Journal of Radioanalytical and Nuclear Chemistry (2022) 331:3107–3115
https://doi.org/10.1007/s10967-022-08353-7

Soil-to-plant transfer factor for stable elements in lemon balm (*Melissa officinalis L.*) and estimates of the daily intakes

Fábio Vitório Sussa[1] · **Marcos Roberto Furlan**[2] · **Marcos Victorino**[3] · **Paulo Sergio Cardoso da Silva**[1]

Received: 3 March 2022 / Accepted: 28 April 2022 / Published online: 3 June 2022

Abstract

This study evaluated the transfer factor (TF) of stable elements from soil to *Melissa officinalis* and the estimated daily intakes for potentially toxic elements. INAA, GFAAS, and ICP-OES techniques were applied to determine the elemental concentration. Br, Ca, Cd, K, Ni, and Rb accumulated the most with the TF (>1.0), followed by Ba, Co, Cr, Cu, Mg, Mn, Na, Pb, Sb, and Zn (0.1–1.0), while As, Fe, Hf, La, Sc, Sm, Th, Ti, and V had the lowest accumulation (<0.1). The daily intake ($\mu g\ day^{-1}$) of As (1.35–10.35), Br (22.5–297), Cd (0.09–0.54), Cr (220–1,270), Cu (31.5–76.5), Ni (0.09–0.54), Pb (4.5–31.5), and Zn (139.5–400.5) even overestimated was still lower than values established by WHO/FAO.

Keywords *Melissa officinalis* L. · Lemon balm · Agriculture management · Transfer factor · Daily intake

Introduction

Lemon balm (*Melissa officinalis* L.) originates from Europe and is now grown all over the world. It is a medicinal and aromatic species popularly used to make tea, which serves as an antioxidant, antiviral, tranquilizer, promotes sleep, reduces stress, and anxiety [1, 2]. Furthermore, lemon balm is used to treat Graves', Alzheimer's, and thyroid diseases [3]. Although many of these medicinal plants appear to be safe, the possible toxicity of these products and toxicity itself depends on the level of product contamination [4]. Medicinal plants may be contaminated during growth, development, and processing stages.

The soil geochemical characteristics, atmospheric deposition, harvesting, and the ability of each plant species to selectively accumulate metals are some of the factors, which could play important roles leading to the contamination of medicinal plants by metals [5]. The determination of major, minor, and trace elements in medicinal plants is of great importance due to the growth of environmental pollution that directly affects the plants and, therefore, their phytotherapics. Besides being essential in the living system, the elements can be at the same time toxic, when at concentrations beyond those necessary for metabolic functions [6, 7]. So, contamination of plant preparation with high concentration of metals can cause health problems [8].

A soil-to-plant transfer factor (TF) is an important parameter that can be used to estimate metal level in medicinal plants as a fraction of soil total concentration, and the TF assessment model is a tool to simplify the transfer estimation of these elements through the food chain [9, 10]. Limited information regarding metal transfer from soil to medicinal plants is available. Therefore, the aim of this paper was to evaluate the TF of As, Ba, Br, Ca, Cd, Co, Cr, Cu, Fe, Hf, K, La, Mg, Mn, Na, Ni, Pb, Rb, Sb, Sc, Sm, Th, Ti, V, and Zn from soil to lemon balm species (*Melissa officinalis* L.) commonly used in folk medicine. Furthermore, this study was designed to estimate the contribution of this species to

---

✉ Fábio Vitório Sussa
fvsussa@gmail.com

Marcos Roberto Furlan
furlanagro@gmail.com

Marcos Victorino
marcosvictorino@uol.com.br

Paulo Sergio Cardoso da Silva
pscsilva@ipen.br

[1] Instituto de Pesquisas Energéticas e Nucleares (IPEN), Centro do Reator de Pesquisas (CERPq), Av. Professor Lineu Prestes 2242, Cidade Universitária, 05508-000 São Paulo, SP, Brazil

[2] Departamento de Ciências Agrárias, Universidade de Taubaté, Estrada Municipal Dr. José Luiz Cembranelli 5000, 12081-010 Taubaté, SP, Brazil

[3] Faculdade Integral Cantareira (FIC), Rua Marcos Arruda, 729, 03022-000 São Paulo, SP, Brazil

the metal daily intakes and compare the estimated intakes with international standards.

Experimental

Experimental design

The experiments were carried out in the Municipal Gardening School area, in Ibirapuera Park, *São Paulo*, Brazil, latitude 23° 35’ S, longitude 46° 39’ O, with the following chemical properties of the 0–0.2 m site topsoil layer, according to *Instituto Agronômico de Campinas* (IAC) [11]: pH ($CaCl_2$) = 6.9; organic matter (OM) = 15 g dm^{-3}, P = 1 mg cm^{-3}; K^+ = 3.5 mmolc dm^{-3}; Ca^{2+} = 64 mmolc dm^{-3}; Mg^{2+} = 8 mmolc dm^{-3}; H + Al = 15 mmolc dm^{-3}; cation exchange capacity (CEC) = 91 mmolc dm^{-3} and sulfur (S) = 30 mmolc dm^{-3} of soil; and base saturation (V%) = 83%. The fertilization recommendation was defined based on soil analysis and followed the *Boletim Técnico* 100 of the IAC for mint fertilization, because there is no recommendation of lemon balm fertilization in São Paulo [12].

The experimental design was completely randomized (CRD) in plastic containers with a capacity of 0.1 m^3 of soil and an area of 0.5 m^2, with three treatments: control (site soil), organic (2 t ha^{-1} poultry manure), and conventional (30 t ha^{-1} of NPK, 6:14:8), and four harvests, every three months, with two replications.

Collection and preparation of samples

Soil samples were collected from a vertical slice on the side of each container (0–0.2 m depth), following IAC recommendation [11] and dried at 100 °C for 12 h in an oven. The dried samples were grinded into powder at 100 mesh (150 µm diameter) size particles and homogenized.

