 2013;93:209–18. [DOI] [PubMed]
12. Barros L, Venturini BA, Baptista P, Estevinho LM, Ferreira IC. Chemical Composition and Biological Properties of Portuguese Wild Mushrooms: A Comprehensive Study. J Agric Food Chem. 2008;56:3856–62. [DOI] [PubMed]

13. Kavishree S, Hemavathy J, Lokesh B, Shashirekha M, Rajarathnam S. Fat and fatty acids of Indian edible mushrooms. Food Chem. 2008;106:597–602. [DOI]
14. Yilmaz N, Türkekul İ, Bulut S, Sahin F, Bayrak ÖF. Fatty acid composition in ten mushroom species collected from Middle Black Sea region of Turkey. Asian J Chem. 2013;25:1216–20. [DOI]
15. Pang Z, Sterner O. Cibaric acid, a new fatty acid derivative formed enzymatically in damaged fruit bodies of Cantharellus cibarius (Chanterelle). J Org Chem. 1991;56:1233–5. [DOI]
16. Daniewski WM, Danikiewicz W, Gołębiewski WM, Gucma M, Łysik A, Grodner J, et al. Search for Bioactive Compounds from *Cantharellus cibarius*. Nat Prod Commun. 2012;7:917–8. [DOI]
17. Blacklock BJ, Scheffler BE, Shepard MR, Jayasuriya N, Minto RE. Functional Diversity in Fungal Fatty Acid Synthesis. The first acetylenase from the Pacific golden chanterelle, Cantharellus formosus. J Biol Chem. 2010;285:28442–9. [DOI] [PubMed] [PMC]
18. Dembitsky VM. Anticancer activity of natural and synthetic acetylenic lipids. Lipids. 2006;41:883–924. [DOI] [PubMed]
19. Mittermeier VK, Dunkel A, Hofmann T. Discovery of taste modulating octadecadien-12-ynoic acids in golden chanterelles (Cantharellus cibarius). Food Chem. 2018;269:53–62. [DOI] [PubMed]
20. Hiroi M. Dehydrocrepenynic acid in Cantharellales and chemotaxonomy. Collect Keynote Speeches Jpn Soc Bact Congr. 2011;55:6. Japanese.
21. Mattila P, Lampi A, Ronkainen R, Toivo J, Piironen V. Sterol and vitamin D2 contents in some wild and cultivated mushrooms. Food Chem. 2002;76:293–8. [DOI]
22. Phillips KM, Ruggio DM, Horst RL, Minor B, Simon RR, Feeney MJ, et al. Vitamin D and Sterol Composition of 10 Types of Mushrooms from Retail Suppliers in the United States. J Agric Food Chem. 2011;59:7841–53. [DOI] [PubMed]
23. Teichmann A, Dutta PC, Staffas A, Jägerstad M. Sterol and vitamin D2 concentrations in cultivated and wild grown mushrooms: Effects of UV irradiation. LWT - Food Sci Technol. 2007;40:815–22. [DOI]
24. Villares A, Mateo-Vivaracho L, García-Lafuente A, Guillamón E. Storage temperature and UV-irradiation influence on the ergosterol content in edible mushrooms. Food Chem. 2014;147:252–6. [DOI] [PubMed]
25. Gil-Ramírez A, Clavijo C, Palanisamy M, Soler-Rivas C, Ruiz-Rodriguez A, Marín FR, et al. Edible mushroom as potential sources of new hypocholesterolemic compounds. In: Proceedings of the 7th international conference on mushroom biology and mushroom products. 2011. pp. 110–9.
26. Koyama N, Aoyagi Y, Sugahara T. Fatty acid compositions and ergosterol contents of edible mushrooms. J Jpn Soc Food Sci. 1984;31:732–8. [DOI]
27. Stojek K, Bobrowska-Korczak B, Kusińska B, Czerwonka M, Decruyenaere J, Decock L, et al. Factors affecting composition of fatty acids in wild-growing forest mushrooms. Mycologia. 2024;116:381–91. [DOI] [PubMed]
28. Dāniele I, Meiere D. The great mushrooms book of Latvia. Riga, Jāņa sēta; 2020.
29. Læssøe T, Petersen JH. Fungi of temperate Europe. Princeton University Press; 2019.
30. National and regional development centres [Internet]. Riga: Ministry of Smart Administration and Regional Development; c2020 [cited 2026 Aug 9]. Available from: https://www.varam.gov.lv/lv/nacionalas-un-regionalas-nozimes-attistibas-centri
31. Number of employed and jobs in local kind of activity units, their value added and value of output in regions, municipalities, cities, towns, rural territories (based on the boundaries in force at the beginning of 2024), neighbourhoods and densely populated areas by economic activity (NACE) (experimental statistics) 2017 - 2023 [Internet]. Official Statistics Portal of Latvia; [cited 2026 Aug 9]. Available from: https://data.stat.gov.lv/pxweb/en/OSP_PUB/START__ENT__UT__UTV/NPV021/
32. Kasparinskis R. Diversity of forest soils and its influencing factors in Latvia [dissertation]. Riga: Latvijas Universitāte; 2012.

