

Concentration Levels of Major and Trace Elements in Rice from Sri Lanka as Determined by the k_0 Standardization Method

R. JAYASEKERA^{*1} AND M. C. FREITAS²

¹Department of Botany, University of Kelaniya, Kelaniya, Sri Lanka; and ²Instituto Tecnológico e Nuclear (ITN), EN 10, P-2686-953 Sacavém, Portugal

Received December 5, 2003; Revised February 23, 2004;

Accepted March 20, 2004

ABSTRACT

Instrumental neutron activation (INAA) with k_0 standardization has been used to determine the concentration levels of a variety of major and trace elements (Al, As, Br, Cd, Cl, Co, Cr, Cs, Cu, Fe, Hg, K, La, Mg, Mn, Mo, Na, Rb, Sc, Se, and Zn) in rice grains (raw and parboiled) and in rice flour collected from local markets in Sri Lanka. In addition, the energy-dispersive X-ray fluorescence (EDXRF) analysis has been used to determine the three elements Ca, P, and S in powdered samples. To evaluate and assure the accuracy and precision of the k_0 standardization method, the IAEA standard reference material V-8 rye flour was analyzed. The results obtained in the present investigation were compared with the results reported from other countries. All of the elements detected in the rice matrices from Sri Lanka were very low in concentration or within normal limits for food plants. Approximate daily dietary intakes of the individual elements supplied through rice were calculated and compared with the available literature values of daily allowances.

Index Entries: INAA; k_0 standardization; neutron activation analysis; rice; trace elements.

INTRODUCTION

Many mineral elements occur in living systems in "trace" quantities. Of the 90 naturally occurring elements, only 17 (C, H, O, N, P, S, Ca, Mg,

* Author to whom all correspondence and reprint requests should be addressed.

K, Cu, Zn, B, Fe, Mo, Cl, Mn, and Ni) are essential for plant life (1), whereas for humans 25 elements (C, H, N, O, S, P, K, Mg, Ca, Cl, Na, F, Si, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Se, Mo, Sn, and I) are currently known to be essential (2); in addition, two other elements, Al and Li, have recently been included as possibly essential (3,4). The 25 essential elements include 4 light metals (Na, K, Mg, and Ca) and 10 heavy metals (Cr, Mn, Fe, Co, Ni, Cu, Zn, Se, Mo, and Sn). Just as some major and trace elements are essential for life, their excesses, imbalances, or deficiencies can result in adverse effects on living systems. The appropriate contents of nutritional elements in plants are essential both for the health of plants and for the nutrient supply to man and animals. The list of "essential" trace elements continues to grow because of the growing knowledge of nutritional requirements and because of the progress in analytical determinations. During the last 30 yr or so, nine new elements have been added to the list of known essential trace elements for man and animal nutrition. In the case of foodstuffs, the form in which the trace elements are present affects the bioavailability of trace elements.

The major entry of trace elements into the body is through diet. Rice (*Oryza sativa* L.), being a staple in the diet of many people in Asian countries, supplies a major proportion of the total daily intake of major and trace elements by these people. Various modern developments in agriculture and technology can affect the trace element content of foods. Because of this, concerns have increased over the contamination of crop plants with various chemical elements by the introduction of mechanized farming, the application of agrochemicals, and the processing of foodstuffs during and after harvest. For instance, water used for irrigation during cultivation together with the trace element content of soil might directly affect the plant content of trace elements. During the postharvest processing, the extent of milling of cereal grains is known to affect the trace element content of cereals such as rice. Milling not only removes the outer layers of the grain, which are rich in minerals but also could potentially contaminate the rice grain with trace elements. Another widely used postharvest practice is parboiling. In the process of parboiling rice, the paddy is soaked in ambient water for some time, the water drained, the paddy steamed (or otherwise heated) to gelatinize the starch, and dried (5). Steaming drives the water-soluble vitamins from the outer layers into the endosperm so that less of these nutrients will be lost during milling and washing. Parboiling also hardens the grain. Parboiled rice is, therefore, more nutritious than what is referred to as "raw" rice. However, concern has been raised about possible contamination of the paddy by trace elements and other contaminants during the process of soaking, if clean water is not used. In order to minimize the adverse impacts of these practices, it is important to measure and continuously monitor the concentration levels of trace elements in foodstuffs such as rice (6,7), as it comprises more than 50% of the average daily intake of the people of Sri Lanka. It is also important to note that some people consume rice or rice-based products for all three meals.