The lemon balm samples collected were washed with ultra-pure water to remove impurities and soil particles present in all plant structures, air-dried and the leaves were separated. After these processes, the leaf samples were dried at 100 °C for 12 h in an oven. The dried samples were grinded into powder at 100 mesh (150 µm diameter) size particles and homogenized.

INAA measurement

The As, Ba, Br, Ca, Co, Cr, Fe, Hf, K, La, Mg, Mn, Na, Rb, Sb, Sc, Sm, Th, Ti, V, and Zn concentrations were determined by relative method of Instrumental Neutron Activation Analysis (INAA) in soil and lemon balm samples. INAA, a sensitive, nondestructive and multi elemental technique, has been frequently used to evaluate inorganic contents in soil and medicinal plants [13–15]. These samples were irradiated at the nuclear research reactor IEA-R1 at IPEN (*Instituto de Pesquisas Energéticas e Nucleares*, Brazil), under two irradiation schemes, short (20 s) and long irradiations (8 h). For the determination of As, Ba, Br, Ca, Co, Cr, Fe, Hf, K, La, Na, Rb, Sb, Sc, Sm, Th, and Zn, about 150 mg of the powdered leaf samples, 100 mg of powdered soil, and 100 mg of the powdered certified reference materials (CRM) from the IAEA-336 Lichen, NIST 1573a Tomato Leaves, NIST 1547 Peach Leaves, NIST 1646a Estuarine Sediment, and USGS STM-2 Table Mountain Syenite were weighed in previously cleaned polyethylene bags. Synthetic standards were also prepared by pipetting convenient aliquots of standard solutions (SPEX Certiprep Inc., USA) using milli-Q water 18.2 MΩ cm at 25 °C (Millipore Corporation, USA), onto small filter paper sheets. The concentration of elements in the synthetic standard are showed in the supplementary information 1. The samples, CRM, and synthetic standard were carried out under a thermal neutron flux of 10^{12} cm^{-2} s^{-1} for 8 h. For determination of Mg, Mn, Ti, and V, approximately 70 mg of the powdered leaf samples, 30 mg of powdered soil, 50 mg of the powdered standard reference materials (SRM) from the NIST 1573a Tomato Leaves, NIST 1547 Peach Leaves, NIST 1646a Estuarine Sediment along with synthetic standard were carried out at the pneumatic facility with a thermal neutron flux of approximately 10^{11} cm^{-2} s^{-1} for 20 s. The gamma-ray spectra were obtained using an EG&G ORTEC counting system (high-resolution solid-state Ge detector, type POP TOP, Model 20,190) with a resolution of 1.9 keV for the 1,332 keV peak of ^{60}Co. In the short irradiation scheme, samples and reference materials were measured for 180 and 120 s respectively. In the long irradiation scheme, samples and reference materials were measured after 7 and 15 days of cooling. Soil samples and reference materials were measured for 3,600 s and the plant samples for 7,200 s. All counts were performed a distance between 0 and 6 cm previously determined to give a dead time lower than 10%. Once chosen the distance all samples were counted at the same geometry. The detector was coupled to an EG&G ORTEC ACE8K card and associated electronics. Spectrum analysis was performed using the VISPECT2 software in TURBOBASIC language.

GF AAS and ICP OES and measurement

For the determination of Cd, Cu, Ni, and Pb about 300 mg each of the powdered soil, leaf samples, and NIST-SRM 1646a Estuarine sediment was digested in 22.5 ml of mixture of concentrated acid solution (HNO_3, HCl, $HClO_4$, H_2O_2 in ratio of 5:15:0.5:2). The corresponding solution was heated until a clear solution appeared. The clear solution was diluted up to 50 ml with distilled water and filtered with Whatman filter paper no.1.

A Perkin Elmer AAnalyst800 Graphite Furnace Atomic Absorption Spectrometer (GF AAS) was used for the determination of the elements Cd, Cu, and Pb. This method provides both sensitivity and selectivity since other elements in the sample will not generally absorb the chosen wavelength and thus, will not interfere with the measurement [16]. Cathode lamps were used as a radiation source. Argon gas was used for all the experiments as a carrier and for cleaning the graphite furnace. The standard working solutions of interest elements were prepared to make the standard calibration curve.

An Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES) was used for the determination of Ni concentrations, because Ni is not very favorable element to be determined by INAA due to the lower neutron capture cross section for the (n, p) reaction and high uncertainty [17]. The detailed methodology for ICP OES measurements, as well as the calibration curves used for the concentrations in all the samples are presented in the literature [18].

Soil-to-plant transfer factor calculation

The transfer factor (TF) was calculated as the ratio of the concentrations of each stable element in the plant (C_{plant}, dry weight) divided by that in the corresponding soil sample (C_{soil}, dry weight) as shown in Eq. (1) [19].

$$TF = \frac{C_{plant}\,(dryweight)}{C_{soil}\ (dryweight} \tag{1}$$

The TF of stable elements were summarized as arithmetic means.

Results and discussion

Quality Assurance and Control

The CRM from the IAEA-336 Lichen, NIST 1573a Tomato Leaves, NIST 1547 Peach Leaves, NIST 1646a Estuarine Sediment, USGS STM-2 Table Mountain, and synthetic standard were analyzed to evaluate the precision and accuracy of the results. As recommended in its certificate, elemental concentrations in the reference material were calculated on a dry weight basis. A subsample of the reference material was separated to determine the moisture content by drying at 85 °C for 24 h. The weight loss obtained was used to correct the results.

In Fig. 1 the Z-score values are shown, calculated for the elements determined in the CRM. For all elements the Z-score values were $|Z|<3$, which means that the results obtained are in the 99% confidence interval of the certified values [20]. For Ni element only the error relative (ER) was verified because the CRM used just provide noncertified values. For these elements, the ER < 10%.