33. Inventoried forest area and standing timber by main tree species in regions, cities, towns, municipalities and rural territories by Territorial unit, Tree species, Indicator and Time period [Internet]. Official Statistics Portal of Latvia; [cited 2026 Aug 9]. Available from: https://data.stat.gov.lv/pxweb/en/OSP_PUB/START/MEP061S/
34. AOAC. Protein (Crude) in animal feed and pet food, Cooper Catalyst Kjeldal Method 984.13. In: Official methods of analysis (16th ed.). Arlington VA, USA: Association of Official Analytical Chemists; 1996.
35. Danell E, Eaker D. Amino acid and total protein content of the edible mushroom *Cantharellus cibarius* (Fries). J Sci Food Agric. 1992;60:333–7. [DOI]
36. Somasheker D, Venkateshwaran G, Srividya C, Krishnanand, Sambaiah K, Lokesh BR. Efficacy of extraction methods for lipid and fatty acid composition from fungal cultures. World J Microb Biot. 2001;17:317–20. [DOI]
37. Water quality - Determination of selected elements by inductively coupled plasma optical emission spectrometry (ICP-OES) (ISO 11885:2007) [Internet]. [cited 2026 Jul 8]. Available from: https://www.iso.org/standard/36250.html
38. Borska E, Kviesis J, Ramata-Stunda A, Nikolajeva V, Ansone-Bertina L, Boroduskis M, et al. Bioactive lipids and allelopathic potential of the invasive plant Heracleum sosnowskyi: insights into its fatty acid composition, antimicrobial and cytotoxic effects. Front Pharmacol. 2025;16:1582694. [DOI] [PubMed] [PMC]
39. Alves SP, Bessa RJ. Comparison of two gas–liquid chromatograph columns for the analysis of fatty acids in ruminant meat. J Chromatogr A. 2009;1216:5130–9. [DOI] [PubMed]
40. Rodríguez-Alcalá LM, Calvo MV, Fontecha J. A Quick, Optimized Method for Routine Analysis of Essential and Trans-Octadecenoic Acids in Edible Fats and Oils by GLC. J Chromatogr Sci. 2012;51:70–81. [DOI] [PubMed]
41. Huang S, Lin C, Tsai S. Vitamin D2 content and antioxidant properties of fruit body and mycelia of edible mushrooms by UV-B irradiation. J Food Compos Anal. 2015;42:38–45. [DOI]
42. Esteve MJ, Farré R, Frígola A, García-Cantabella JM. Simultaneous Determination of Thiamin and Riboflavin in Mushrooms by Liquid Chromatography. J Agric Food Chem. 2001;49:1450–4. [DOI] [PubMed]
43. Juraja SM, Trenerry V, Millar RG, Scheelings P, Buick DR. Asia Pacific food analysis network (APFAN) training exercise: the determination of niacin in cereals by alkaline extraction and high performance liquid chromatography. J Food Compos Anal. 2003;16:93–106. [DOI]
44. Bernaś E, Jaworska G. Vitamins profile as an indicator of the quality of frozen Agaricus bisporus mushrooms. J Food Compos Anal. 2016;49:1–8. [DOI]
45. Riches E. The rapid, simultaneous analysis of 12 water-soluble vitamin compounds [Internet]. Waters Corporation, Manchester, UK; c2019 [cited 2025 Aug 10]. Available from: https://www.waters.com/nextgen/lv/en/library/application-notes/2009/rapid-simultaneous-analysis-water-soluble-vitamin-compounds.html
46. Muceniece R, Revina BL, Kviesis J, Jansons A, Kopiks K, Jekabsons K, et al. Nettle Leaf Water Extracts for Hepatoprotection: Insights into Bioactivity and Mitochondrial Function. Plants (Basel). 2025;14:992. [DOI] [PubMed] [PMC]
47. Klavins L, Perkons I, Mezulis M, Viksna A, Klavins M. Procyanidins from Cranberry Press Residues—Extraction Optimization, Purification and Characterization. Plants. 2022;11:3517. [DOI] [PubMed] [PMC]
48. Ribeiro B, de Pinho PG, Andrade PB, Baptista P, Valentão P. Fatty acid composition of wild edible mushrooms species: A comparative study. Microchem J. 2009;93:29–35. [DOI]