During the last two decades or so, the clinical interest in the trace elements has been expanding. One of the major reasons for this is the realization that imbalances of trace elements (i.e., deficiencies or excesses) in man might be an important contributory factor to some major chronic diseases (8–10). Research directed to achieving a better understanding of the role of the trace elements in plant and human metabolism will require a variety of different approaches, and the accurate measurement of trace element concentrations in foodstuffs is only one of these. Such measurements will continue to have an important role in the detection and confirmation of deficiency states and could contribute effectively to the improvement of human nutrition through better assessment and planning. The primary objective of this study was to obtain data on the elemental concentrations, including those of the potentially toxic elements in rice grain and rice flour from Sri Lanka, and to compare them with maximum permissible levels prescribed in international literature and guidelines (11,12). In addition, no detailed studies of major and trace elements in rice grains and rice flour from Sri Lanka had been performed previously and the results of this study are intended to be used as baseline values for future comparisons.

MATERIALS AND METHODS

In order to improve the accuracy of the results, the first author (R.J.) participated directly in the whole analytical procedure, including the sampling (13). The rice grains, “raw polished” (local name: Rathu Kekulu) and parboiled (brown variety), and the rice flour, each from two different producers, were purchased at local markets in Sri Lanka. The rice grains were cleaned of sand/stones and unhusked paddy seeds and washed quickly with tap water, as normally would be at home. All samples in clean polyethylene bags were then dried in an oven at 60°C for 36 h. All of the samples were brought to the Instituto Tecnológico E Nuclear (ITN), where they were freeze-dried (model: Heto DW8) for 4 d. About 25 g of each of the freeze-dried samples were then ground down to a fine powder (<200 µm) using a mill equipped with a Teflon vial and Teflon balls (model: Mikro-Dismembrator, B. Braun, Biotech) in which the samples were kept and placed for 10 min in liquid nitrogen before grinding. The parboiled grains were not grindable because parboiling hardens the grain resulting in less breakage. The ground samples were further homogenized by mixing in a rotating plastic bottle (model: WAB-Turbula, T2C, Switzerland) for 6 h, stored in precleaned plastic bottles, and screw-capped tightly to avoid absorption of water. These plastic bottles were then stored over silica gel in a desiccator. Three replicates of the standard reference material (SRM), IAEA V-8 rye flour, were separately dried according to the instructions given in the certificate for the determination of the water content.

In the recent past, instrumental neutron activation (INAA) with k_0 standardization followed by high-resolution γ -ray spectrometry has

become one of the most promising and widely applicable analytical methods for simultaneous multielement analysis of biological material (14–17). This technique does not require prior sample preparation, thus diminishing the risk of contamination or loss of certain elements during sample digestion. For the analysis of samples by the k_0 standardization method, about 250–450 mg of the samples was weighed into a small polyethylene vial (0.84 cm³; type: W; Vrije University, Amsterdam). This vial was then capped, heat-sealed, and placed in a medium-sized vial for a short irradiation (30 s) of one sample at a time. A disk of 8 mm diameter cut from 0.1-mm (thickness) Au–Al foil (0.1% Au, IRMM-530RA) was then gum-taped to the medium-sized vial and irradiated together with each sample, the gold (Au) being the comparator. Samples of the standard, V-8 rye flour were also prepared for irradiation as described earlier. After a decay time of 7 d, a number of samples, standards, and the blanks were irradiated simultaneously for 7 h (long irradiation) for the production and detection of longer-lived induced activities. For the long irradiation, two to three small vials used for the short irradiation were placed in a medium-sized vial together with a gold foil disk and capped for irradiation. The real samples of the parboiled rice grains were prepared for irradiation using the same procedure described earlier, as they were ungrindable.

The energy-dispersive X-ray fluorescence (EDXRF) analysis was used to determine only calcium (Ca), phosphorus (P), and sulfur (S) in powdered samples of raw rice and rice flour, as most of the other elements in the rice matrices were below or close to the detection limits of the technique. For the EDXRF analysis, the pellets of 3.2 cm diameter were prepared by pressing about 2 g of the powdered material with a 15-ton manual press after adding 1 ml of a liquid binder (800-4-Chemplex). An EDXRF spectrometer (Kevex Delta XRF Analyst System) equipped with secondary targets and filters was used for the quantitative measurement of Ca, P, and S. The details of the procedure, including the evaluation of spectra and calibration, have been described elsewhere (18,19).