Element concentration in soil and lemon balm

Summarized elemental concentrations in all the soils and the lemon balm leaf samples (on the dry weight basis) are shown in Tables 1 and 2, respectively. The number of samples (N^a) considers only the results above the detection limit.

As can be seen in Table 1, Ca, Fe, K, Mg, and Ti are the most abundant elements in soil in concentrations of thousands mg kg^{-1}. Whereas the concentrations of the elements Ba, Cr, Mn, Na, V, and Zn are in the order of hundreds like mg kg^{-1}. The elements As, Br, Cu, Hf, La, Ni, Pb, Rb, and Th presented concentrations in the order of tenths mg kg^{-1}. The lowest concentrations were observed for the elements Cd, Co, Sb, and Sm. The maximum/minimum ratios were less than 10 for 24 elements and > 10 for the element Cu.

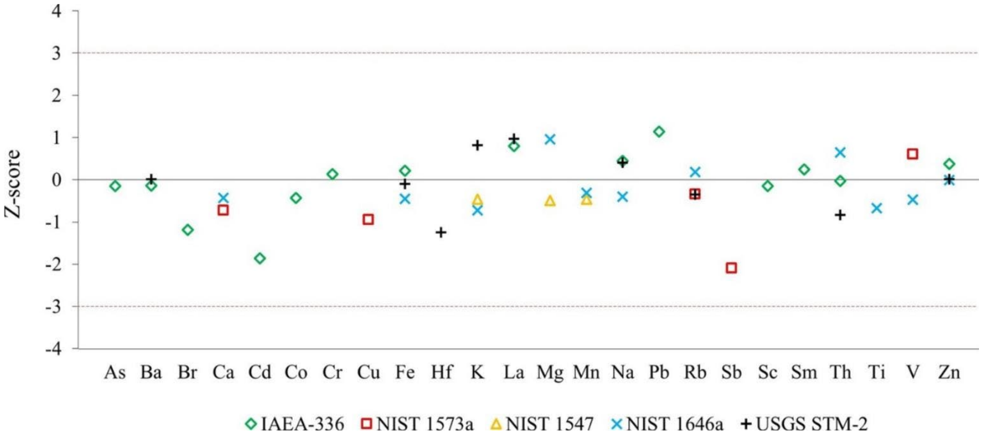

Fig. 1 *Z*-score values obtained for the elements determined in geological and biological reference materials

Table 1 Concentration of 25 elements for three cultivation systems soil samples (mg kg^{-1} dry weight)

	As	Ba	Br	Ca	Cd	Co	Cr	Cu	Fe	Hf	K	La	Mg
N[a]	24	8	24	23	23	24	24	24	24	24	24	24	24
Minimum	27	68	20	5,640	0.03	2.9	84	1	57,799	12	1,445	18	13,086
Maximum	40	196	26	12,346	0.07	3.7	133	28	72,201	20	3,244	31	34,477
Max./Min.	1	3	1	2	2	1.3	2	24	1	2	2	2	3
Mean	33	110	23	8,500	0.05	3.2	100	17	65,637	17	2,460	23	24,195
Median	32	92	23	8,205	0.05	3.2	99	17	66,134	17	2,447	22	23,600
Geometric Mean	33	104	23	8,256	0.05	3.2	99	15	65,557	17	2,418	23	23,772
	Mn	Na	Ni	Pb	Rb	Sb	Sc	Sm	Th	Ti	V	Zn	
N[a]	24	23	24	22	10	18	24	22	23	17	24	7	
Minimum	109	175	7	10	5	0.7	16	2.3	27	3,727	37	53	
Maximum	223	538	15	34	30	3.9	19	5.2	35	13,594	246	332	
Max./Min.	2	3	2	3	6	5	1	2.3	1	4	7	6	
Mean	160	391	11	14	17	1.9	18	3.2	31	8,842	176	111	
Median	160	388	11	12	17	1.4	18	3.1	30	8,814	178	78	
Geometric Mean	157	384	11	13	15	1.7	18	3.1	31	8,566	168	91	

[a] Numbers of samples for which concentration were determined

According to [21], the observed variation is related to agricultural management, control, organic and conventional, as shown in Fig. 2. The fertilized systems showed higher concentrations of major and minor nutrients. It has been reported that fertilizer systems are sources of these elements and contribute to soil improvement [22]. For safety assessment of heavy metals in soil, according to the regulation for heavy metals in soils from São Paulo, the allowable limits for As, Cd, Cr, Cu, Pb and Zn are 35, 3.6, 150, 760, 150, and 1,900 mg kg^{-1} for agricultural soil, respectively [23]. The mean concentrations of potentially those toxic elements did not exceed these allowable limits.

As can be seen in Table 2, Ca, Fe, K, and Mg are abundant elements in the lemon balm leaf samples. Calcium is an essential element for plants and its content varied from 8,849 to 24,628 mg kg^{-1}. Iron is an essential element for plant protein synthesis (433–4,138 mg kg^{-1}). Potassium (20,617–41,139 mg kg^{-1}), an essential element that is generally supplied to plants by means of fertilization processes, also showed a wide variation with a higher value found in the organic system (Fig. 3). Magnesium (1,622–7,622 mg kg^{-1}), besides being a chlorophyll component, is also an enzyme co-factor. In lemon balm leaves, [24–27] reported similar results for Ca, Fe, K and Mg.