49. Haritos VS, Horne I, Damcevski K, Glover K, Gibb N, Okada S, et al. The convergent evolution of defensive polyacetylenic fatty acid biosynthesis genes in soldier beetles. Nat Commun. 2012;3:1150. [DOI] [PubMed]

50. Okada S, Zhou XR, Damcevski K, Gibb N, Wood C, Hamberg M, et al. Diversity of Δ12 Fatty Acid Desaturases in Santalaceae and Their Role in Production of Seed Oil Acetylenic Fatty Acids. J Biol Chem. 2013;288:32405–13. [DOI] [PubMed] [PMC]
51. Beluhan S, Ranogajec A. Chemical composition and non-volatile components of Croatian wild edible mushrooms. Food Chem. 2011;124:1076–82. [DOI]
52. Zavastin DE, Biliută G, Dodi G, Macsim A, Lisa G, Gherman SP, et al. Metal content and crude polysaccharide characterization of selected mushrooms growing in Romania. J Food Compos Anal. 2018;67:149–58. [DOI]
53. Li X, Guo Y, Zhuang Y, Qin Y, Sun L. Nonvolatile taste components, nutritional values, bioactive compounds and antioxidant activities of three wild *Chanterelle* mushrooms. Int J Food Sci Technol. 2018;53:1855–64. [DOI]
54. Agrahar-Murugkar D, Subbulakshmi G. Nutritional value of edible wild mushrooms collected from the Khasi hills of Meghalaya. Food Chem. 2005;89:599–603. [DOI]
55. Çağlarlrmak N, Ünal K, Ötles S. Nutritional value of edible wild mushrooms collected from the Black Sea region of Turkey. Micol Apl Int. 2002;14:1–5.
56. Chen S, Oh SR, Phung S, Hur G, Ye JJ, Kwok SL, et al. Anti-Aromatase Activity of Phytochemicals in White Button Mushrooms (*Agaricus bisporus*). Cancer Res. 2006;66:12026–34. [DOI] [PubMed]
57. Revol-Cavalier J, Quaranta A, Newman JW, Brash AR, Hamberg M, Wheelock CE. The Octadecanoids: Synthesis and Bioactivity of 18-Carbon Oxygenated Fatty Acids in Mammals, Bacteria, and Fungi. Chem Rev. 2025;125:1–90. [DOI] [PubMed] [PMC]
58. Bengu AS. The fatty acid composition in some economic and wild edible mushrooms in Turkey. Prog Nutr. 2020;22:185–92. [DOI]
59. Brzezicha-Cirocka J, Grembecka M, Grochowska I, Falandysz J, Szefer P. Elemental composition of selected species of mushrooms based on a chemometric evaluation. Ecotoxicol Environ Saf. 2019;173:353–65. [DOI] [PubMed]
60. Bārdule A, Lazdiņš A, Bārdulis A, Lazdiņa D, Stola J. Fractions and Chemical Content of Forest Litterfall in Scots Pine (Pinus sylvestris L.) Stand in Level II Forest Monitoring Plot. Proc Latv Univ Agric. 2012;27:16–21. [DOI]
61. Eight-toothed spruce bark beetle emergency in Latvia [Internet]. Latvian Public Media LSM; c2023 [cited 2025 Aug 10]. Available from: https://eng.lsm.lv/article/society/environment/eight-toothed-spruce-bark-beetle-emergency-in-latvia.a495556/
62. Reimann C, Siewers U, Tarvainen T, Bityukova L, Eriksson J, Gilucis A, et al. Baltic soil survey: total concentrations of major and selected trace elements in arable soils from 10 countries around the Baltic Sea. Sci Total Environ. 2000;257:155–70. [DOI] [PubMed]
63. Zālītis P. Latvijas meža tipoloģija un tās sākotne (Latvian forest typology and its origins). Daugavpils Universitātes Akadēmiskais apgāds, Saule; 2013.
64. Zołotajkin M, Ciba J, Kluczka J, Skwira M, Smoliński A. Exchangeable and Bioavailable Aluminium in the Mountain Forest Soil of Barania Góra Range (Silesian Beskids, Poland). Water Air Soil Pollut. 2011;216:571–80. [DOI] [PubMed] [PMC]
65. Sesli E, Tuzen M, Soylak M. Evaluation of trace metal contents of some wild edible mushrooms from Black sea region, Turkey. J Hazard Mater. 2008;160:462–7. [DOI] [PubMed]
66. Stankevičieně D. Heavy metals in agaricoid fungi from a deciduous forest under direct human impact. In: Callery P, editor. Metal ions in biology and medicine: proceedings of the 8th International Symposium on Metal Ions in Biology and Medicine. 2004. pp. 182–5.