Irradiations

For the INAA k_0 analysis, all samples, blanks, and the V-8 rye flour standard were subjected to two different irradiations: (1) for 30 s (short irradiation) to detect and determine the radioisotopes with short half-lives and (2) after they were allowed to decay for 7 d, for 7 h (long irradiation) to observe the radioisotopes with long half-lives. Both irradiations were performed at a thermal neutron flux density of 2.3×10^{12} n/cm² s at the Portuguese Research Reactor at ITN, Sacavém. The selection of timing parameters (i.e., irradiation, decay [cooling] and counting times), together with the radioactive properties of the elements analyzed are summarized in Table 1.

Table 1
Irradiation and Counting Details of Rice Samples
and the Relevant Nuclear Data Used for the Analysis

Irradiation Duration	Measurements		Nuclide Sought	Radioactive Properties			
	Cooling Time	Counting Time		Gamma Energy (keV)	Half-life		
Short irradiation (30 s)	10-15 min	300 s	²⁸ Al	1778.9	2.2 min		
			³⁸ Cl	1642.4	36 min		
			⁶⁶ Cu	1039.2	12.7 h		
			⁴² K	1524.7	12.4 h		
			²⁷ Mg	843.8; 1014.2	9.5 min		
			⁵⁶ Mn	846.8; 1810.7	2.6 h		
			²⁴ Na	1368.6	15.0 h		
	60-90 min	600 s	³⁸ Cl	1642.4	36 min		
			⁴² K	1524.7	12.4 h		
			²⁷ Mg	843.8; 1014.2	9.5 min		
			⁵⁶ Mn	846.8; 1810.7	2.6 h		
			²⁴ Na	1368.6	15.0 h		
			150 min	600 s	¹⁹⁸ Au	411.8	2.7 d
Long irradiation (7 h)	4 d	2 h	⁷⁶ As	559.1	1.1 d		
			⁸² Br	776.5	1.5 d		
			¹¹⁵ Cd	527.9	2.2 d		
			⁴² K	1524.7	12.4 h		
			¹⁴⁰ La	328.9; 815.8; 1596.5	1.7 d		
			⁹⁹ Mo	140.5	2.75 d		
			²⁴ Na	1368.6	15.0 h		
	10 d	300 s	¹⁹⁸ Au	411.8	2.7 d		
	30 d	3.30 h	⁶⁰ Co	1173.2; 1332.5	5.3 yr		
			⁵¹ Cr	320.1	27.7 d		
			¹³⁴ Cs	604.7; 795.8	2.1 yr		
			⁵⁹ Fe	1099.2	44.5 d		
			²⁰³ Hg	279.2	2.7 d		
			⁸⁶ Rb	1076.6	18.7 d		
⁴⁶ Sc			889.3; 1120.5	83.8 d			
		⁷⁵ Se	264.7	120 d			
		⁶⁵ Zn	1115.5	244 d			

Counting

The gamma spectra of the irradiated materials were recorded using a 158-cm³, liquid-nitrogen-cooled, ORTEC GEM series HPGe detector with a resolution of 1.85 keV at the 1.33 MeV photopeak of ⁶⁰Co and an efficiency of 30%. This detector was used in conjunction with a CANBERRA 4096-channel analyzer. All of the spectra obtained were converted to concentration data using the GELIAN and SINGCOMP software programs (20,21). In some samples, the concentration of certain elements could not be satisfactorily determined, possibly the result of the unforeseen changes in the cooling times performed on the activated samples and/or high errors in counting statistics affecting the sensitivity. Those cases are indicated as "not analyzed" (n.a.). The detection limits of the INAA k_0 for individual elements vary significantly, depending on the background of the spectra. The details of the k_0 standardization method are described in earlier publications (14,15). To assure adequate quality control of the results, the standard reference material (SRM) IAEA V-8 rye flour was analyzed.