Essential and non-essential microminerals are present in lemon balm leaves with significant quantities in the following order Ti > Na > Ba > Cr > Zn > Br > Ni > Mn > Rb > Cu > Pb > V > As. The lower concentrations were observed for Hf, La, Sb, Sc, Sm, and Th. Very few values have been reported in the literature for Hf, Rb, Sb, Sc, Ti, and V in lemon balm. In general, most elements are agreement with the pondered values reported in literature [29]. Except for Ni which presented levels that can be considered toxic, about 10 times the level for common plants [23, 27, 28]. The critical toxicity levels on plants are > 10 mg kg^{-1} dry weight (DW) in sensitive species, > 50 mg kg^{-1} DW in moderately tolerant species, and > 1,000 mg kg^{-1} DW in Ni hyperaccumulator plants [30].

Transfer factor of stable elements

Soil-to-plant TF of the 25 elements (As, Ba, Br, Ca, Cd, Co, Cr, Cu, Fe, Hf, K, La, Mg, Mn, Na, Ni, Pb, Rb, Sb, Sc, Sm, Th, Ti, V, and Zn) as a function of agricultural management are presented in Fig. 4.

The TF values for most elements varied widely depending on the control, organic and conventional systems. According to the agricultural management, TF values showed a decreasing order of control > conventional > organic. The higher TF values for control systems is due to pH in the control soil analyzed being in the range of 6–7, which it boosts metals mobility and plant uptake [31]. Although soil

Table 2 Concentration of 25 elements in Lemon balm leaf sample (mg kg^{-1} dry weight)

	As	Ba	Br	Ca	Cd	Co	Cr	Cu	Fe	Hf	K	La	Mg	Mn	Na	Ni	Pb	Rb	Sb	Sc	Sm	Th	Ti	V	Zn
N[a]	7	22	24	24	24	23	23	24	24	17	24	20	24	24	22	22	21	24	14	24	17	17	13	21	24
Minimum	0.3	46	5	8,849	0.02	0.2	5	7	433	0.1		0.2	1,622	8	18	3	1	10	0.1	0.03	0.03	0.1	68	0.4	31
Maximum	2.3	102	66		0.12	2.8	283	17	4,138	1.2		1.9	7,680	41	266	46	7	28	0.5	1.21	0.23	2.0	494	5.2	89
	8	2	12	3	6	17	55	2	10	16	2	12	5	5	15	15	5	3	4	35	7	18	7	15	3
Mean	1.2	66	24		0.05	0.8	65	11	1,212	0.4		0.6	5,428	19	79	21	4	18	0.2	0.3	0.08	0.6	176	1.7	54
	1.0	62	14		0.05	0.6	50	10	852	0.2		0.4	5,800	19	43	22	3	18	0.2	0.2	0.05	0.3	118	1.2	56
Geometric Mean	0.8	64	19		0.05	0.6	38	11	994	0.3		0.5	5,161	18	55	14	3	18	0.2	0.2	0.06	0.4	142	1.3	52
Literature																									
[24]		56 ±3	7.69		0.06	0.30	8.1 ±0.5	14.8 ±0.3	174 ±4				630 ±70	123 ±3	54 ±1	2.7 ±0.2		19.2 ±0.7	0.025	0.041				0.31	33 ±2
[25]						0.45	1.96	13.5	900				4,050	63.5	490										30
[26]								4-30	25-300					15-800	trace										15-800
[27]				8,456					435				2166		60.8								1.6		
[28]	0.03	38.11			0.04											1.31	0.07	17.99						1.32	
[29]	0.009-1.5	1-198	< 40		3-30	0.18–0.24	0.1–0.5		1–1,000	0.01–0.4		0.003-15		30-500	trace	0.1-3.0	0.1–10	20-70	0.06-4.3	0.13–0.14	0.1–0.8	< 5.0		5-50	1-150

[a] Numbers of samples determined

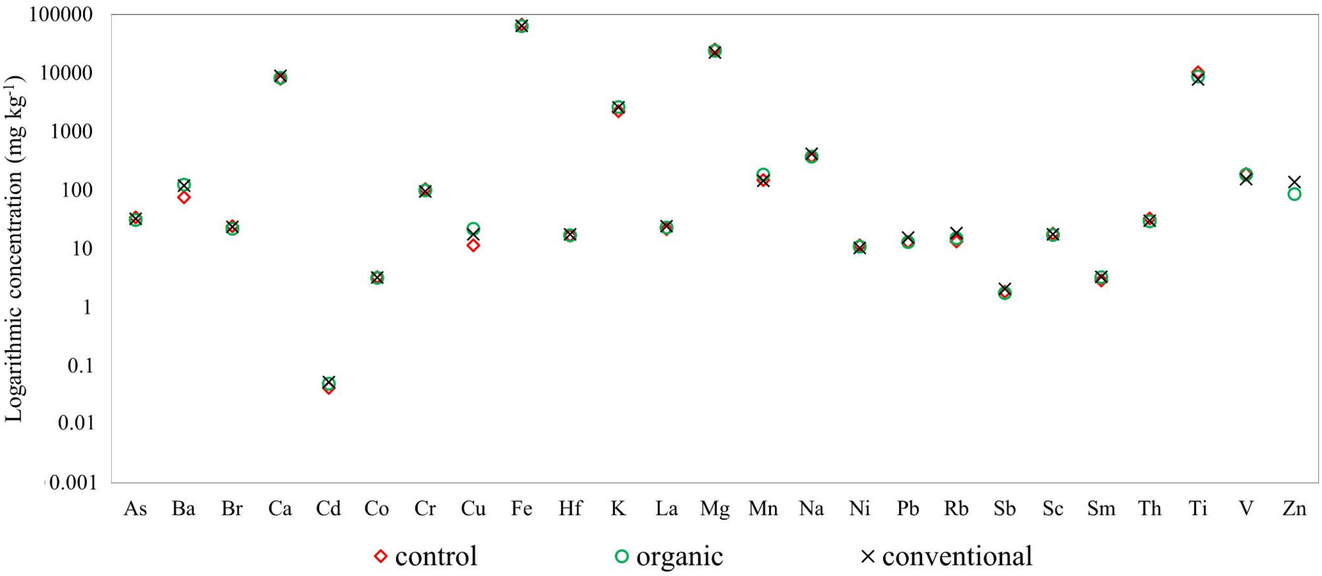

Fig. 2 Mean value of logarithmic concentration in soil from control, organic and conventional cultivation systems for lemon balm