67. Borovička J, Řanda Z. Distribution of iron, cobalt, zinc and selenium in macrofungi. Mycol Prog. 2007;6:249–59. [DOI]
68. Valiulis D, Stankevičiene D, Kvietkus K. Metal accumulation in some fungi species growing in Lithuania. Atmos Phys. 1995;17:47–51.

69. Tabors G, Nikodemus O, Dobkeviča L, Kļaviņa L, Ajanoviča A, Viligurs K, et al. Assessment of atmospheric pollution with heavy metals and nitrogen using Pleurozium schreberi mosses as bioindicator in Latvia: spatial and temporal aspects. Environ Exp Biol. 2017;15:143–50. [DOI]
70. Grinfelde I, Siltumens K, Grybauskiene V, Bertins M, Pilecka-Ulcugaceva J. Influence of industry on air pollution in Jelgava city. In: Osadcuks V, Aboltins A, Palabinskis J, editors. Proceedings of the 23rd International Scientific Conference Engineering for Rural Development; 2024 May 22-24; Jelgava, Latvia. Latvia University of Life Sciences and Technologies; 2024. pp. 914–20. [DOI]
71. Falandysz J, Chudzińska M, Barałkiewicz D, Drewnowska M, Hanć A. Toxic elements and bio-metals in Cantharellus mushrooms from Poland and China. Environ Sci Pollut Res. 2017;24:11472–82. [DOI] [PubMed] [PMC]
72. Mleczek M, Budka A, Kalač P, Siwulski M, Niedzielski P. Family and species as determinants modulating mineral composition of selected wild-growing mushroom species. Environ Sci Pollut Res Int. 2021;28:389–404. [DOI] [PubMed] [PMC]
73. Rózsa S, Măniuțiu DN, Poșta G, Gocan TM, Andreica I, Bogdan I, et al. Influence of the Culture Substrate on the Agaricus blazei Murrill Mushrooms Vitamins Content. Plants. 2019;8:316. [DOI] [PubMed] [PMC]
74. Lee SR, Joo WJ, Baek YU, Lee YK, Yu SW, Kim YR, et al. Intracellular substrates of a heme-containing ascorbate oxidase in Pleurotus ostreatus. J Microbiol. 2009;47:178–86. [DOI] [PubMed]
75. Zięba P, Sękara A, Bernaś E, Krakowska A, Sułkowska-Ziaja K, Kunicki E, et al. Supplementation with Magnesium Salts—A Strategy to Increase Nutraceutical Value of Pleurotus djamor Fruiting Bodies. Molecules. 2021;26:3273. [DOI] [PubMed] [PMC]
76. Okamura M. Separative Determination of Ascorbic Acid Analogs Contained in Mushrooms by High-Performance Liquid Chromatography. J Nutr Sci Vitaminol. 1998;44:25–35. [DOI] [PubMed]
77. Maeda J, Allum AJ, Mussallem JT, Froning CE, Haskins AH, Buckner MA, et al. Ascorbic Acid 2-Glucoside Pretreatment Protects Cells from Ionizing Radiation, UVC, and Short Wavelength of UVB. Genes (Basel). 2020;11:238. [DOI] [PubMed] [PMC]
78. Sayari M, van der Nest MA, Steenkamp ET, Rahimlou S, Hammerbacher A, Wingfield BD. Characterization of the Ergosterol Biosynthesis Pathway in Ceratocystidaceae. J Fungi (Basel). 2021;7:237. [DOI] [PubMed] [PMC]
79. Muszyńska B, Sułkowska-Ziaja K, Ekiert H. Phenolic acids in selected edible basidiomycota species: Armillaria mellea, Boletus badius, Boletus edulis, Cantharellus cibarius, Lactarius deliciosus and Pleurotus ostreatus. Acta Sci Pol Hortorum Cultus. 2013;12:107–16.
80. Fogarasi M, Socaciu MI, Sălăgean CD, Ranga F, Fărcaș AC, Socaci SA, et al. Comparison of Different Extraction Solvents for Characterization of Antioxidant Potential and Polyphenolic Composition in Boletus edulis and Cantharellus cibarius Mushrooms from Romania. Molecules. 2021;26:7508. [DOI] [PubMed] [PMC]
81. Barros L, Baptista P, Ferreira IC. Effect of Lactarius piperatus fruiting body maturity stage on antioxidant activity measured by several biochemical assays. Food Chem Toxicol. 2007;45:1731–7. [DOI] [PubMed]