RESULTS AND DISCUSSION

The analytical results obtained for the IAEA V-8 rye flour are presented in Table 2, along with the certified/noncertified values. It is evident that both the precision and accuracy of the analytical method are good. The k_0 standardization method has been proved to be more powerful and convenient than the relative method for multielement analysis, and the accuracy of the method is usually better than 10% for most of the elements (16,22).

The average concentrations of 24 major and trace elements in the two types of rice grain (i.e., raw and parboiled) and in rice flour, each purchased from two different leading producers, are listed in Table 3. Because of the low concentration levels present, which are below or close to the detection limit of the technique, both Cd and Hg were detected only in two samples. In Table 3, each value represents the average of two or three independent determinations, except for a few cases. It is interesting to note that the mean concentration levels of most of the elements detected in "raw" rice compare favorably with those of the parboiled rice. Only the three elements cesium, manganese, and rubidium were substantially higher in parboiled rice than in raw rice (*see* Table 3). In the case of parboiled rice grains, the real samples (grains) were analyzed by the k_0 method, as they were not grindable. Therefore, it was not possible to determine Ca, P, and S in the parboiled grains by the EDXRF analysis. Overall, the values obtained in the present investigation are more or less consistent with the concentration values given by NIST for SRM 1568a rice flour (Table 3), except for higher values of Br, which is noncertified, and lower values for Na and Rb in the SRM 1568a.

In terms of the concentration values obtained, it is reasonable to compare the "raw" rice with rice flour, as the rice flour is commercially pro-

Table 2
Analytical Values Obtained (in mg/kg)
for Constituent Elements in IAEA V-8 Rye Flour
by the k_0 Standardization Method

Element	Certified/Non- Certified Value	Measured Value
	X ± CI	X ± CI
(Al)	3 ± 1.5	4.89
Br	0.38 ± 0.07	0.364 ± 0.001
Ca	149 ± 10	n.a.
(Cd)*	17 ± 10	<500
Cl	570 ± 108	636 ± 45
(Co)*	2.5 ± 1.5	<10
Cr	-	0.94 ± 0.15
(Cs)*	2 ± 1	<10
Cu	0.95 ± 0.19	<1
Fe	4.1 ± 0.7	5.23 ± 0.27
Hg	-	0.028
K	1925 ± 135	2234 ± 88
(La)	-	0.002
Mg	121 ± 9	133 ± 12.7
Mn	2.06 ± 0.12	2.08 ± 0.10
(Mo)*	120 ± 70	133 ± 19.6
(Na)	2.5 ± 1.0	2.6 ± 1.2
P	592 ± 87	-
Rb	0.48 ± 0.07	0.609 ± 0.046
(S)	620 ± 90	-
(Sc)	-	0.001 ^a
Zn	2.53 ± 0.33	2.72 ± 0.05

Note: X: mean concentration; CI: confidence interval at 95%; (): noncertified information values; n.a.: not analyzed.

* Concentration in micrograms per kilogram.

^a Mean of two identical values.

duced by grinding raw rice grains; despite the producer-to-producer concentration variations, the two types of rice matrix compare favorably with each other, with slightly lower values for Fe, Mg, and Se in rice flour.

In another exercise, the present results (Table 3) were compared with the results obtained by INAA for similar rice types of other countries (6,7) (Table 4). The Al content in all the rice samples from Sri Lanka is characterized by higher values than in samples from Iraq (6). The confidence interval (CI) values reported from Iraq and Japan (6) compare favorably

Table 3
Concentrations of Elements (Mean \pm SD in mg/kg Dry Weight) Determined
in Rice Samples from Sri Lanka