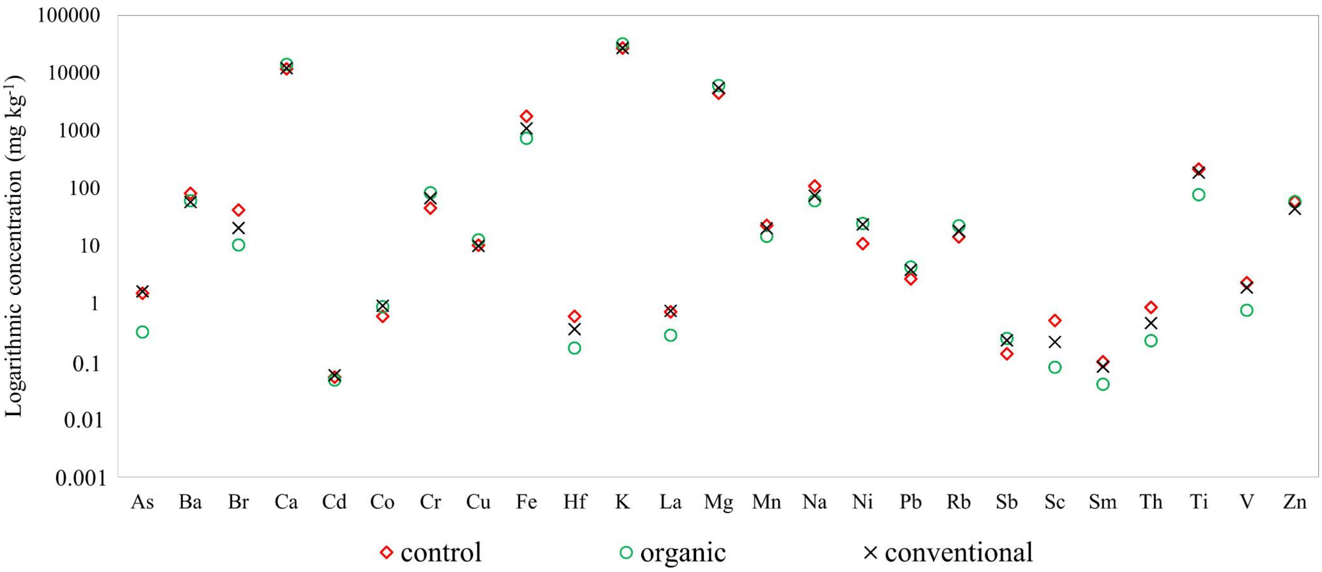

Fig. 3 Mean value of logarithmic concentration in leaves from control, organic and conventional cultivation systems for lemon balm

analysis was not performed after fertilization, it is known that the organic fertilizers addition increases the strong elemental adsorption into organic matter and increases soil pH, which renders it less bioavailable to plants [32, 33].

In Table 3 is showed the transfer factor range for the elements. The average transfer factors are in the following order K > Ni > Rb > Ca > Cd > Br > Cu > Ba > Cr > Zn > Pb > Co > Na > Mg > Mn > Sb > As > La > Hf > Th > Sm > Fe > Ti > Sc > V. It is observed that the elements which showed a higher transfer factor were Br, Ca, Cd, K, Ni, and Rb (> 1.0), followed by Ba, Co, Cr, Cu, Mg, Mn, Na, Pb, Sb, and Zn (0.1–1.0), while As, Fe, Hf, La, Sc, Sm, Th, Ti, and V had the lowest accumulation (< 0.1).

Among the heavy metals that showed the highest TF in lemon balm leaf are Cd and Ni. These might be due to the higher mobility of Cd that naturally occurs in soil [34, 35] and the increased concentration of Ni from leaves as opposed to the soil may suggest the effect of anthropogenic sources, application of animal manures, chemical and organic fertilizer [36–38]. Nevertheless, Ni accumulator plants may also reflect their potential to sequester high levels of Ni in their tissue [27], under normal growing conditions, plants

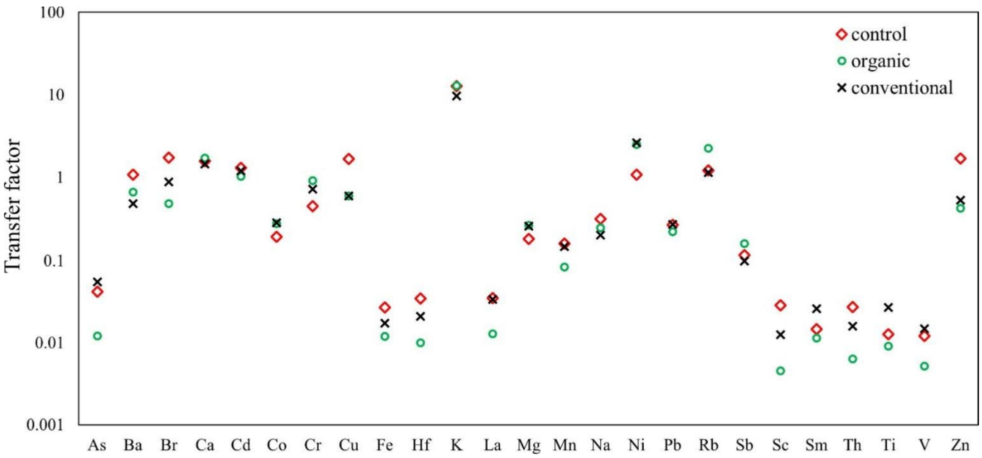

Fig. 4 Transfer factor of elements from soils into lemon balm sample

Table 3 Soil-to-plant transfer factor (TF) of stable elements

	As	Ba	Br	Ca	Cd
TF	0.01–0.05	0.48 – 1.10	0.48–1.74	1.44–1.56	1.02–1.30
Average	0.04	0.70	1.03	1.58	1.18
	Co	Cr	Cu	Fe	Hf
TF	0.20–0.30	0.45–0.91	0.60–1.70	0.01–0.02	0.01–0.03
Average	0.25	0.70	0.95	0.02	0.02
	K	La	Mg	Mn	Na
TF	9.67–12.8	0.01–0.03	0.18–0.26	0.08–0.16	0.20–0.31
Average	12.05	0.03	0.23	0.13	0.25
	Ni	Pb	Rb	Sb	Sc
TF	1.07–2.60	0.22–0.27	1.14–2.24	0.10–0.16	0.004–0.03
Average	2.15	0.25	1.60	0.13	0.01
	Sm	Th	Ti	V	Zn
TF	0.01 – 0.02	0.006–0.03	0.01–0.03	0.005–0.01	0.42–1.70
Average	0.02	0.02	0.02	0.01	0.70

can potentially accumulate certain metal ions up to orders of magnitude greater than the surrounding medium [39]. Similarly, in a study conducted by [31], the highest TF values were found for Cd (in order of 1.2) in *Mentha piperita* used as a medicinal plant.

Estimated daily intake

Since medicinal plants are one of the most relevant sources of essential nutrients and toxic elements it is very important to determine the estimated daily intake (EDI) of potentially toxic elements. The data obtained from this study was used to estimate the daily intake (μg day^{-1}) for an adult of 70 kg and the results were reported in dry weight. The intake values per day for potentially toxic elements (As, Br, Cd, Cr, Cu, Ni, Pb, and Zn) were determined assuming a consumption of 4.5 g (dry weight) of sectioned drug [40, 41] and obtained values are given in Table 4. Obtained data were compared to the data prescribed by World Health Organization and, Food and Agriculture Organization (WHO/FAO).

In fact, among the elements determined in this paper, only As, Cd, and Pb have been limited in plants used as raw material for medicinal purposes, in concentrations of 1.0, 0.3, and 10 mg kg^{-1}, respectively [42]. In Fig. 3, it can be noted that this value was exceeded in samples grown in the conventional and control cropping systems for arsenic only. But the results show that the estimated daily intake for 4.5 g lemon tea range from 1.35 to 10.35 μg day^{-1}. Provisional tolerable daily intake (PTDI) for inorganic As (not for total As) is 2.14 μg kg^{-1} body weight day^{-1}, equivalent to 150 μg day^{-1} [43]. Consequently, a real comparison between our results and the PTDI is not possible [44]. However, considering that all the arsenic existing in the lemon balm is in its inorganic form, in this improbable case, the intake does not present a health risk.

For Br, Cd, Cr, Cu, Ni Pb, and Zn the estimated daily intake results does not exceed the toxicological reference values established by the WHO/FAO, and consequently a health risk situation by tea consumption does not exist [45–47]. The estimation of probable values of intake through leaves (fully plant) consumption shows that the content of toxic elements is well below the permitted limits

Table 4 Estimated daily intake of adult (EDI/70kg) of potentially toxic elements

	Element			
Parameter	As	Br	Cd	Cr
	μg day^{-1}			
EDI	1.35–10.35	22.5–297	0.09–0.54	220–1,270
TDI	150	70,000	70	14,000
	Cu	Ni	Pb	Zn
	μg day^{-1}			
EDI	31.5–76.5	0.09–0.54	4.5–31.5	140–400
TDI	3,500	350	250	70,000

TDI, Tolerable Daily Intake calculated based on PTDI [45–47] recommended by the Joint WHO/FAO and does not present a risk to the consumption in the tea form.

Conclusions

In conclusion, most elements occurred at low levels in leaves of lemon balm, except for Ni that presented toxic metal levels, about 10 times the normal level for plants. The soil-to-plant TF determined, allowed the evaluation of the proportion of the content of the elements present in the soil that is transferred to the plants. The results of the present study revealed that Br, Ca, Cd, K, Ni, and Rb accumulated with the higher transfer factor values, between 1.0 and 12; followed by Ba, Co, Cr, Cu, Mg, Mn, Na, Pb, Sb, and Zn with a TF in the range of 0.1–1.0, while As, Fe, Hf, La, Sc, Sm, Th, Ti, and V had the lowest accumulation, with a TF usually <0.1. Among the potentially toxic elements that showed the highest TF in lemon balm are Ni (2.15) and Cd (1.18). Although soil-to-plant TF values are low, the presence of heavy metals in *Melissa officinalis* leaves reflect the transfer of metals from the soil, their absorption and translocation. This condition indicates that part of the total contaminant content in the soil is biologically bioavailable to the evaluated plant species and exposes the potential risk that the consumption of medicinal plants may pose. The daily intake values of As, Br, Cd, Cr, Cu, Ni, Pb, and Zn even overestimated were still below the toxicological reference values established by the WHO/FAO, and consequently a health risk situation by tea consumption does not exist. This work does not only improve understanding of soil-to-plant transfer mechanism of stable elements but also increase available TF data on *Melissa officinalis* used as medicinal plants and contributing to design a best quality control of plant materials.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10967-022-08353-7.

Acknowledgements The authors thank CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico (The Brazilian National Research Council) for financial support (Process nº 141,977/2012-4) and IPEN-CNEN/SP.