	Raw (Polished) Grains		Parboiled Grains	
	Producer 1 ^a	Producer 2 ^a	Producer 1 ^a	Producer 2 ^a
Al	5.64 \pm 1.45	11.0 \pm 0.78	5.31 \pm 0.29	8.41 \pm 0.81
As	0.034 \pm 0.006	0.034 \pm 0.001	0.065 \pm 0.012	0.092 \pm 0.001
Br	0.308 \pm 0.030	0.208 \pm 0.002	0.221 \pm 0.010	0.259 \pm 0.008
Ca ⁺	94.6 \pm 2.6	94.2 \pm 7.8	-	-
Cd	0.192 (0.088) ^b	<0.5	<0.5	<0.5
Cl	191 \pm 18	240 \pm 8	137 \pm 4	146 \pm 1.4
Co [*]	104 \pm 5	35 \pm 1	39 \pm 2	39 \pm 1
Cr	1.11 \pm 0.01	0.96 \pm 0.01	0.37 \pm 0.04	0.64 \pm 0.33
Cs	0.016 \pm 0.003	0.015 \pm 0.006	0.046 \pm 0.004	0.032 \pm 0.006
Cu	3.37 \pm 0.70	n.a.	2.80 \pm 0.24	2.72 \pm 0.76
Fe	17.6 \pm 3.5	16.8 \pm 0.8	12.9 \pm 2	20.0 \pm 3.1
Hg	<0.01	<0.01	0.033 (0.014) ^b	<0.01
K	1995 \pm 205	1810 \pm 42	2105 \pm 120	2275 \pm 49
La	0.0020 \pm 0.0001	0.007 \pm 0.001	0.004 \pm 0.002	0.0028 \pm 0.0003
Mg	845 \pm 85	677 \pm 4	954 \pm 12	1105 \pm 35
Mn	12.4 \pm 0.6	8.74 \pm 0.26	19.4 \pm 2	20.6 \pm 0.21
Mo	0.824 \pm 0.049	0.893 \pm 0.040	0.920 \pm 0.14	0.675 \pm 0.156
Na	11.3 \pm 0.8	7.9 \pm 1.9	10.6 \pm 1.0	19.7 \pm 6.2
P ⁺	1800 ^c	1450 \pm 150	-	-
Rb	18.9 \pm 1.6	23.7 \pm 0.6	47.5 \pm 3	44.3 \pm 0.99
S ⁺	1250 \pm 50	1250 \pm 50	-	-
Sc [*]	1.1 \pm 0.1	2.5 \pm 0.5	1 ^c	2 \pm 1
Se	0.217 (0.058) ^b	n.a.	0.177 (0.044) ^b	0.115 (0.041) ^b
Zn	22.3 \pm 2.8	21.1 \pm 0.2	25.8 \pm 1	26.0 \pm 0.35

with the present results from Sri Lanka (137–357 mg/kg). The three elements Mg, Mo, and Rb are substantially higher in the samples from Sri Lanka than the values reported in refs. 6 and 7 for the rice samples from other countries. The very high levels of Sc in the samples from Iraq (480–950 μ g/kg) seem to be an indicator of contamination of the samples by external dust (23). The contents of the other elements are more or less mutually consistent with the values published in refs. 6 and 7.

As already mentioned, rice is the dietary staple for many Sri Lankans, and it accounts for more than 50% of the dry diet. Therefore, we decided

Table 3
(continued)

	Rice Flour		NIST Rice Flour
	Producer 1 ^a	Producer 2 ^a	SRM 1568a [§]
Al	7.45 ± 0.93	3.17 ± 0.98	4.4 ± 1.0
As	0.035 ± 0.001	0.061 ± 0.006	0.29 ± 0.03
Br	0.310 ± 0.013	0.267 ± 0.022	8 ^d
Ca	70.0 ± 0.65	71.1 ± 2	118 ± 6
Cd	<0.5	<0.5	0.022 ± 0.002
Cl	357 ± 13	250 ± 6	300 ^d
Co [*]	51 ± 3	11.9 ± 0.4	18 ^d
Cr	0.86 ± 0.08	0.64 ± 0.06	-
Cs	0.016 ± 0.005	0.011 ± 0.001	-
Cu	3.26 ± 0.25	n.a.	2.4 ± 0.3
Fe	10.5 ± 0.49	7.86 ± 1.56	7.4 ± 0.9
Hg	<0.01	<0.01	0.0058 ± 0.0005
K	1470 ± 71	1550 ± 127	1280 ± 8
La	0.008 ± 0.006	0.003 ± 0.002	-
Mg	502 ± 43	573 ± 4	560 ± 20
Mn	11.3 ± 0.3	11.3 ± 0.3	20.0 ± 1.6
Mo	1.02 ± 0.04	1.45 ± 0.04	1.46 ± 0.08
Na	9.8 ± 0.4	8.34 ± 0.02	6.6 ± 0.8
P	1450 ± 50	1600 ± 100	1530 ± 80
Rb	20.0 ± 0.35	23.7 ± 0.21	6.14 ± 0.09
S	1200 ^c	1200 ^c	1200 ± 20
Sc [*]	1.7 ± 0.1	1 ± 0.1	-
Se	n.a.	0.108 ± 0.002	0.38 ± 0.04
Zn	22.3 ± 0.07	20.9 ± 0.07	19.4 ± 0.5

^a Different producers; n.a.: not analyzed.

^{*} µg/kg.

[§] Mean ± 95% expected coverage statistical tolerance interval.

^c Mean of two identical values.

^d Noncertified values.

[†] EDXRF values only for powdered samples.

^b Counting statistics errors.

that it would be interesting to calculate the daily dietary intakes of the elements measured. Approximate daily dietary intakes of the individual elements supplied through rice grains and rice flour (on a dry weight basis) are presented in Table 5, assuming that an adult, healthy individual in Sri Lanka eats rice grains for two meals (about 300 g dry weight), and rice

Table 4
Elemental Concentrations (mg/kg) Obtained by INAA in Rice from Different Countries

Element	Iraq		Brazil		Japan		Iran		Italy	
	Range		Polished Grains		Parboiled Grains		Concentration		Concentration	
Al	1.55	- 2.62	-	-	-	-	-	-	-	-
As	0.07	- 0.13	0.093	- 0.362	0.310	± 0.021	0.03	± 0.01	0.03	± 0.01
Br	0.26	- 0.42	0.36	- 2.11	0.33	± 0.02	1.24	± 0.69	1.55	± 0.13
Cl	75.1	- 319	-	-	-	-	169	± 11.3	32.7	± 5.33
Co*	16	- 100	19.6	- 25.4	27.9	± 4.3	-	-	-	26 ± 8
Cr	0.05	- 0.18	-	-	-	-	0.73	± 0.35	1.18	± 0.03
Cu	1.55	- 3.17	-	-	-	-	4.8	± 0.31	3.59	± 0.69
Fe	2.0	- 5.44	5.76	- 88.0	12.6	± 1.2	-	-	-	41.7 ± 3.4
K	530	- 970	328	- 654	1079	± 58	1930	± 93	978	± 92
Mg	48.3	- 129	-	-	-	-	-	-	-	-
Mn	2.39	- 6.6	-	-	-	-	17.5	± 0.74	20.5	± 0.7
Mo	0.205	- 0.396	-	-	-	-	-	-	-	-
Na	8.76	- 25.8	6.6	- 17.2	16.2	± 0.7	15.6	± 0.65	11.8	± 0.41
Rb	0.20	- 0.50	2.32	- 5.17	11.0	± 0.7	-	-	-	-
Sc*	480	- 950	2.16	-	1.11	± 0.08	-	-	-	-
Se	0.099	- 0.137	-	-	-	-	-	-	-	0.02 ± 0
Zn	7.12	- 14.7	14.0	- 17.9	7.61	± 0.66	19.9	± 1.2	20.2	± 3.83

^c Range for six types of polished grains.

* µg/kg.

Source: Data from refs. 6 and 7.

Table 5
Approximate Daily Dietary Intake of the Individual Elements
Supplied Through Rice

	Raw Rice*	Parboiled Rice*	Rice Flour*	DA ^a
Consumption g/day	300	300	200	
Al	2.50 mg	2.1 mg	1.1 mg	-
Ca	28.3 mg	-	14.1 mg	0.8 g
Cl	64.8 mg	42.6 mg	60.8 mg	-
Cu	1.01 mg	828 µg	652 µg	3 mg
Fe	5.16 mg	4.9 mg	1.8 mg	10-20 mg
K	571 mg	657 mg	302 mg	2-5 g
Mg	228 mg	309 mg	108 mg	0.7 g
Mn	3.18 mg	6 mg	2.2 mg	4 mg
Na	3.9 mg	5.91 mg	2.8 mg	1-2 mg
P	750 mg	-	460 mg	-
Rb	6.4 mg	13.8 mg	4.4 mg	-
S	540 mg	-	360 mg	-
Zn	6.5 mg	7.8 mg	4.3 mg	15 mg
As	10.2 µg	11.1 µg	9.6 µg	
Br	77.4 µg	72 µg	57.8 µg	
Cd	57.6 µg	-	-	
Co	21 µg	11.7 µg	6.4 µg	3 µg ^b
Cr	312 µg	156 µg	150 µg	0.1 mg
Cs	4.8 µg	11.7 µg	2.8 µg	
Hg	-	9.9 µg	-	
La	1.5 µg	1.2 µg	1.2 µg	
Mo	257.7 µg	239.4 µg	248 µg	0.3 mg
Sc	0.6 µg	0.6 µg	0.4 µg	
Se	65.1 µg	43.8 µg	21.6 µg	0.1 g

* Based on the mean concentration value of the two producers.