References

1. Zarei A, Changizi-Ashtiyani S, Taheri S, Hosseini N (2015) A Brief Overview of the Effects of *Melissa officinalis* L. Extract on the Function of Various Body Organs Zahedan. J Res Med Sci DOI. https://doi.org/10.17795/zjrms1007
2. Miraj S, Rafieian-Kopaei, Kiani S (2016) *Melissa officinalis* L: A review study with an antioxidant prospective Evid. Based Complement Altern Med DOI. https://doi.org/10.1177/2156587216663433
3. Weitzel C, Petersen M (2011) Cloning and characterisation of rosmarinic acid synthase from *Melissa officinalis* L. Phytochem DOI. https://doi.org/10.1016/j.phytochem.2011.01.039
4. WHO (2007) WHO monographs on selected medicinal plants. WHO press, Geneva, Switzerland
5. Al Moaruf OA, Muibat OB, Asiata OI, Isiaka AO, Nureni OO (2004) Heavy trace metals and macronutrients status in herbal plants of Nigeria. Food Chem DOI. https://doi.org/10.1016/j.foodchem.2003.06.004
6. Fei T, Dehong L, Fengqun Z, Junhua L, Hua T, Xiangzhong K (2010) Determination of trace elements in Chinese medicinal plants by instrumental neutron activation analysis. J Radioanal Nucl Chem DOI. https://doi.org/10.1007/s10967-010-0503-y
7. Ebrahim AM, Eltayeb MH, Khalid H, Mohamed H, Abdalla W, Grill P, Michalke B (2012) Study on selected trace elements and heavy metals in some popular medicinal plants from Sudan. J Nat Med DOI. https://doi.org/10.1007/s11418-012-0630-6
8. Stanojkovic-Sebic A, Pivic R, Josic D, Dinić Z, Stanojković A (2015) Heavy metals content in selected medicinal plants commonly used as components for herbal formulations. Tarim Bilim Derg DOI. https://doi.org/10.1501/Tarimbil_0000001334
9. Shigeo U, Keiko T, Ikuko H (2007) Soil-to-Plant Transfer Factors of Stable Elements and Naturally Occurring Radionuclides (1) Upland Field Crops Collected in Japan. J Nucl Sci Technol DOI. https://doi.org/10.1080/18811248.2007.9711851
10. Mbong E, Umoh O (2014) Soil plant heavy metal relations and transfer factor index of habitats densely distributed with *Citrus reticulata* (tangerine). J Res Environ Sci Toxicol DOI. https://doi.org/10.14303/jrest.2014.014
11. Instituto Agronômico de Campinas [homepage internet]. Centro de Pesquisa e Desenvolvimento de Solos e Recursos Ambientais. https://www.iac.sp.gov.br/produtoseservicos/analisedosolo/retiraramostrasolo.php. Accessed 14 apr 2022
12. Raij BV, Cantarella H, Quaggio JA, Furlani AMC (1997) Recomendações de adubação e calagem para o Estado de São Paulo. 2 ed. Campinas: IAC (Boletim técnico 100). http://www.etecsaosimao.com.br/_documentos/_pdf/_apoio_ao_aluno/_livros/BOLETIM_100_IAC_Completo.pdf. Accessed 14 apr 2022
13. Thien BN, Ba VN, Man NT, Loan TTH (2021) Analysis of the soil to food crops transfer factor and risk assessment of multi-elements at the suburban area of Ho Chi Minh city, Vietnam using instrumental neutron activation analysis (INAA). J Environ Manage DOI. https://doi.org/10.1016/j.jenvman.2021.112637
14. Yamashita C, Saiki M, Sertié J (2006) Elemental analysis of leaves and extracts of Casearia medicinal plants by instrumental neutron activation analysis. J Radioanal Nucl Chem DOI. https://doi.org/10.1007/s10967-006-0327-y
15. Sussa FV, Damatto SR, Fávaro DIT, Mazzilli BP, Silva PSC (2009) Radioactive and stable elements' concentration in medicinal plants from Brazil. J Radioanal Nucl Chem DOI. https://doi.org/10.1007/s10967-009-0126-3
16. Zeiner M, Cindric IJ (2017) Review – trace determination of potentially toxic elements in (medicinal) plant materials Anal Methods DOI. https://doi.org/10.1039/C7AY00016B
17. Moreira EG, Vasconcellos MBA, Saiki M (2005) Measurement uncertainty assessment in the Instrumental Neutron Activation Analysis of chromium, manganese, molybdenum, and nickel in stell. In: International Nuclear Atlantic Conference. Santos. INAC 2005. https://www.ipen.br/biblioteca/cd/inac/2005/full/Dica.pdf Accessed 19 apr 2022
18. Shirisha K, Sahrawat KL, Devi PB, Wani SP (2014) Simple and Accurate Method for Routine Analysis of Heavy Metals in Soil, Plant, and Fertilizer Commun Soil Sci Plant Anal DOI. https://doi.org/10.1080/00103624.2014.911303

19. Calvo DLO, Dominguez JCH, Ardaiz CW, Moreno CM (2008) Factores de Transferencia Suelos-Hojas del Ni en Melocotones. Posibles Alteraciones por la Bajada de pH del Suelo. Agricola Vergel 313:35–40
20. Peter B (1996) Ph.D. Thesis, Delft University of technology, The Netherlands
21. Silveira PM, Cunha AA (2002) Variabilidade de micronutrientes, matéria orgânica e argila de um Latossolo submetido a sistemas de preparo Pesq Agropececu Bras DOI. https://doi.org/10.1590/S0100-204X2002000900017
22. Ourives OEA, Souza GM, Tiritan CS, Santos DH (2010) Fertilizante orgânico como fonte de Fósforo no cultivo inicial de *Brachiaria brizantha* cv. Marandú Pesq Agropecu Trop DOI. https://doi.org/10.5216/pat.v40i2.5138
23. CETESB (2021) Decisão de diretoria nº 125/2021/E - Aprovação da Atualização da Lista. de Valores Orientadores para Solo e Água Subterrânea, São Paulo
24. Silva PSC, Franscisconi LS, Gonçalves RDMR (2016) Evaluation of Major and Trace Elements in Medicinal Plants. J Braz Chem Soc DOI. https://doi.org/10.5935/0103-5053.20160123
25. Petenatti ME, Petenatti EM, Del Vitto LA, Téves MR, Caffini NO, Marchevsky EJ, Pellerano RG (2011) Evaluation of macro and microminerals in crude drugs and infusions of five herbs widely used as sedatives Rev Braz Farmacog DOI. https://doi.org/10.1590/S0102-695X2011005000129
26. Duke JA, Bogenschutz-Godwin MJ, duCellier J, Duke PAK (2002) Handbook of medicinal herbs. CRC Press, Florida, USA, Boca Raton
27. Yaman C (2020) Lemon balm and sage herbal teas: Quantity and infusion time on the benefit of the content Cienc e Agrotecnologia DOI. https://doi.org/10.1590/1413-7054202044023220
28. Caldeirão L, Sousa J, Nunes LCG, Godoy HT, Fernandes JO, Cunha SC (2021) Herbs and herbal infusions: Determination of natural contaminants (mycotoxins and trace elements) and evaluation of their exposure. Food Res Int DOI. https://doi.org/10.1016/j.foodres.2021.110322
29. Kabata-Pendias A (2011) Trace elements in soils and plants, Taylor and Francis Group. LLC, Florida, U.S.A
30. Chen C, Huang D, Liu J (2009) Functions and Toxicity of Nickel in Plants: Recent Advances and Future Prospects Clean DOI. https://doi.org/10.1002/clen.200800199
31. Jalali M, Meyari (2022) A Heavy metal contents, soil-to-plant transfer factors, and associated health risks in vegetables grown in western Iran. J Food Compost Anal DOI. https://doi.org/10.1016/j.jfca.2021.104316
32. Glavač NK, Djogo S, Ražić S, Kreft S, Veber M (2017) Accumulation of heavy metals from soil in medicinal plants Arh Hig Rada Toksikol DOI. https://doi.org/10.1515/aiht-2017-68-2990
33. Oluyemi EA, Feuyit G, Oyekunle JAO, Ogunfowokan AO (2008) Seasonal variations in heavy metal concentrations in soil and some selected crops at a landfill in Nigeria. Afr J Environ Sci Technol 2:89–96
34. Alam MGM, Snow ET, Tanaka A (2003) Arsenic and Heavy Metal Contamination of Vegetables Grown in Samta Village. Bangladesh Sci Total Environ DOI. https://doi.org/10.1016/S0048-9697(02)00651-4
35. Trevizam AR, Villanueva FCA, Muraoka T, Filho VFN, Junior CHA (2010) Aplicação de fósforo para imobilização química do cádmio em solo contaminado Quim Nova DOI. https://doi.org/10.1590/S0100-40422010000600003
36. Oliva SR, Espinosa AJF (2007) Monitoring of heavy metals in topsoils, atmospheric particles and plant leaves to identify possible contamination sources. Microchem J DOI. https://doi.org/10.1016/j.microc.2007.01.003
37. Olowoyo JO, van Heerden E, Fisher JL, Baker C (2010) Trace metals in soil and leaves of *Jacaranda mimosifolia* in Tshwane area, South Africa Atmospheric Environ DOI. https://doi.org/10.1016/j.atmosenv.2010.01.048
38. Rai PK, Lee SS, Zhang M, Tsang YF, Kim K (2019) Heavy Metals in Food Crops: Health Risk, Fate, Mechanisms, and Management Environ Int DOI. https://doi.org/10.1016/j.envint.2019.01.067
39. Kim IS, Kang H, Kyung H, Jonhson-Green P, Lee EJ (2003) Investigation of heavy metal accumulation in *Polygonum thunbergii* for phytoextraction Environ Pollut DOI. https://doi.org/10.1016/s0269-7491(03)00190-8
40. Begaa S, Messaoudi M (2018) Thermal neutron activation analysis of some toxic and trace chemical element contents in *Mentha pulegium* L. Radiochim Acta DOI. DOI:https://doi.org/10.1515/ract-2018-2942
41. Agência Nacional de Vigilância Sanitária, Formulário de Fitoterápicos da Farmacopeia Brasileira, 2ª edição. https://www.gov.br/anvisa/pt-br/assuntos/farmacopeia/formulario-fitoterapico/arquivos/2021-fffb2-final-c-capa2.pdf. Accessed 24 Fev 2022
42. WHO (1998) Quality Control Methods for Medicinal Plants Materials. WHO press, Geneva, Switzerland
43. FAO/WHO (1989) Evaluation of certain food additives and contaminants. Thirty-third Report of the Joint FAO/WHO Expert Committee on Food Additives. WHO technical Report Series. Geneva, Switzerland
44. Muñoz O, Bastias JM, Araya M, Morales A, Orellana C, Rebolledo R, Velez D (2005) Estimation of the dietary intake of cadmium, lead, mercury, and arsenic by the population of Santiago (Chile) using a Total Diet Study Food Chem Toxicol DOI. https://doi.org/10.1016/j.fct.2005.05.006
45. FAO/WHO (1993) Evaluation of certain food additives and contaminants. 41s Report of the Joint FAO/WHO Committee on Food Additives. Geneva, Switzerland
46. Joint FAO/WHO (1999) Expert Committee on Food Additives, World Health Organization, Food and Agriculture Organization of the United Nations & International Programme on Chemical Safety. Summary of evaluations performed by the Joint FAO/WHO Expert Committee on Food Additives (JECFA): 1956–1997. World Health Organization. (first through forty-ninth meetings)
47. WHO (2013) Expert Committee on Biological Standardization; Meeting and World Health Organization. WHO Expert Committee on Biological Standardization. Sixty-Third Report; World Health Organization, Geneva, Switzerland