^a Daily dietary allowance for humans (24).

^b Of vitamin B₁₂.

flour (about 200 g) in the form of various preparations for one meal (breakfast or dinner). For the calculation in Table 5, the mean concentration value of the two producers for each element was taken. Available literature values (24) of "daily allowances" (DA) (i.e., the dietary intake of a given element that a human can consume per day) are also presented in column 5 of Table 5. For the human-essential elements such as Ca, Cr, Cu, Fe, K, Mg,

Mn, Mo, Se, and Zn, the daily dietary intakes through rice are lower than the DAs. They are considerably higher for Co and are slightly higher for Na than the DA values. The DA of 3 μg of Co represents only the amount associated with vitamin B₁₂. The toxicity of Co is, however, low at these concentrations; also, in humans and animals, Co does not accumulate in a target organ (25). It is known that in humans, Co is required in the form of the Co-containing vitamin B₁₂, and most of the dietary Co is not assimilated, thus excreted (25). Therefore, the higher values for Co in Table 5 could not pose a problem for human health. It should, however, be emphasized that the levels of elements in prepared food (in this case, the boiled rice) are more relevant than raw products, as some elements are partially lost as a result of cooking (e.g., Br, Cl, and Hg) or some are added from water and utensils used in cooking. Therefore, the values in Table 5 can be considered as a guide for the approximate daily intake of elements through rice.

Overall, the variations observed in different rice samples from Sri Lanka as well as from other countries can generally be attributed to a number of factors such as varietal differences, soil composition, geographical location, environmental factors, agricultural chemicals, postharvest processing, and the quality of trace element analysis. In general, the values obtained for the rice samples from Sri Lanka in this study are either lower than or consistent with general values published for food plants (11).

CONCLUSIONS

It appears that the rice samples from Sri Lanka had normal levels of both the nutritional (essential) and the nonessential elements. All of the concentration levels of potentially toxic elements such as Cd and Hg (detected only in two samples) were very low in concentration or within normal limits for food plants. The nondestructive analytical technique used, the INAA k_0 method, proved to be well suited to the assay of rice matrices, even in their normal state, as in the case of parboiled grains, for their trace element content.

ACKNOWLEDGMENTS

The first author (R.J.) gratefully acknowledges the financial support received from the International Atomic Energy Agency (IAEA) in the form of a fellowship at ITN, Sacavém, Portugal. We thank Dr. Fátima Araújo and Mr. Pedro M. F. Valério for their help in the analysis of calcium, phosphorus, and sulfur by EDXRF, and Ms. Ausenda Machado for technical assistance in the INAA k_0 analysis.

REFERENCES

1. F. B. Salisbury and C. W. Ross, *Plant Physiology*, 4th ed., Wadsworth, San Francisco (1992).
2. M. Geldmacher-von Mallinckrodt and D. Meissner, General aspects of the role of metals in clinical chemistry, in *Handbook on Metals in Clinical and Analytical Chemistry*, H. G. Seiler, A. Sigel, and H. Sigel, eds., Marcel Dekker, New York, pp. 13–29 (1994).
3. F. H. Nielsen, Evolutionary events culminating in specific minerals becoming essential for life, *Eur. J. Nutr.* **39(2)**, 62–66 (2000).
4. G. N. Schrauzer, Lithium: occurrence, dietary intakes and nutritional essentiality, *J. Am. Coll. Nutr.* **21**, 14–21 (2002).
5. P. R. Jennings, W. R. Coffman, and H. E. Kauffman, *Rice Improvement*, International Rice Research Institute (IRRI), Los Baños, Philippines (1979).
6. S. M. Al-Jobori, K. M. Shihab, M. Jalil, A. Saad, and A. Mohsin, Multielement determination in rice, wheat, and barley by instrumental neutron activation analysis, *Biol. Trace Element Res.* **26–27**, 637–645 (1990).
7. E. Cortes Toro, H. A. Das, J. J. Fardy, et al., Toxic heavy metals and other trace elements in foodstuffs from 12 different countries, *Biol. Trace Element Res.* **43–45**, 415–422 (1994).
8. R. Doll and R. Peto, The causes of cancers: quantitative estimate of avoidable risk of cancer in the United States today, *J. Natl. Cancer Inst.* **66B**, 1193–1308 (1981).
9. J. Chen, H. D. Foster, and L. Zhang, Cancer and soil characteristics in the People's Republic of China, *Environ. Geochem. Health* **16**, 565–588 (1994).
10. K. S. Kasprzak, W. Bal, and A. A. Karaczyn, The role of chromatin damage in nickel-induced carcinogenesis. A review of recent developments, *J. Environ. Monit.* **5(2)**, 183–187 (2003).
11. A. Kabata-Pendias and H. Pendias, *Trace Elements in Soils and Plants*, CRC, Boca Raton, FL (1984).
12. *Codex Alimentarius Commission. Contaminants*, CAC/VOL. XVII-Ed. 1, FAO, Rome (1984).
13. G. V. Iyengar and B. Sansoni, Sample preparation of biological materials for trace element analysis, in *Elemental Analysis of Biological Materials*, Technical Reports No. 197, International Atomic Energy Agency, Vienna (1980).
14. M. C. Freitas and E. Martinho, Neutron activation analysis of reference materials by the k_0 -standardization and relative methods, *Anal. Chim. Acta* **219**, 317–322 (1989).
15. M. C. Freitas and E. Martinho, Determination of trace elements in reference materials by the k_0 -standardization method (INAA), *Talanta* **36(4)**, 527–531 (1989).
16. B. Smodiš, R. Jačimović, S. Jovanović, and P. Stegnar, Determination of trace elements in standard reference materials by the k_0 -standardization method, in *Nuclear Analytical Methods in the Life Sciences*, R. Zeisler and V. P. Guinn, eds., Humana, Totowa, NJ, pp. 43–51 (1990).
17. S. B. Sarmani, I. Abugassa, A. Hamzah, and M. D. Yahya, Elemental analysis of herbal preparations for traditional medicines by neutron activation analysis with the k_0 -standardization method, *Biol. Trace Element Res.* **71–72**, 365–376 (1999).
18. M. F. Araújo, A. Conceição, T. Barbosa, M. T. Lopes, and M. Humanes, Elemental composition of marine sponges from the Berlengas Natural Park–Western Portuguese Coast, *X-Ray Spectrom.* **32**, 428–433 (2003).
19. R. Jayasekera, M. C. Freitas, and M. F. Araújo, Bulk and trace element analysis of spices: the applicability of k_0 -standardization and energy dispersive X-ray fluorescence, *J. Trace Elements Med. Biol.* **17(4)**, 221–228 (2004).
20. J. Op De Beeck, GELIAN Program, Institute for Nuclear Sciences, University of Ghent, Belgium (1978).

21. F. De Corte, The k_0 -standardization method—a move to the optimization of neutron activation analysis, Agregé thesis, University of Ghent, Belgium (1987).
22. M. C. Freitas, Instrumental neutron activation analysis of geological and biological reference materials using the k_0 -standardization method, in *Nuclear Analytical Methods in the Life Sciences*, R. Zeisler and V. P. Guinn, eds., Humana, Totowa, NJ, pp. 189–194 (1990).
23. R. Bargagli, *Trace Elements in Terrestrial Plants*, Springer-Verlag, New York (1998).
24. H. Sigel, A. Sigel, and H. G. Seiler, Overview and use of the handbook, in *Handbook on Metals in Clinical and Analytical Chemistry*, H. G. Seiler, A. Sigel, and H. Sigel, eds., Marcel Dekker, New York, pp. 1–12 (1994).
25. L. Thunus and R. Lejeune, Cabalt, in *Handbook on Metals in Clinical and Analytical Chemistry*, H. G. Seiler, A. Sigel, and H. Sigel, eds., Marcel Dekker, New York, pp. 333–338 (1994).